"ORIGINAL"

PLANETARY RESEARCH CENTER

LOWELL OBSERVATORY
FLAGSTAFF, ARIZONA 86001

FINAL REPORT - NGR-03-003-007
JULY 1, 1968 - JUNE 30, 1974

(NASA-CR-138941) PLANETARY RESEARCH CENTER Final Report, 1 Jul. 1968 - 30 Jun. 1974 (Lowell Observatory) 52 p HC $4.25 CSCL 03A

N74-30293

Unclas
G3/30 54887

INTRODUCTION

Mars, Jupiter, and Venus, like the Earth, are known to be dynamic planets. The atmospheric and/or surface features of the former two can be seen to change from year to year, from month to month, and even from day to day, with only a modest telescope. Venus, on the other hand, is featureless to the eye, but photographs of the planet in ultraviolet light show transient dark markings which are variable in both position and morphology.

Astronomers have long believed that if the changes occurring on our neighboring planets could be monitored in sufficient detail, a better understanding of the physical conditions in their atmospheres and on their surfaces would be achieved. However, except for changes occurring over relatively long time scales, such studies have been frustrated by the impossibility of obtaining a sufficiently continuous observing record from a single observing site.

In order to overcome this problem, Lowell Observatory, with support from NASA, undertook in 1968 the organization of a photographic planetary patrol. Contractual agreements were arranged with several observatories around the world, and in 1969 these institutions embarked upon a coordinated program of planet photography. The present document, which constitutes the final report under NGR-03-003-007, will summarize the history, accomplishments, and scientific results of this international effort. Although NGR-03-003-007 is terminating, we wish to emphasize that the patrol program itself is continuing with funding under NGR-03-003-001, the regular sustaining grant for the Planetary Research Center.

HISTORY OF THE PROGRAM

Eight different observatories, whose locations are shown in Figure 1, have participated in the Planetary Patrol during the past five years. Observations have been carried out at Mauna Kea Observatory in Hawaii, Cerro Tololo Inter-American Observatory in Chile, and Lowell Observatory from 1969 until the present. New Mexico State University participated briefly during 1969. Observations were made at Mount Stromlo Observatory near Canberra, Australia, from 1969 through 1971. Perth Observatory and the Indian Institute of Astrophysics joined the network in 1971. Perth continues to participate, but observations in India ended in 1973. The Republic Observatory at Johannesburg, South Africa, cooperated in the program from 1969 through 1973.

In order that the photographs from the various Patrol stations have the desired degree of homogeneity, all stations were equipped with essentially identical 35-mm camera systems. These cameras automatically record the place, date, U.T., and filter color on the edge of each film frame. 24-inch, F/75 Boller and Chivens telescopes were installed at Mauna Kea, Cerro Tololo, and Perth. New 24-inch, F/75 optics were installed in existing telescopes at Lowell and in India. The refracting telescopes at Mount Stromlo and Republic Observatories were fitted with Barlow lenses to bring their effective focal lengths to within 1 percent of that of the F/75 reflectors.

For periods of several months around each opposition of Mars and Jupiter and during several Venus apparitions, photographs of the planets were taken hourly at each Patrol station. Exposure sequences were normally made in four colors: red, green, blue, and ultraviolet. A standard sequence in each color consists of fourteen frames taken in rapid succession. The exposed films from all stations were sent to the Planetary Research Center in Flagstaff, where they were calibrated and processed under strictly controlled conditions. After development, the rolls were edited and the individual image sequences graded for quality. All usable sequences were copied, then mounted and catalogued.

Readers interested in further details concerning the organization and history of the Patrol are referred to the following two published papers:

Baum, W. A., Millis, R. L., Jones, S. E., and Martin, L. J. (1970). "The International Planetary Patrol Program." Icarus 12, 435.

*Baum, W. A. (1973). "The International Planetary Patrol Program: An Assessment of the First Three Years." Planet. Space Sci. 21, 1511.

ACCOMPLISHMENTS

In the five-and-one-half years that it has operated, the Planetary Patrol Program has produced a photographic collection of unprecedented size, homogeneity, and continuity with time. The numbers of 14-frame sequences produced during the years 1969 through 1973, broken down according to station and planet, are listed in Table I. The total corresponds to more than 1,200,000 individual images and more than 16 miles of film. It exceeds by five times the number of image sequences in our historical collection spanning the previous 60 years, which was itself the largest collection of planetary photographs in the world prior to the Patrol.

*Copy attached

TABLE I

Number of Usable 14-Image Sequences
International Planetary Patrol Program 1969-1973

Station	Mars	Jupiter	Venus[4]
Lowell	4,773	5,859	300
Mauna Kea	8,989	14,675	1,071
Cerro Tololo	8,284	12,608	119
Magdalena Peak[1]	518	262	---
Mount Stromlo[2]	2,428	4,282	---
Perth[3]	3,049	5,274	18
Kavalur[3]	425	117	---
Republic	5,510	8,386	287
TOTAL	33,976	51,463	1,795

GRAND TOTAL = 87,234

[1]Operational 1969 only
[2]Operational 1969-1971
[3]Operational 1971-1973
[4]Not observed in 1969

Figure 2 is an excellent illustration of the degree of continuity in the Patrol collection. The figure shows a series of 12 photographs of Mars spaced at approximately two-hour intervals and spanning one rotation of the planet. Because of the near synchronism of the rotational periods of the Earth and Mars, any particular observatory sees nearly the same face of Mars night after night. Only by means of a patrol network can one obtain a sufficiently continuous photographic record of all faces of the planet. With the present Patrol collection one has better than an 80-percent chance of finding photographic sequences showing any desired feature on any particular date during the last three apparitions of Mars.

Another example of the excellent Patrol coverage of dynamic phenomena on Mars is given in Figure 3. Here we see the development and regression of the great dust storm which occurred in 1971 at the time of the Mariner 9 encounter. Patrol coverage of this storm is such that we have been able to plot its progress on a near-hourly basis. The results have been published in several papers (Capen and Martin, 1971; Capen and Martin, 1972a; Martin, 1974a). A preprint of one is enclosed. An interesting "ministorm" was also covered in 1971 (Capen, 1974), as well as another major storm in 1973 (Martin, 1974a). Color images documenting the 1973 storm are shown in Figure 4. These color images were produced from ordinary black-and-white Patrol images using the color reconstruction technique developed here by Jones and Cook (1974).

Inge has prepared a series of albedo maps of Mars based on the Patrol images. These maps, which are shown at a greatly reduced scale in Figure 5, have been distributed widely throughout the scientific community. This mapping project will be continued for the next several apparitions of Mars to provide a basis for studies of long-term changes in the planet's albedo features.

Inge has also used Patrol photography to produce a series of maps showing the classical albedo features of Mars superimposed on the planet's topography as recorded by Mariner 9. An example of these maps is shown in Figure 6. Inge and Baum (1973) have published a discussion of the correlation between albedo and topography (see attached reprint).

Many studies of Mars in addition to the few mentioned above have been based on the Patrol photography. We will not describe each of them here. Publications resulting from these studies are among those listed in the final section. The interested reader is invited to consult the literature for details.

It is seen in Table I that images of Jupiter comprise well over half of the Patrol collection. There is a wealth of detail visible on these images, and the planet exhibits both gradual and abrupt changes. We have confirmed the existence of a 90-day oscillation in the longitude of the Great Red Spot (Millis and O'Dell, unpublished); and Layton (1971) and Inge (1973a) have studied rotational velocities of cloud features as a function of color and of latitude, respectively.

At present we are readying equipment which will enable us to digitize Jupiter images (as well as those of other planets) so that they can be processed far more thoroughly by computer techniques. Specifically, we plan to rectify images geometrically so that we can construct time-lapse sequences of various Jovian cloud features. It is hoped that flow patterns will become apparent from these sequences and, as a result, a better understanding of the global circulation of Jupiter's atmosphere will be achieved.

Examples of the dark markings which are seen on ultraviolet Patrol photographs of Venus are shown in Figure 7. Caldwell has used the Patrol photographs to determine the rotational period of these features, and Bowell is presently investigating the correlation between these features and the degree of polarization of the planet.

While the Patrol collection has formed the basis for much of the research at the Planetary Research Center and will continue to do so for the foreseeable future, it has also been consulted frequently by scientists from other institutions. Several investigators have come to the Center for varying periods of time, while many others have received film copies from us for use at their own laboratories. We expect to see a continued use of the Patrol collection by the general scientific community and encourage this practice in every way we can. A partial list of outside users of the Patrol collection is given in Table II.

FUTURE PATROL ACTIVITIES

Although this is the final report under NGR-03-003-007, which has provided financial support for the Planetary Patrol Program, the program itself, as we mentioned before, will continue with support from NGR-03-003-001. We are, however, reducing the Patrol in the sense that fewer observing stations will be maintained and observations will be confined to fewer months per year. The rationale for an extended, but reduced, photographic patrol has been given in the most recent proposals under NGR-03-003-007 and NGR-03-003-001.

Photographic studies are not the only planetary studies that can benefit from synoptic observations. In fact, we have already carried out photometric observations of the Galilean satellites from the Patrol stations at Lowell, Cerro Tololo, and Perth. We expect to continue diversification of this type.

SUMMARY

During the six years that NGR-03-003-007 has been in effect, a network of eight observing sites in five countries was set up, equipped, and devoted to photography of Mars, Jupiter, and Venus. This network has produced a collection of photographs which is many times more comprehensive than any that existed previously. The collection is a truly unique astronomical resource which has yielded several interesting discoveries concerning the nature of dynamic physical processes on our neighboring planets. It will continue to do so for years to come.

TABLE IIA

Guest Investigators Using Patrol Films

Dr. Kenneth O'Dell
Northern Arizona University

Dr. William M. Sinton
Institute for Astronomy
University of Hawaii

*Ms. A. Scott
New Mexico State University

*Dr. G. de Vaucouleurs
University of Texas, Austin

Dr. J. Bergstrahl
Jet Propulsion Laboratory

Mr. Grahame Browne
University of Leicester
England

Dr. William M. Hartmann
Planetary Science Institute

Mr. J. C. Robinson
New Mexico State University

Mr. John Fountain
Lunar and Planetary Laboratory
University of Arizona

Dr. P. Charvin
Institute National d'Astronomie
ēt de Geophysique, France

Mr. Ray Arvidson
Brown University

Mr. J. Kelly Beatty
California Institute of Technology

Dr. Gary Layton
Northern Arizona University

Dr. Michael J. S. Belton
Kitt Peak National Observatory

Mr. Larry Giver
NASA - Ames Research Center

*Dr. William M. McKinney
University of Wisconsin at
Stevens Point

Dr. A. L. Lane
NASA Headquarters
Washington, D. C.

Dr. James Underwood
West Texas State University

Dr. Bradford A. Smith
New Mexico State University

Dr. Raymond Hide
Meteorological Office
England

*Mr. P. C. Crump
Mauna Kea Observatory

Dr. Richard Shorthill
Boeing Research Laboratory

Mr. Mike Malin
California Institute of Technology

*Dr. Michael Price
IITRI and Planetary Science Institute

*Multiple visits

TABLE IIB

Recipients of Patrol Images

Mariner 1969 Imaging Science Team
c/o Mr. Alan Herriman
Jet Propulsion Laboratory

*Dr. Robert Murphy
Institute for Astronomy
University of Hawaii

Dr. Albert J. Pallmann
Saint Louis University

*Ms. Susan Smith
New Mexico State University

*Dr. Audouin Dollfus
Observatoire de Paris

*Dr. G. de Vaucouleurs
University of Texas, Austin

Dr. Eric Clausen
Minot State College

Dr. Brian O'Leary
NASA - Ames Research Center

*Dr. Bruce Hapke
University of Pittsburgh

Mr. J. Kelly Beatty
California Institute of Technology

Dr. Paul Richter
California State University
at Northridge

*Dr. James Westphal
California Institute of Technology

Dr. William M. Hartmann
Planetary Science Institute

Mr. Bruce A. Waddington
California Institute of Technology

Dr. Michael J. S. Belton
Kitt Peak National Observatory

*Dr. William M. Sinton
Institute for Astronomy
University of Hawaii

Mr. Larry Giver
NASA - Ames Research Center

Mr. John Fountain
Lunar and Planetary Laboratory
University of Arizona

Dr. P. Charvin
Institute National d'Astronomie
et de Geophysique, France

*Mr. Marvin Mayo
Van Nuys, California

*Dr. T. McCord
Massachusetts Institute of Technology

*Dr. Richard Shorthill
Boeing Research Laboratory

Dr. J. C. Bhattacharyya
Indian Institute for Astrophysics
India

*Dr. Thomas F. Greene, The Boeing
Company and University of Washington

Dr. Edward L. G. Bowell
Observatoire de Paris

*Multiple requests

TABLE IIB (cont'd)

Recipients of Patrol Images (cont'd)

Dr. G. E. Hunt
Meteorological Office
England

*Ms. A. Scott
New Mexico State University

Dr. J. Bergstrahl
Jet Propulsion Laboratory

Mr. P. C. Crump
Mauna Kea Observatory

Dr. Edwin Barker
McDonald Observatory

*Mr. J. C. Robinson
New Mexico State University

Dr. D. J. Adams
University of Leicester
England

Dr. Carl Sagan
Cornell University

Dr. Wesley A. Traub
Smithsonian Astrophysical Observatory

Dr. Andrew P. Ingersoll
California Institute of Technology

TABLE IIC

Recipients of Special Catalogue Searches of Patrol Films

Dr. Edwin S. Barker
McDonald Observatory

Dr. C. Boyer
IAU Data Center, France

Dr. Wesley A. Traub
Smithsonian Astrophysical Observatory

Dr. Thomas F. Greene
University of Washington

Dr. G. E. Hunt
Meteorological Office, England

*Multiple requests

PUBLICATIONS

The publications listed below are based at least in part on the Planetary Patrol collection:

Baum, W. A. (1972a). "High Resolution Planetary Observations." Space Research 12, 1671, Akademie-Verlag, Berlin.

Baum, W. A. (1972b). "Where Will the Martian Dust be When Viking Arrives?" Bull. Amer. Astron. Soc. 4, 374.

Baum, W. A. (1972c). "Results Emerging from the International Planetary Patrol Programme." Proceedings of the NATO Advanced Study Institute on Planetary Atmospheres held at Istanbul, Turkey, 22 August - 2 September 1972.

Baum, W. A. (1973). "The International Planetary Patrol Program: An Assessment of the First Three Years." Planet. Space Sci. 21, 1511.

Baum, W. A. (1974). "Earth-Based Observations of Martian Albedo Changes." Icarus, in press.

Baum, W. A., and Ferguson, H. M. (1974). "A Four-Year Comparison of Astronomical Observing Conditions at Seven Observatories." Bull. Amer. Astron. Soc., in press.

Baum, W. A., and Martin, L. J. (1973). "Behavior of the Martian Polar Caps Since 1905." Bull. Amer. Astron. Soc. 5, 296.

Baum, W. A., Millis, R. L., Jones, S. E., and Martin, L. J. (1970). "The International Planetary Patrol Program." Icarus 12, 435.

Boyce, P. B. (1973). "Remote Sensing Photometric Studies of Mars in 1971." Icarus 18, 134.

Boyce, P. B., and Faure, B. Q. (1970). "Photometric Behavior of Semi-Permanent Martian Clouds." Bull. Amer. Astron. Soc. 2, 233.

Boyce, P. B., and Thompson, D. T. (1972). "A New Look at the Martian 'Violet Haze' Problem. I. Syrtis Major-Arabia, 1969." Icarus 16, 291.

Caldwell, J. J. (1972). "Retrograde Rotation of the Upper Atmosphere of Venus." Icarus 17, 608.

Capen, C. F. (1971). "Martian Yellow Clouds--Past and Future." Sky and Telescope 41, 117.

Capen, C. F. (1972). Contributions to sections 3.5, 3.6, 4.0, 4.1, and 4.2 of Mars Scientific Model (Eds. C. Michaux and R. L. Newburn), JPL Document No. 606-1.

Capen, C. F. (1973). "The Planet Mars in 1973." Sky and Telescope **46**, 53.

Capen, C. F. (1974). "A Martian Yellow Cloud - July 1971." Icarus **22**, No. 3, in press.

Capen, C. F., and Martin, L. J. (1971). "The Developing Stages of the Martian Yellow Storm of 1971." Lowell Obs. Bull. No. 157.

Capen, C. F., and Martin, L. J. (1972a). "Mars' Great Storm of 1971." Sky and Telescope **43**, 276.

Capen, C. F., and Martin, L. J. (1972b). "Survey of Martian Yellow Storms." Bull. Amer. Astron. Soc. **4**, 374.

Capen, C. F., and Martin, L. J. (1973). "The Martian Yellow Cloud of July 1971." Bull. Amer. Astron. Soc. **5**, 266.

Inge, J. L. (1972). "Jovian Rotation Profiles for 1970 and 1971." Publ. Astron. Soc. Pacific **84**, 641.

Inge, J. L. (1973a). "Short-Term Jovian Rotation Profiles, 1970-1972." Icarus **20**, 1.

Inge, J. L. (1973b). "Martian Albedo Features and Topography." (Lambert azimuthal equal-area projection, 0°, 120°, 240° meridians, 1:28,600,000). Lowell Observatory Map Series.

Inge, J. L. (1973c). "Martian Albedo Features and Topography." (Mercator map, 1:25,000,000). Lowell Observatory Map Series. Also Mercury **2**, No. 6, 10/11 (centerfold).

Inge, J. L. (1973d). "The Red Planet Mars." Color map supplement to National Geographic Magazine **143**, February 1973.

Inge, J. L. (1974). "Mars 1973." (Albedo map, 1:25,000,000). Lowell Observatory Map Series.

Inge, J. L., and Baum, W. A. (1973). "A Comparison of Martian Albedo Features with Topography." Icarus **19**, 323.

Inge, J. L., Capen, C. F., Martin, L. J., and Faure, B. Q. (1971). "Mars 1969." (Albedo map, 1:35,200,000). Lowell Observatory Map Series.

Inge, J. L., Capen, C. F., Martin, L. J., Faure, B. Q., and Thompson, D. T. (1971). "A New Map of Mars from Planetary Patrol Photographs." Sky and Telescope **41**, 336.

Inge, J. L., Capen, C. F., Martin, L. J., and Thompson, D. T. (1971). "Mars 1971" (Albedo map, 1:25,000,000). Lowell Observatory Map Series.

Jones, S. E., and Cook, N. O. (1974). "Producing Color Photographs of the Planets from Filtered Black-and-White Images." Sky and Telescope **47**, 57.

Layton, R. G. (1971). "Vertical Shear in the Jovian Equatorial Zone." Icarus **15**, 480.

Martin, L. J. (1974a). "The Major Martian Yellow Storm of 1971." Icarus **22**, No. 2, in press.

Martin, L. J. (1974b). "The Major Martian Dust Storms of 1971 and 1973." Icarus, in press.

Martin, L. J., Baum, W. A., and Crump, P. C. (1973). "The Distribution of Clouds on Mars in 1969 and 1971." Bull. Amer. Astron. Soc. **5**, 298.

Martin, L. J., and McKinney, W. M. (1974). "North Polar Hood of Mars in 1969 (May 18 - July 25). I. Blue Light." Icarus, in press.

Martin, L. J., and Smith, J. L. (1971). "Mapping Martian Clouds from 1969 Photographs." Publ. Astron. Soc. Pacific **83**, 606.

Thompson, D. T. (1971). "A Statistical Study of Martian 'Blue Clearing' in 1969." Bull. Amer. Astron. Soc. **3**, 281.

Thompson, D. T. (1972a). "Martian Regional Contrasts in 1971." Bull. Amer. Astron. Soc. **4**, 374.

Thompson, D. T. (1972b). "The Variation in Contrast of Syrtis Major in 1971." Bull. Amer. Astron. Soc. **4**, 313.

Thompson, D. T. (1973a). "Interpretation of Diurnal Contrast Changes on Mars." Bull. Amer. Astron. Soc. **5**, 296.

Thompson, D. T. (1973b). "A New Look at the Martian 'Violet Haze' Problem. II. 'Blue Clearing' in 1969." Icarus 18, 164.

Thompson, D. T. (1973c). "Time Variation of Martian Regional Contrasts." Icarus 20, 42.

THE INTERNATIONAL PLANETARY PATROL NETWORK

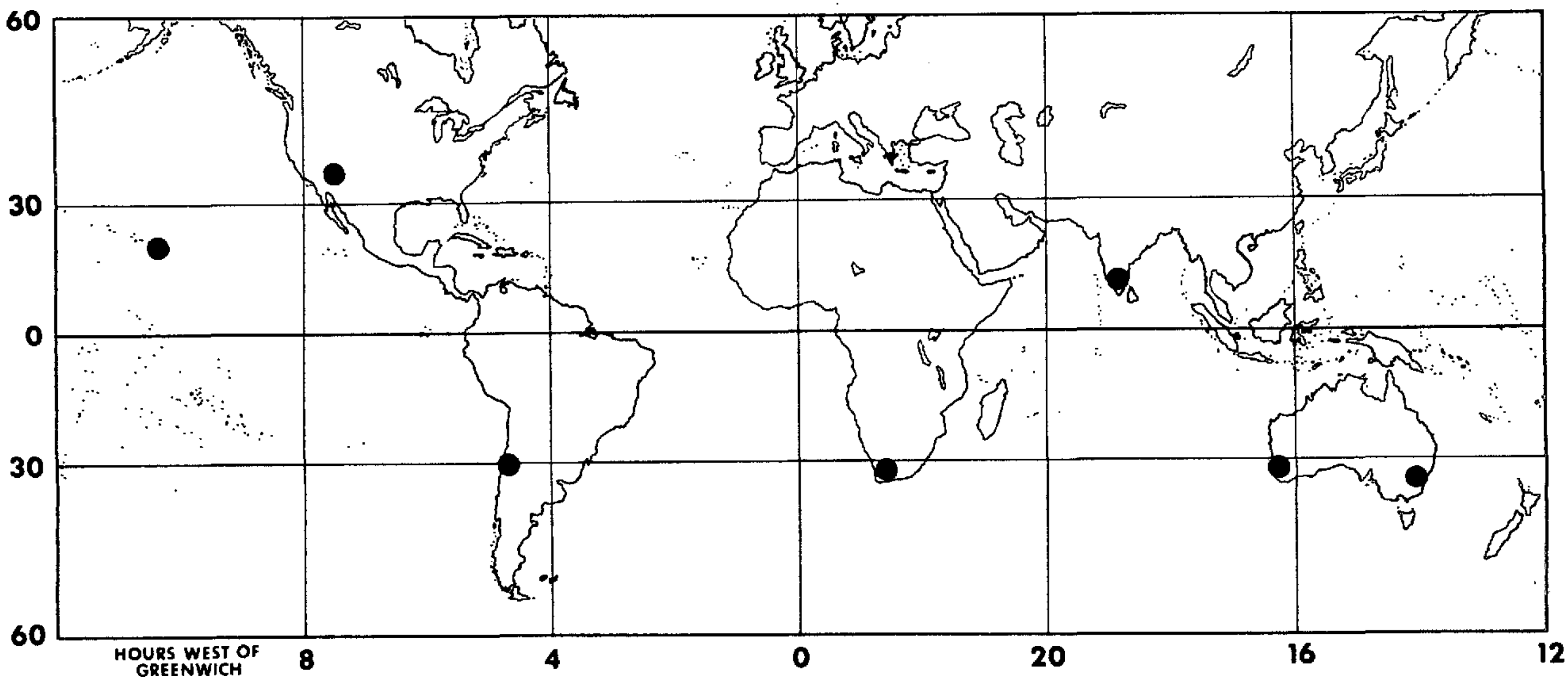


Figure 1.

FINAL REPORT - NGR-03-003-007

July 1, 1968 - June 30, 1974

PURPOSE OF GRANT

"To establish and operate a Planetary Patrol Program"

Submitted: July 31, 1974

William A. Baum

William A. Baum
Principal Investigator

Robert Millis

Robert L. Millis
Co-Investigator

ELG Bowell

Edward L. G. Bowell
Co-Investigator

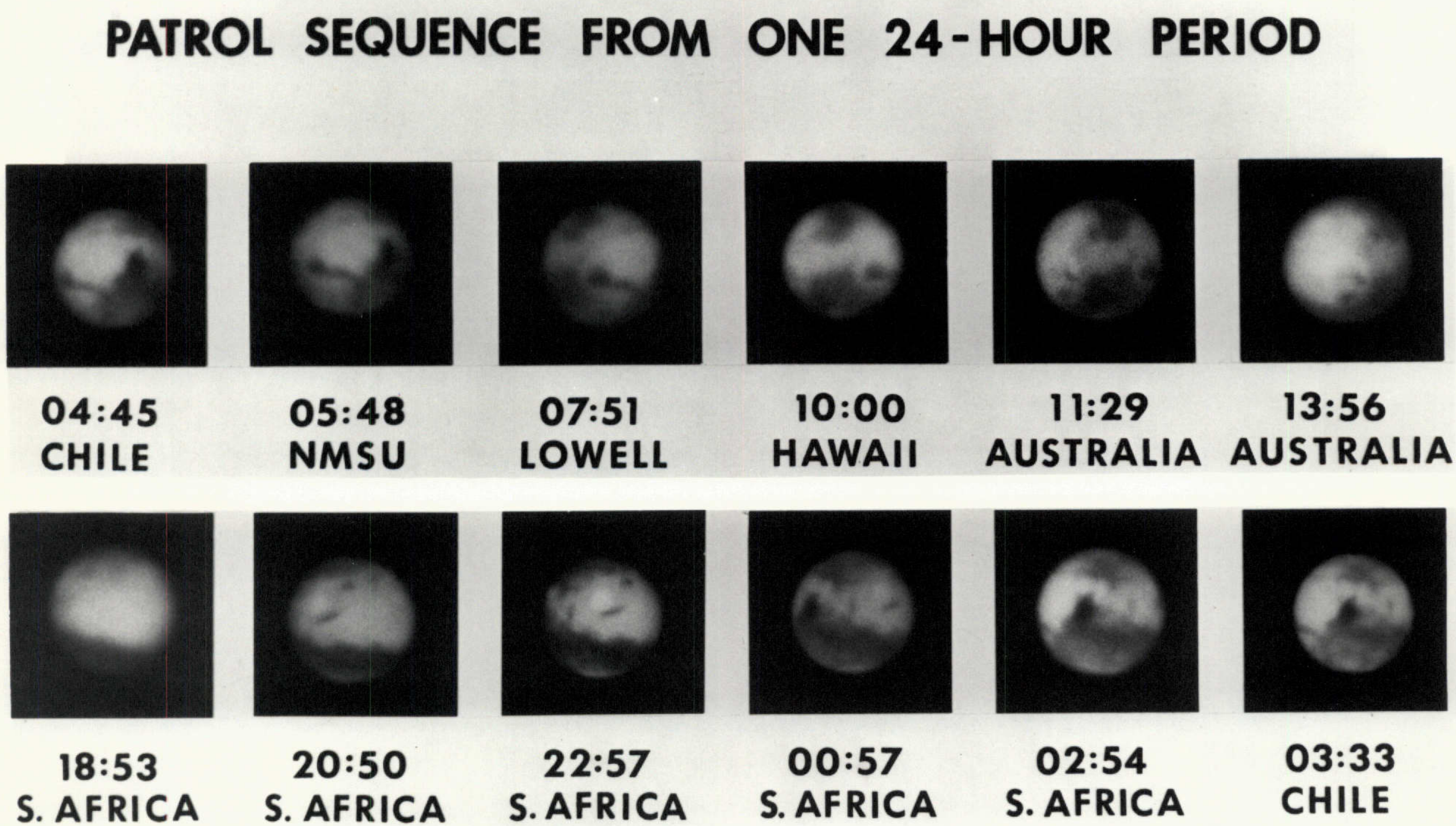
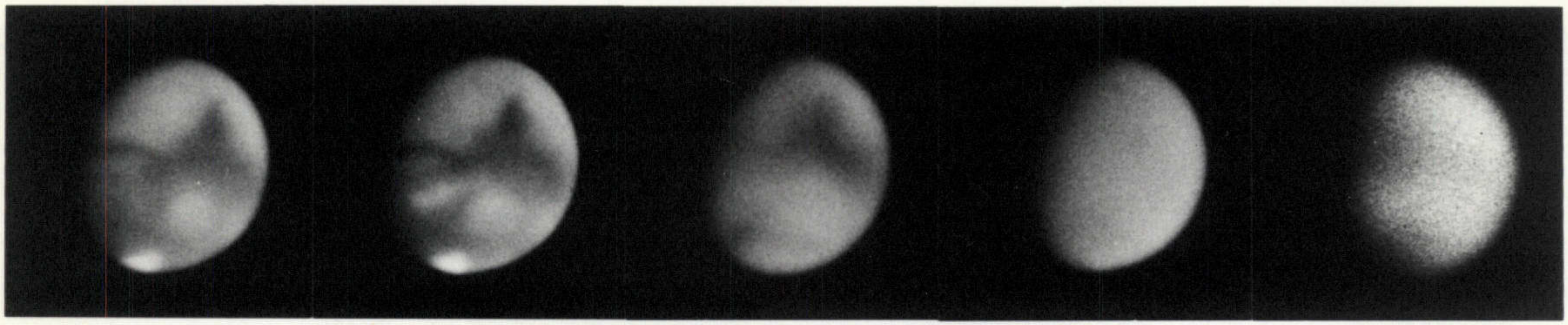

PATROL SEQUENCE FROM ONE 24-HOUR PERIOD
04:45
CHILE
05:48
NMSU
07:51
LOWELL
10:00
HAWAII
11:29
AUSTRALIA
13:56
AUSTRALIA
18:53
S. AFRICA
20:50
S. AFRICA
22:57
S. AFRICA
00:57
S. AFRICA
02:54
S. AFRICA
03:33
CHILE

Figure 2.

MARS 1971 — YELLOW STORM

Before Storm	Beginning of Storm	Surface Partly Obscured	Surface Completely Obscured	Surface Partly Cleared



Sept. 21	Sept. 22	Oct. 3	Oct. 21	Dec. 20
0.48	0.48	0.54	0.64	1.09 A.U. from Earth

International Planetary Patrol Program
Lowell Observatory, Flagstaff, Arizona

16

Figure 3.


1973 DUST STORM ON MARS
Solis Lacus Region
Day 1 = 13 Oct. 1973
Pre Storm
Day 1
2
3
4
6
8
34
International Planetary Patrol Program
Lowell Observatory, Flagstaff, Arizona

Figure 4

Figure 4. This sequence of eight images illustrates the main development of the 1973 dust storm in the Solis Lacus region. The first image shows the "normal" appearance of that region just before the onset of the storm, the next six show successive stages of the build-up, and the last image shows a partial return to normal.

MARTIAN ALBEDO FEATURES

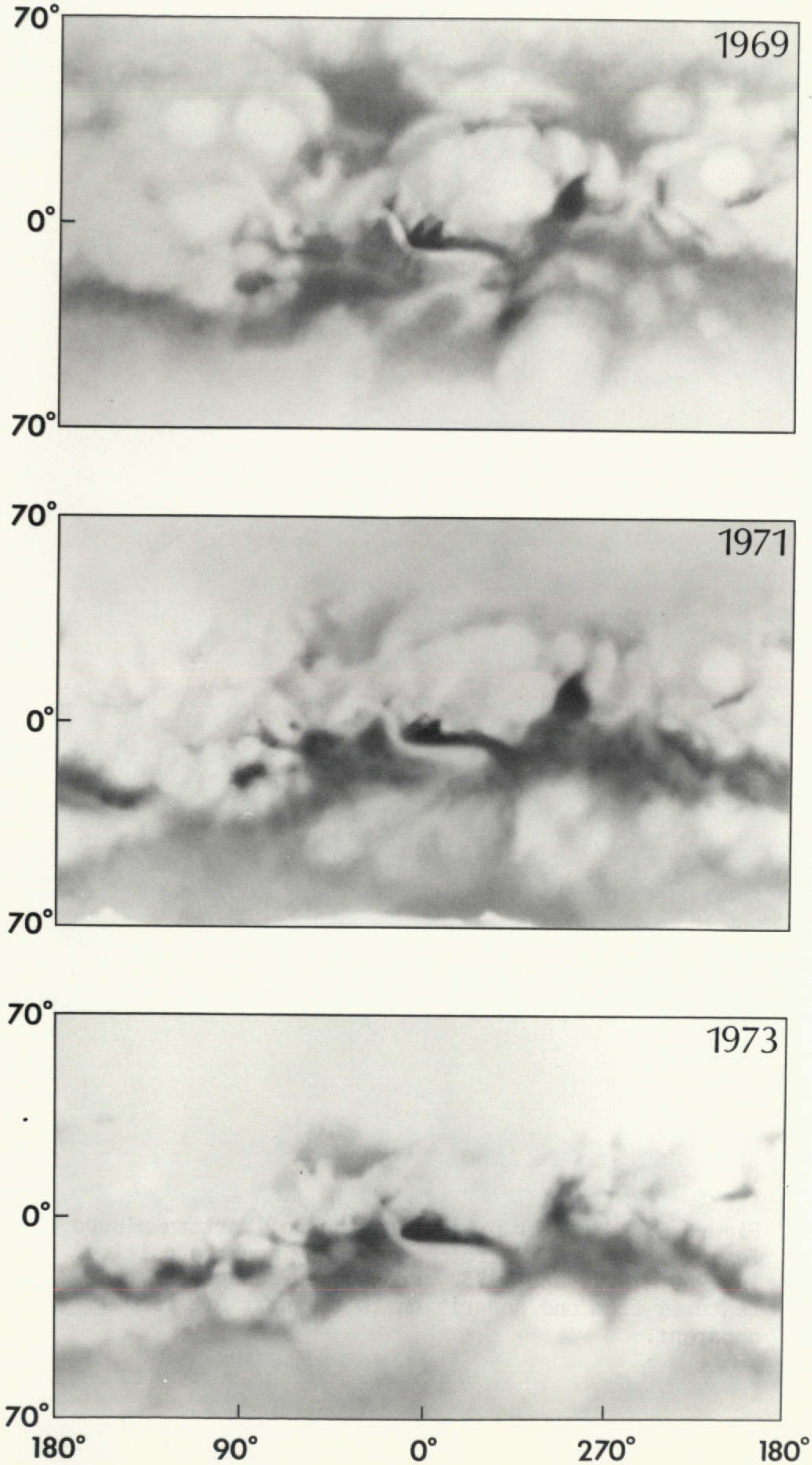


Figure 5.

Figure 5. Mercator projection maps of Martian albedo features based on Patrol photography near opposition in 1969, 1971, and 1973. Pronounced changes in the features from one apparition to the next are readily apparent.

MARTIAN ALBEDO FEATURES AND TOPOGRAPHY

Planetary Research Center

LOWELL OBSERVATORY

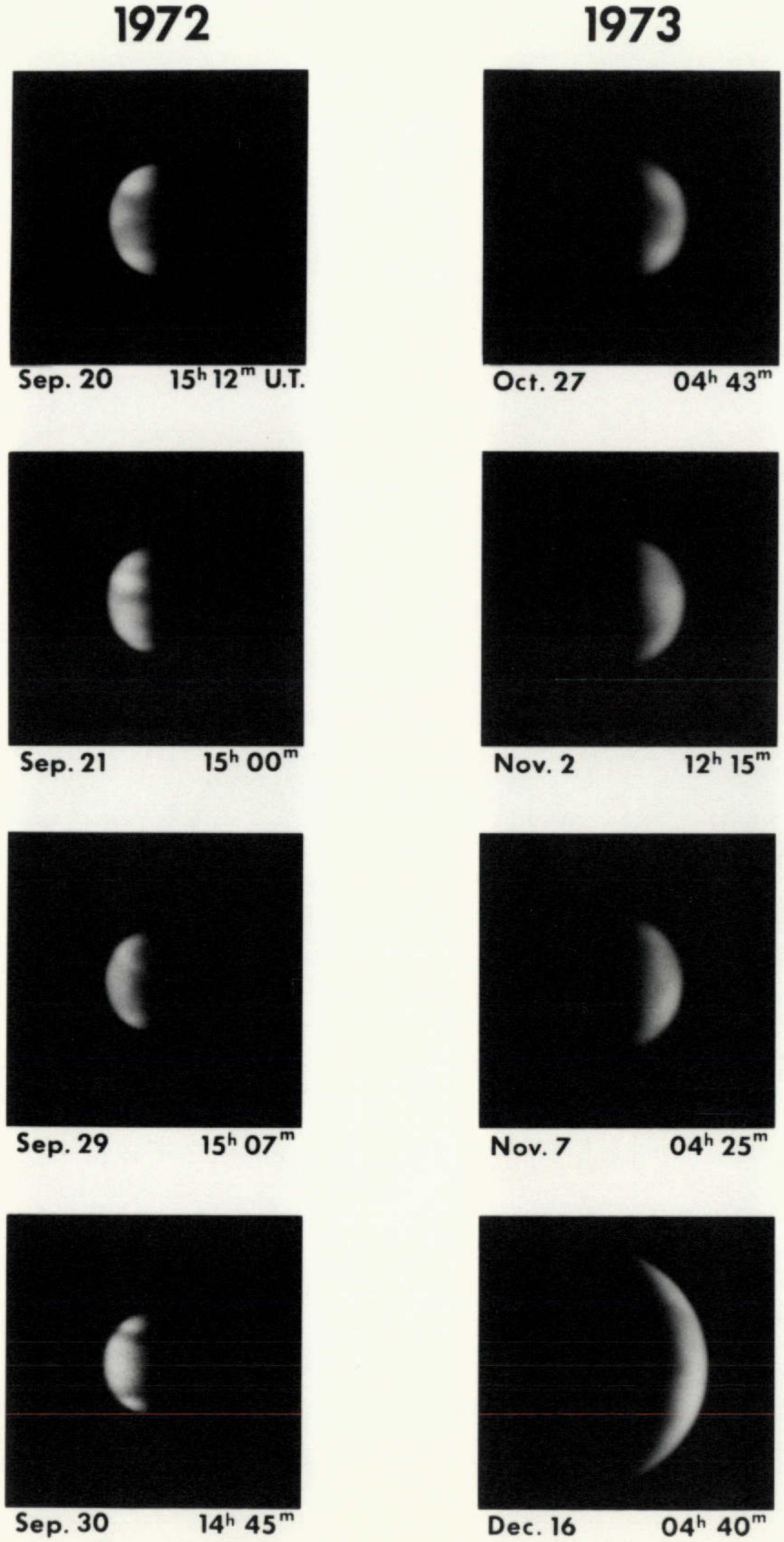
FLAGSTAFF, ARIZONA 86001, U.S.A.

Albedo features are derived from Earth-based International Planetary Patrol photographs obtained during Martian apparitions of 1969 and 1971. The positions of these features were controlled by projecting the photographs optically onto orthographic graticules. The topographic mapping is an enhanced rendition of the USGS shaded relief map of Mars, MM-25M-IR, which was based on an uncontrolled photomosaic (second version) of Mariner 9 MTVS images. The cooperation of the USGS Center of Astrogeology in Flagstaff is gratefully acknowledged.

Figure 6.

19

ULTRAVIOLET PHOTOGRAPHS OF VENUS



International Planetary Patrol Program
Lowell Observatory, Flagstaff, Arizona

Figure 7.

21

ATTACHMENT A

THE INTERNATIONAL PLANETARY PATROL PROGRAM AS ASSESSMENT OF THE FIRST THREE YEARS

BY W A BAUM A73-42978
PLANETARY RESEARCH CENTER LOWELL OBSERVATORY, FLAGSTAFF, ARIZONA U.S.A.

ATTACHMENT B

THE MAJOR MARTIAN YELLOW STORM OF 1971

Leonard J. Martin

Planetary Research Center
Lowell Observatory
Flagstaff, Arizona 86001

ABSTRACT

Extensive Earth-based photography produced by the International Planetary Patrol has been used to map the positions of brightened areas (clouds) during the 1971 storm on Mars. The mapping was done on an hourly basis from two days prior to the onset of the storm through its twenty-second day. Summaries of these maps are presented to illustrate the changes that take place during the course of a Martian day, as well as the changes from one day to the next. It is shown that the storm goes through a daily cycle of regeneration, although each day it advances farther than it did the day before. The possible influence of Martian topography on the progress of the storm is examined. Comparisons between red- and blue-filter photographs of the storm are presented cartographically and are discussed. Areas most affected by the storm during this period are summarized in Figure 8.

HISTORICAL BACKGROUND

From a record of 70 years of Martian observations, Antoniadi (1930) surmised that yellow clouds are common and tend to occur close to perihelion. The major yellow storm of 1956 was the first event of global proportions to be photographed from its initial cloud through its life of several months (Slipher, 1962). The behavior of the 1956 storm was analyzed by Miyamoto (1957), Dollfus (1961, 1965), Gifford (1964), and de Mottoni (1964, 1969). Nevertheless, yellow cloud activity was still considered a rare phenomenon during the last decade.

The discovery by Capen (1970) of a bright yellow cloud in the southern hemisphere (315°W; 30°S) during the 1969 apparition and its close similarity and location to the 1956 initial yellow cloud prompted a thorough review of the historical plate collection and observing records at the Lowell Observatory archives for other occurrences and locations (Capen and Martin, 1972a). This study indicated that major yellow storms of hemispheric proportions have indeed tended to arise in a preferred southern location near the latitude of maximum insolation, probably at the initial positions of the 1956 and 1969 clouds and during late Martian southern spring and early summer, when Mars was close to perihelion. A preliminary summary of these results, with a prediction of the appearance of a yellow cloud in the Hellespontus-Noachis region, was published (Capen, 1971), and the Mariner 8 and 9 team leaders were alerted to possible interference with their topographic mapping program.

The first report of the appearance of the 1971 yellow storm in Noachis came from D. Milon at Harvard on September 25 (Marsden, 1971). The initial cloud was later identified at Lowell Observatory on International Planetary Patrol photographs taken at the Republic Observatory on September 22. The brilliant elongated cloud first appeared near the morning terminator in the Hellespontus-Noachis region. It was not visible on photographs obtained the previous day. A preliminary report of the developing stages of the 1971 yellow storm and a general description of the entire period of disturbance have been previously published by Capen and Martin (1972b). The present paper is based on the detailed measurement of the apparent cloud boundaries (i.e., the anomalously brightened areas); and it treats the diurnal behavior of the storm, its daily progress, and the evolution of a general obscuring haze.

PRESENT STUDY

Photography from the International Planetary Patrol (Baum, 1973) provides us with the first opportunity to make a detailed and comprehensive study of a major atmospheric event on Mars. This Program, coordinated by the Planetary Research Center of Lowell Observatory, yielded almost uninterrupted coverage during the 1971 apparition. The storm, which began in September of 1971, was also the most extensive one for which we have photographic documentation, although storms of this proportion have been reported by visual observers in the past

(Antoniadi, 1930). The Planetary Patrol network photographed this storm hourly up to and beyond the arrival date of Mariner 9. This fortunate overlap between Earth-based observations and orbiting spacecraft observations provides a record throughout the life of the storm.

The storm began less than a month and a half after opposition, so that the Earth-based photographs initially show only 31° of phase. It had been the closest approach of Mars since 1924, so the apparent diameter was still nearly 20 seconds of arc. It was also fortunate that the South Pole of Mars was tilted toward us by 15°, because most of the early storm activity took place in the southern hemisphere between the latitudes of -20° and -50°. By the time of the Mariner 9 arrival in mid-November, the amount of photographic coverage from Earth was becoming less comprehensive, the disk had shrunk to 11.5 seconds of arc, and the phase angle had increased to 43°. Also, the planet had been nearly totally obscured by the storm for almost a month, making detailed mapping from Earth-based photography impossible. Mariner 9 recorded the decline of the storm, which took place gradually in December and January. Patrol photography from that period showed general clearing trends over broad areas as inferred from the increasing contrasts of the larger albedo features.

Patrol photography was intensively used to map the positions of all transient brightenings appearing on red, green, blue, and ultraviolet photographs for 24 days, beginning two days before the start of the storm. In order to simplify the wording, these brightenings are referred to as "red clouds," "green clouds," "blue clouds," "ultraviolet clouds," or combinations thereof throughout this paper, and this terminology should not be over-interpreted. By the twenty-second day the planet had become totally blanketed with dust and haze to the extent that contrast differences between light and dark areas were too small and ill-defined for reliable mapping.

The plotting of cloud positions from the photographs was done with our planet image projector (Baum, 1968). A separate map was made for each day. On these, outlines were plotted for each color and each hour that photographs were available. If more than one photographic image sequence in a particular color was available for a particular hour, only the better was ordinarily used, but some consideration was also given to the regularity of the interval between sequences. Each outline was based on measurement of the best three images of each 14- or 28-image sequence. The resulting daily maps were then used to compile the map figures presented in this paper. The background albedo map for all of them is the 1971 Lowell map (Inge et al.,1971) showing Mars as it appeared on Planetary Patrol photographs near the date of opposition.

Contrasts decreased rapidly with the onset of the storm so that normal albedo features became nearly unrecognizable after several days and eventually disappeared altogether. This extensive dilution of contrast could not be delineated on maps, but is illustrated in Figure 1. These are all red-light photographs showing the same face of the planet.

The first picture at the upper left represents the normal contrasts of albedo features as seen near opposition. The succeeding pictures illustrate the progressive loss of contrast through the twenty-second day of the storm. Although distance and phase angle affect the images somewhat, the progressive obscuration of familiar albedo features by the storm is obvious. Despite the good "seeing" indicated by the sharpness of the limb, the photograph of October 14 is nearly featureless except for the small south polar cap. Until the 1971 storm, no Mars photographs had ever been taken in red light which show so few details within such a sharp-edged disk. The loss of contrast seemed even more rapid in green light than in red, with extensive obscuration occurring within a few days.

Photographs taken within a few minutes through different-colored filters yield different cloud outlines when the brightened areas are plotted. Figure 2 illustrates the outlines thus obtained from a single four-color set of Planetary Patrol sequences, all taken about one-half hour before local noon at the 0° meridian. Brightenings plotted from red- and green-light photographs are typically somewhat similar to one another. Likewise, those from blue- and ultraviolet-light photographs bear more resemblance to one another than to those from red or green photographs. Figure 2 is based on photographs taken during the fourth day of the storm, when the outline of the storm seen in blue light and the blue clouds lying west of the storm region seemed to be progressing towards each other. The bright core of the storm was seen over Noachis in red, green, and blue. Note that the blue outline extended to the northwest, taking in about the same area covered by the ultraviolet outline, which had moved down from the north during the previous two days. The blue-ultraviolet cloud on the left extended from the morning terminator, and the smaller blue cloud did not appear to be a part of this storm at that time. This was the day before the storm began a very rapid expansion to the southwest.

Figure 3 illustrates the relationships between the location of the bright areas of the storm, the position of the Sun, and the central meridian seen from Earth at various times of the Martian day. The eleventh day at two-hour intervals is used as an example, and the outlines are the same as those for that day in Figure 7; i.e., they were derived from red-light images. The thin solid line represents the longitude of the central meridian as seen from Earth at that hour, while the heavy dashed line represents the sub-solar meridian, i.e., the locus of noon. Each map section has been trimmed on the east (right) and west (left) at the approximate limb and terminator, and therefore shows, without foreshortening, the longitudinal range of the photographs. The six maps represent 150° of rotation, or ten Martian hours, in 30-degree (two-hour) steps.

This figure is an example of the daily regeneration of the storm and its hourly progress, which is similar to, but not strictly dependent upon, the rotation rate. In a very general way, the brightened areas advance across the map with the Sun, but they do so in an irregular way that indicates a strong regional dependence. The daily and hourly variations in shape and position of these brightenings rule out an interpretation based solely on optical scattering geometry. One should also note that the brightenings are on average centered around local noon--not around the central meridian nor around a Minnaert point midway between. These storm brightenings were seen best in red light and were generally near the center of the visible disk; whereas most Martian clouds are seen best nearer the limb or terminator and in blue light.

The daily positions of the storm in red light were not repeatable at the same hour each Martian day. Figure 4 compares the positions every fourth day at the hour when the Sun was on the 0° meridian. It demonstrates that the daily advance of the storm was far from uniform, although an hourly progression is seen on the daily maps. Note that the western boundary for Day 5 is farther west than the boundary for Day 9.

The twenty maps in Figures 5 and 7 show prominent storm areas as seen in red light from the onset of the storm until there was a nearly total obscuration of the planet. Abnormally brightened areas have been outlined from red-filter photographs, which show the most contrast and are fairly representative of what can be seen in green as well. For comparison, Figure 6 shows the clouds seen on blue photographs during the first ten days. These three figures (5, 6, and 7) provide a detailed record of the storm's growth and the characteristics of its progress.

The days are numbered in terms of rotations of Mars, starting with the first day that the storm could be identified. The beginning of each Martian day is defined here as the time the sub-solar point crossed the 180° meridian. The Earth dates (U.T.) are shown below the day number.

Each outline is labelled with a number representing the nearest hour in terms of a division of the Martian day. This time scale is Martian Apparent Solar Time at the 0° meridian. Each hour represents 15° of rotation, with 12 noon as the time the Sun's path crosses 0° longitude. Each map also shows the longitude of the central meridian (CM), or sub-Earth longitude, when it was noon at 0° longitude. One can thereby judge which portion of the planet was visible from the Earth during any one observation, since the CM advances westward at approximately the rate of 15° per Martian hour.

In Figures 5, 6, and 7, the abnormally brightened areas are delineated by closed lines whenever possible, but there are cases, represented by open lines, when part of the boundary was ill-defined, or was not in view. When needed to avoid ambiguity, small triangles have been placed on the open lines, pointing to the brightened side.

All abnormally bright areas were mapped, whether or not they could be considered a part of the storm. Outlines shown with broken lines indicate bright areas that were judged probably not a part of the storm. This judgement was based upon the appearance of the planet prior to the onset of the storm and the progress of the storm as seen on red- and green-light photographs.

Much of the original mapping was done at hourly intervals, but the outlines reproduced in Figures 5, 6, and 7 are restricted to approximately two-hour intervals in order to avoid congestion. The actual intervals used were determined by appropriate selection of the material available. The Planetary Patrol yielded usable film on an average of 14 hours per day during this period, the least being eight hours (Days 12 and 15), and the most being 19 hours (Day 18). Fortunately, the hours best covered by the Patrol generally occurred when the more active areas of the storm were in view.

The storm clouds were not as bright or as easily defined in blue as they were in red and green. Most of the brightenings seen in blue light on the first day of the storm were not untypical of the "normal" Mars, so they were probably not associated specifically with the storm and are shown as dashed lines on Figure 6. By the tenth day, however, the activity in blue can no longer be disassociated from the storm system. The blue cloud activity that had been going on in the western hemisphere of Mars prior to the onset of the storm and the blue-light configuration of the storm itself showed a remarkable progression toward one another during the first six days. After that, the blue clouds in and around the Tharsis region could no longer be isolated from storm activity. Blue clouds were present in the Syrtis Major region prior to the storm, but they disappeared after Day 3. After Day 6, evening limb clouds were the only activity in blue that did not appear to be directly associated with the red and green storm clouds. Note that the hourly changes in configuration and position of the storm were more uniform in blue than they were in red.

INTERPRETATION OF THE DAILY MAPS

Day 1 (22 September 1971). On the first day, the storm remained very localized, although its sudden appearance across a wide area suggests a very rapid increase in atmospheric activity. Hellas had been a bright object since the yellow cloud of July (Capen, 1974); and prior to the onset of the global storm in September, Hellas was second only to the south cap in brightness, appearing on the blue photographs as well as red and green. There was a gap between Hellas and the initial storm cloud. Although separated, the initial storm cloud and the bright patch in Hellas were roughly the same brightness and color. The agitation of dust may have continued within the Hellas basin throughout the July-to-September interval. The limited movement that did occur the first day was to the west-southwest, expanding from the initial cloud area (labelled 5 hours) to the line labelled 7, where it stopped. The eastern and southeastern boundaries remained stationary until after 9 hours, when the cloud contracted towards the west. The bright areas did often contract as well as expand, although the storm generally was a rapidly expanding phenomenon throughout the first few weeks. Comparison of the Day 1 map with the preliminary relief maps from Mariner 9 UVS data, referred to hereafter as "Hord UVS Relief Map" (Hord et al., 1972; Hord, 1973), shows a possible correlation between upward slopes and the direction of expansion of brightened storm areas.

Day 2. On the second day, the brightening in Hellas at first appeared separate (at 4 hours), but two hours later it had bridged across to the new storm area of the previous day. This same pattern of behavior was often repeated in the following days. (See Days 3, 4, 6, 13, 14.) The storm characteristically went through a daily regeneration, often seen beginning in Hellas and each day expanding a little farther to the west. The bright areas may have been contracting or dying down each night, only to have been rejuvenated with added strength on the following morning. On the other hand, the progressive reduction of contrast steadily became more widespread over the planet. Hess (1973) proposed a feedback mechanism of increased temperatures and winds which allows storms of this size to become self-perpetuating.

Day 3. Although coverage was limited, Day 3 illustrates a case of brightening in separated areas, with a gap at 330° longitude, which was near the center of the cloud seen on Day 1.

Day 4. This was the final day that the storm remained within its initial core area. Daily expansion had been very limited in comparison with what followed. The Hord UVS Relief Map shows a high area centered around 345° and -40°, suggesting that the expansion had been upslope from Hellas to envelop a higher upland area (Noachis).

Day 5. The expansion rate suddenly increased, and the storm expanded to the southwest toward, but not over, the polar cap. The more northerly pair of lines labelled 14 and 16 encircled the Argyre I basin. The Hord UVS Relief Map indicates a broad ridge sloping downwards from the Noachis uplands into Argyre I, which the storm seemed to follow instead of a lower route. It also progressed very rapidly in that region. Note that the distance between boundaries for hours 10 and 12 represents an advancement of about 700 kilometers per hour. This, of course, does not imply that dust was actually transported over that distance in two hours.

Day 6. The South Polar Cap became partially obscured. For the first time northward protrusions occurred at two points. Eastward progress was again upslope and across a broad front. Note the continued avoidance of the Mare Amphitrites region (330° and -60°), which appeared dark during this period.

Day 7. Storm-brightened areas were seen in the northern hemisphere for the first time. The two northward protrusions at hour 16 were both towards higher plateau areas according to the Hord UVS Relief Map. The larger and higher Tharsis uplands area was approached by the 14-hour line, but storm-brightened areas were seldom seen above the 7-kilometer elevation contour.

Day 8. The westward expansion goes beyond the 180° meridian by the 24th hour. The tendency for bright areas to show as separate spots was increasing as they became more distributed around the planet.

Day 9. The gap near 20° west longitude and 40° south latitude, to the east of the 12-hour enclosed area, was also a feature on about half of the days that followed. This is the same downslope region that was bridged so rapidly on Day 5.

Day 10. Evening limb brightenings were seen at several times at northern mid-latitudes. This had been observed since Day 6 in blue, but was seen in red as well on the tenth day.

Day 11. The total area encompassed by the storm had become elongated in a mainly east-west direction, and this remained the dominant situation through the twentieth day. See also Figure 3.

Day 12. Photographic coverage was lacking for the region west (left) of the 15-hour outline, but the maps for several preceding days indicate that the storm was indeed underway there. Thus, the lack of outlines in that region on Days 12, 14, 15, and 17 does not imply storm abatement there.

Day 14. Hellas still remained the first area of the day to brighten. Its outline coincides with the line labelled 5 hours. Photographic coverage was not available for earlier hours during this day.

Day 15. This was the first day that we can be certain that the storm had definitely circled the globe at mid-latitudes. The advancing brightened area connected with Hellas from the east. This behavior continued through the next five days.

Day 18. Mare Cimmerium became bounded on both the north and the south as a new area of brightening was identified advancing westward along the equator. Mare Cimmerium is shown on the Hord UVS Relief

Map as a low area with slightly higher ground to both the north and the south.

Day 20. The two days following Day 20 were also mapped but are not presented because the lack of contrast rapidly reduced the accuracy of plotting. See Figure 1.

SUMMARY

Some of the more important components of the storm are summarized in Figure 8. The main core included a low basin in the east (Hellas) and sloped up to an upland in the west (Noachis). The region of the secondary core also sloped upwards to the west from a low area which included the northern part of the Argyre I basin. The area between cores sloped down to the west. The topography referred to is from the Hord UVS Relief Map. Most of the action occurred between 20° and 50° south. The progression of brightenings was generally westward. Speed and direction seem to have been influenced by elevation differences, by the diurnal heating cycle, and by pre-existing regional differences of some kind. There also seemed to be a tendency for the disturbance to perpetuate itself, with only diurnal abatement, after it once invaded a region.

Figure 8 would, with minor adjustments, also describe the major components of the 1956 major storm (Slipher, 1962), as well as the yellow cloud disturbance which occurred in July 1971 (Capen, 1974).

Although yellow (or red-green) clouds have been photographed again in 1973, it may be a long time before a storm comparable in size to the 1971 storm is recorded. The storm that began in mid-October 1973 did become planetwide and surpassed the 1956 storm in areal coverage, although its duration has not yet been determined. If storms of this size are seen more frequently in the future, it would suggest that major climatic changes on Mars may occur with enough frequency to be within the scope of photographic records. We plan to use Planetary Patrol photography for continued studies of Martian atmospheric phenomena. Preliminary studies of the 1973 apparition are already underway.

C. F. Capen is thanked for major contributions to both the research and the preparation of this paper, made during numerous helpful discussions. The author also thanks the Lowell darkroom staff, S. Jones, H. Ferguson, and N. Cook, for help in preparation of the illustrations. W. A. Baum supervised the research and provided considerable guidance in the preparation of this paper. This work was supported by NASA under research grant NGR-03-003-001.

REFERENCES

Antoniadi, E-M. (1930). "La Planete Mars 1659-1929," pp. 39-47, Hermann et Cie, Paris, France.

Baum, W. A. (1968). Planetary and lunar notes from Prague. Sky and Telescope 35, 8.

Baum, W. A. (1973). The International Planetary Patrol Program: An assessment of the first three years. Planet. and Space Science 21, 1511.

Capen, C. F. (1970). Observational patrol of Mars in support of Mariners VI and VII. Technical Rept. 32-1492, Jet Propulsion Laboratory, Pasadena, California.

Capen, C. F. (1971). Yellow clouds--past and future. Sky and Telescope 41, 117.

Capen, C. F. (1974). A Martian yellow cloud - July 1971. Icarus, submitted for publication.

Capen, C. F., and Martin, L. J. (1972a). Survey of Martian yellow storms. Bull. Amer. Astron. Soc. 4, 374.

Capen, C. F., and Martin, L. J. (1972b). Mars' great storm of 1971. Sky and Telescope 43, 276.

Dollfus, A. (1961). Polarization studies of the planets. In "The Solar System," Vol. III, "Planets and Satellites" (Eds. G. P. Kuiper and B. Middlehurst), pp. 343-399, University of Chicago Press, Chicago.

Dollfus, A. (1965). Étude de la planète Mars de 1954 a 1958. Annales d'Astrophysique 28, 722.

Gifford, F. A. (1964). A study of Martian yellow clouds that display movement. Monthly Weather Rev. 92, 435.

Hess, S. L. (1973). Martian winds and dust clouds. Planet. Space Sci. 21, 1549.

Hord, C. W. (1973). Revised ultraviolet pressure-altitude contour map of Mars from Mariner 9 experiment. Private communication to C. Capen.

Hord, C. W., Barth, C. A., Stewart, A. I., and Lane, A. L. (1972). Mariner 9 ultraviolet spectrometer experiment: Photometry and topography of Mars. Icarus 17, 443.

Inge, J. L., Capen, C. F., Martin, L. J., and Thompson, D. T. (1971). Mars - 1971, albedo map, Lowell Obs. Map Series.

Marsden, B. G. (1971). I.A.U. Circular 2358, Smithsonian Astrophysical Obs.

Miyamoto, S. (1957). The great yellow cloud and the atmosphere of Mars. Report of visual observations during the 1956 opposition. Contrib. from the Inst. of Astrophysics and Kwasan Obs., University of Kyoto, 71.

Mottoni, G. de (1964). L'Opposizione de Marte del 1956. Publ. Dell' Osservatorio Astronomico di Milano-Merate, Nuova Serie 12, Genova.

Mottoni, G. de (1969). Sintensi grafica complementare della fogografie di Marte nel 1956. Publ. Dell'Osservatorio Astronomica di Milano-Merate, Nuova Serie 19, Genova.

Slipher, E. C. (1962). "Mars - The Photographic Story," Northland Press, Flagstaff, Arizona.

ATTACHMENT B

FIGURE CAPTIONS

Figure 1. Red-filter photographs showing Mars just after opposition and during the early part of the storm. The central meridians are all between 0° and 5°, illustrating the successive obscuration of familiar albedo features.

Figure 2. Cloud outlines seen on one set of Planetary Patrol photographic sequences. The yellow storm is on the right (east), while other blue and ultraviolet brightenings are on the left. The albedo features shown on the base map used for Figures 2 through 8 do not represent the appearance of these features during the storm, but show Mars as it was photographed from Earth around the time of the 1971 opposition.

Figure 3. Evolution of the storm during a typical day. The eleventh day of the storm at two-hour intervals, showing how the brightened area (in red light) advanced as the planet rotated. See text.

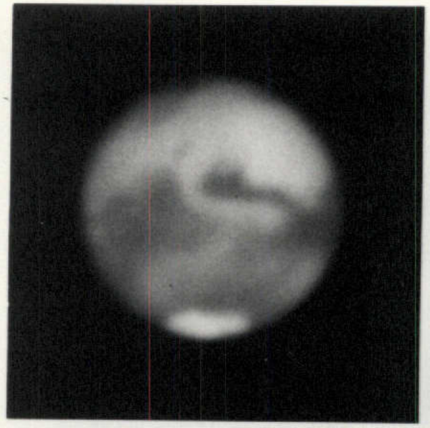
Figure 4. Evolution of the storm over four-day intervals. Numbers on the cloud outlines refer to days in terms of Mars' rotations beginning with the initial day of the storm. Plots are from red-light photographs, all at about the same Apparent Solar Time every fourth day.

Figure 5. The first ten days of the storm. Outlined areas appeared as bright clouds on red-filter photographs. Dashed outlines show bright areas which may not be part of the storm.

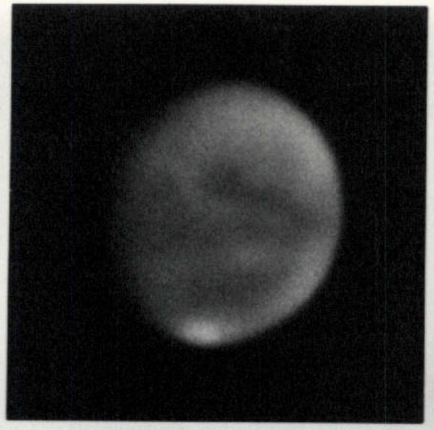
Figure 6. Bright cloud outlines from blue-filter photographs. Each "day" represents one rotation of Mars. Please see text for a description of time used.

Figure 7. This is a continuation of Figure 5 showing plots from red-filter photographs at approximate two-hour intervals. See text.

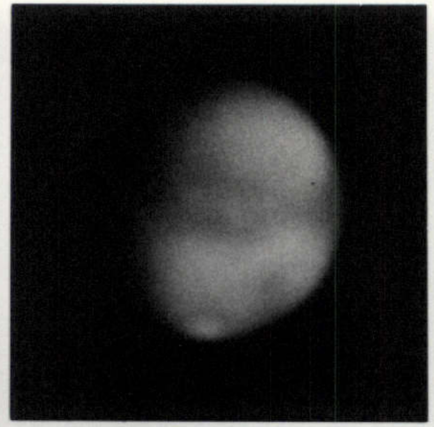
Figure 8. A summary of the storm's major bright components seen during the first 22 days in red light. The base map is the 1971 Lowell Mars map showing albedo features at the time of opposition.



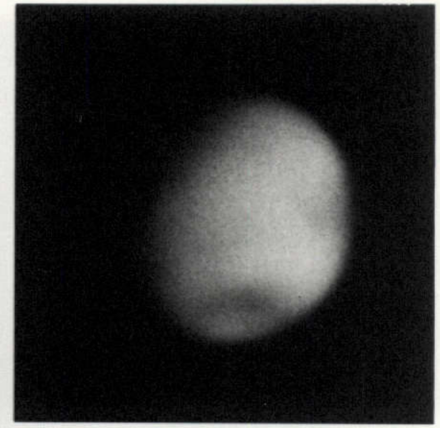
NORMAL
Aug. 12



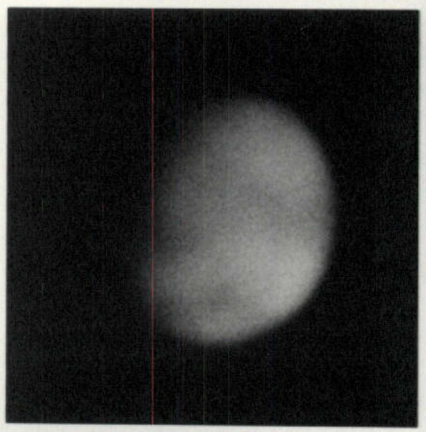
DAY 2
Sept. 24



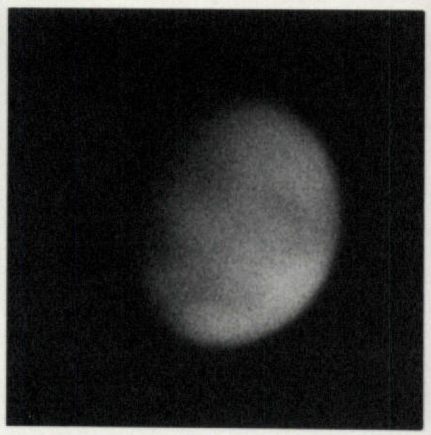
DAY 5
Sept. 27



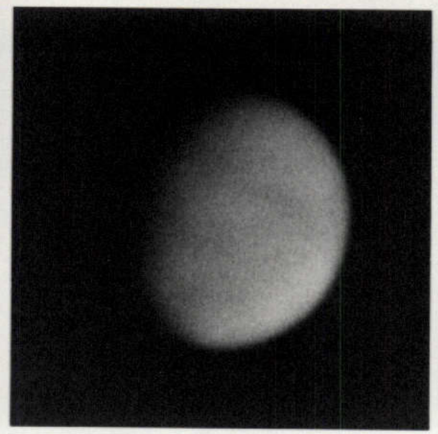
DAY 8
Sept. 30



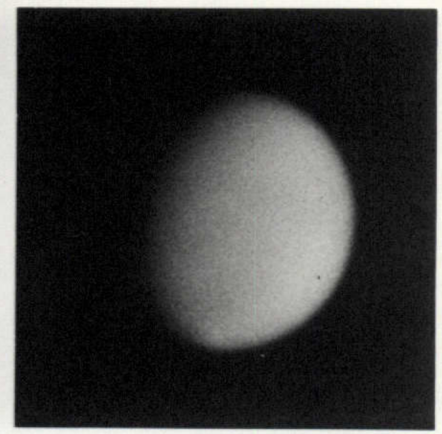
DAY 11
Oct. 3



DAY 14
Oct. 6



DAY 17
Oct. 9

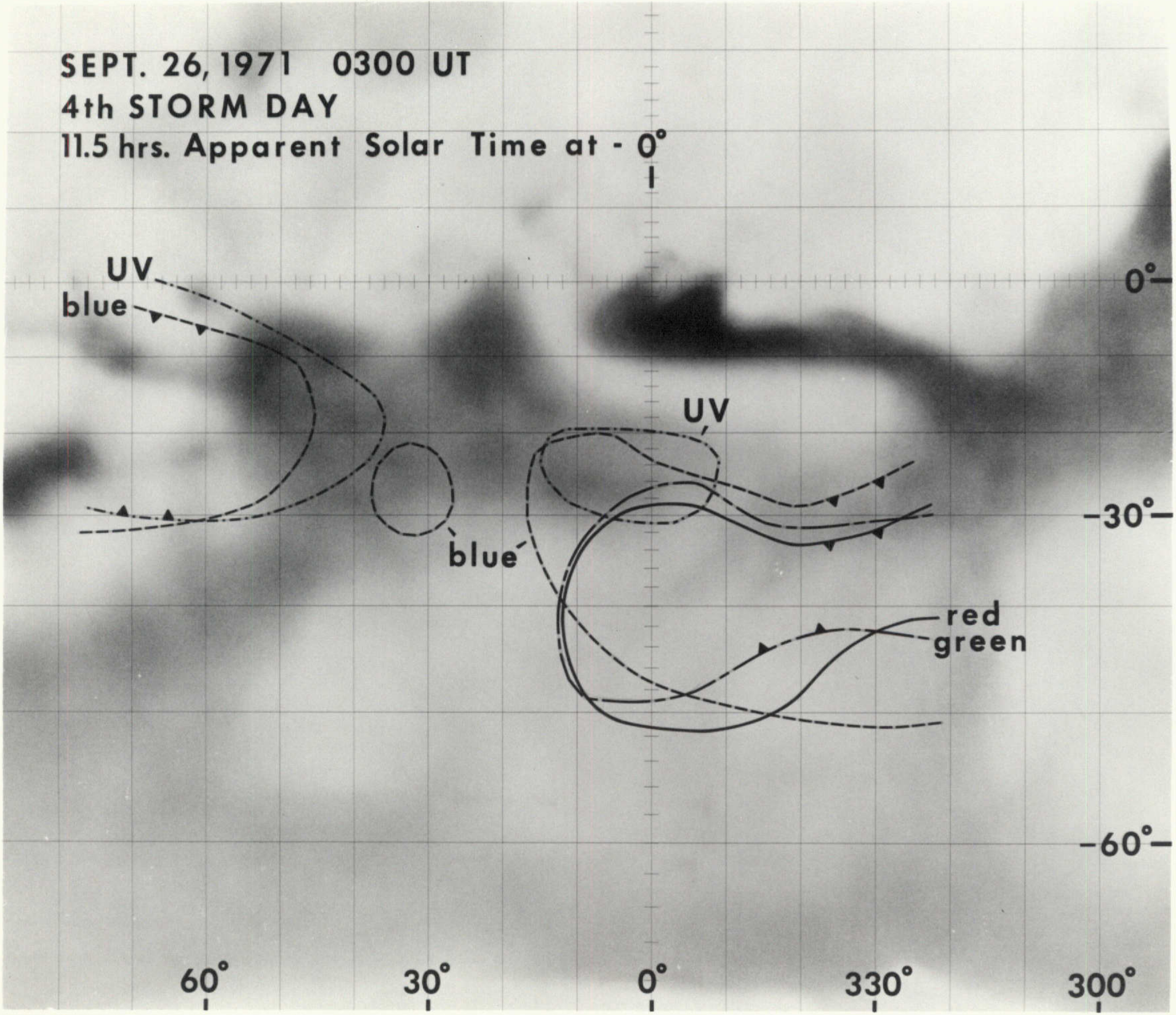


DAY 22
Oct. 14

43

ATTACHMENT B

Figure 1.



44

ATTACHMENT B

Figure 2.

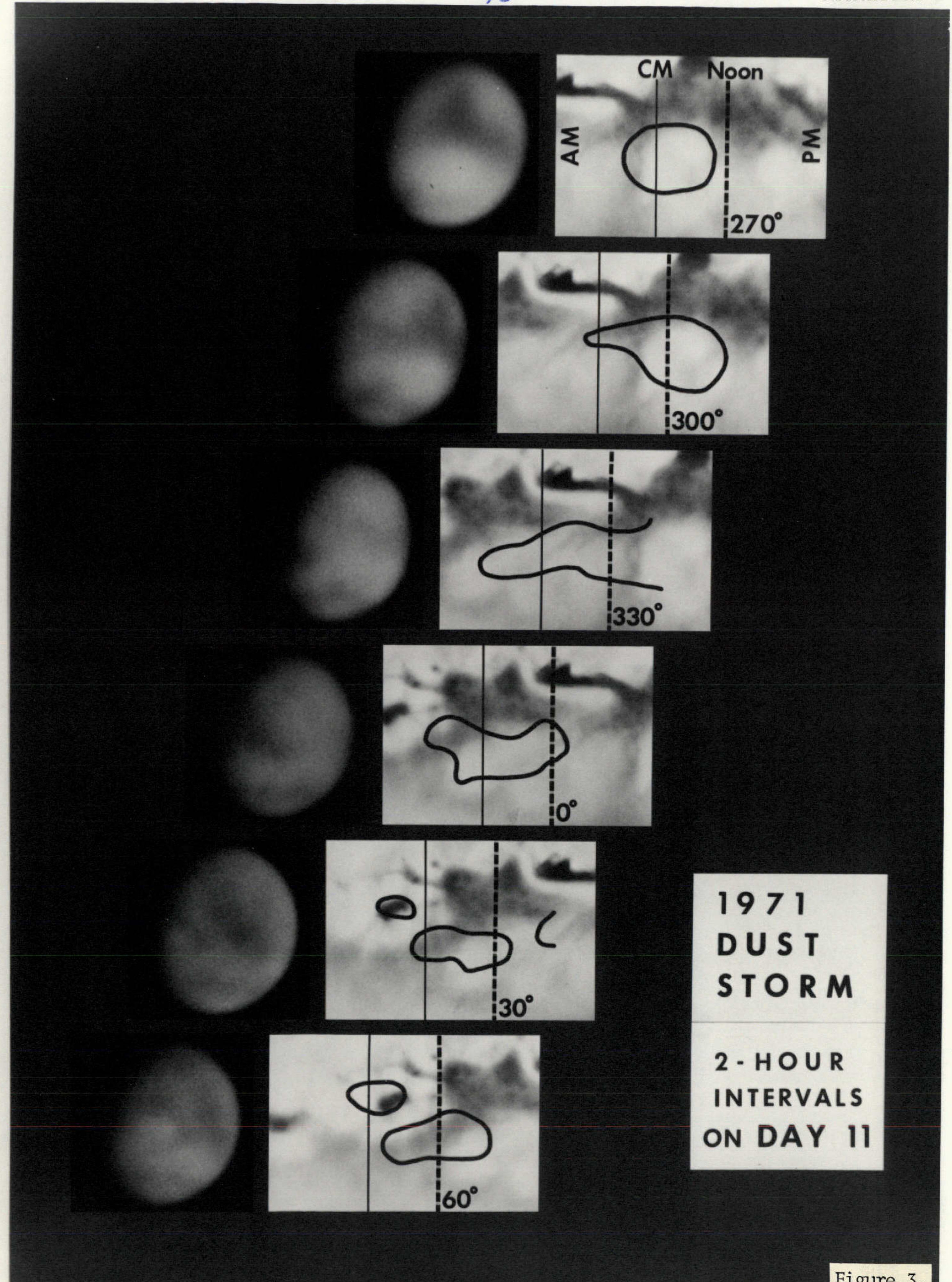
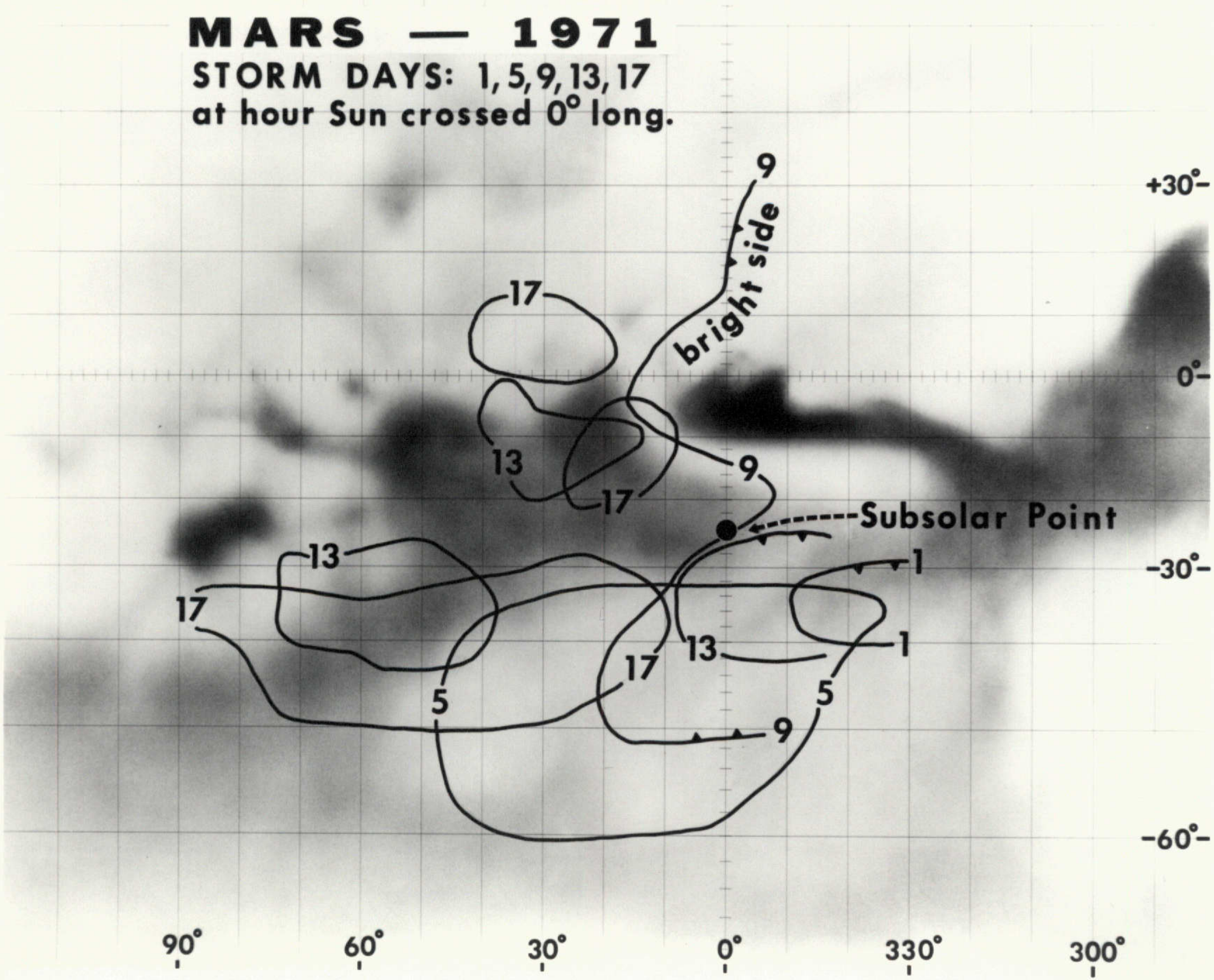

CM
Noon
AM
PM
270°
300°
330°
0°
30°
60°
1971
DUST
STORM
2-HOUR
INTERVALS
ON DAY 11

Figure 3.



46

ATTACHMENT B

Figure 4.

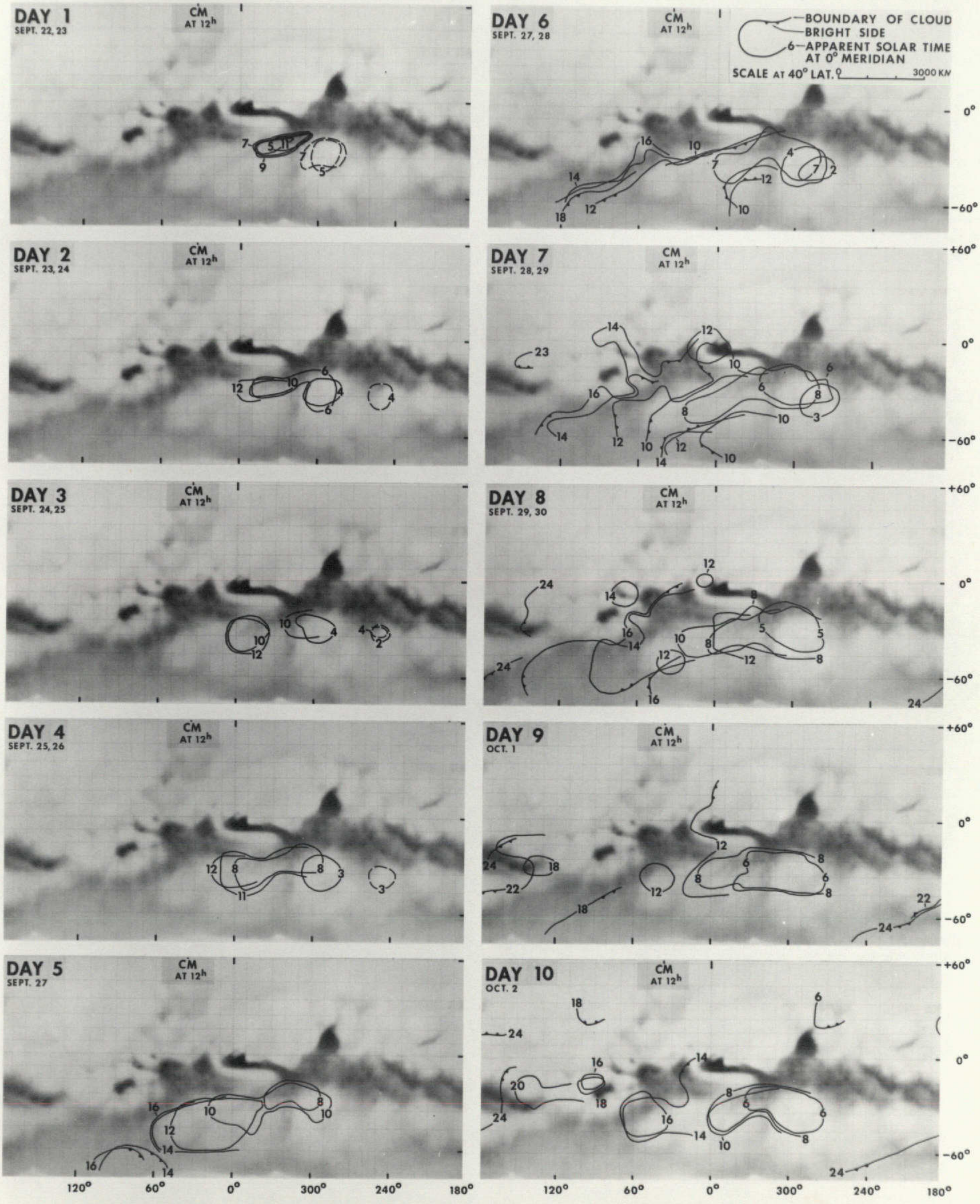

DAY 1
SEPT. 22, 23
DAY 2
SEPT. 23, 24
DAY 3
SEPT. 24, 25
DAY 4
SEPT. 25, 26
DAY 5
SEPT. 27
DAY 6
SEPT. 27, 28
DAY 7
SEPT. 28, 29
DAY 8
SEPT. 29, 30
DAY 9
OCT. 1
DAY 10
OCT. 2
CM AT 12h
BOUNDARY OF CLOUD
BRIGHT SIDE
6—APPARENT SOLAR TIME AT 0° MERIDIAN
SCALE AT 40° LAT. 0 3000 KM
+60°
0°
-60°
120° 60° 0° 300° 240° 180°

Figure 5.

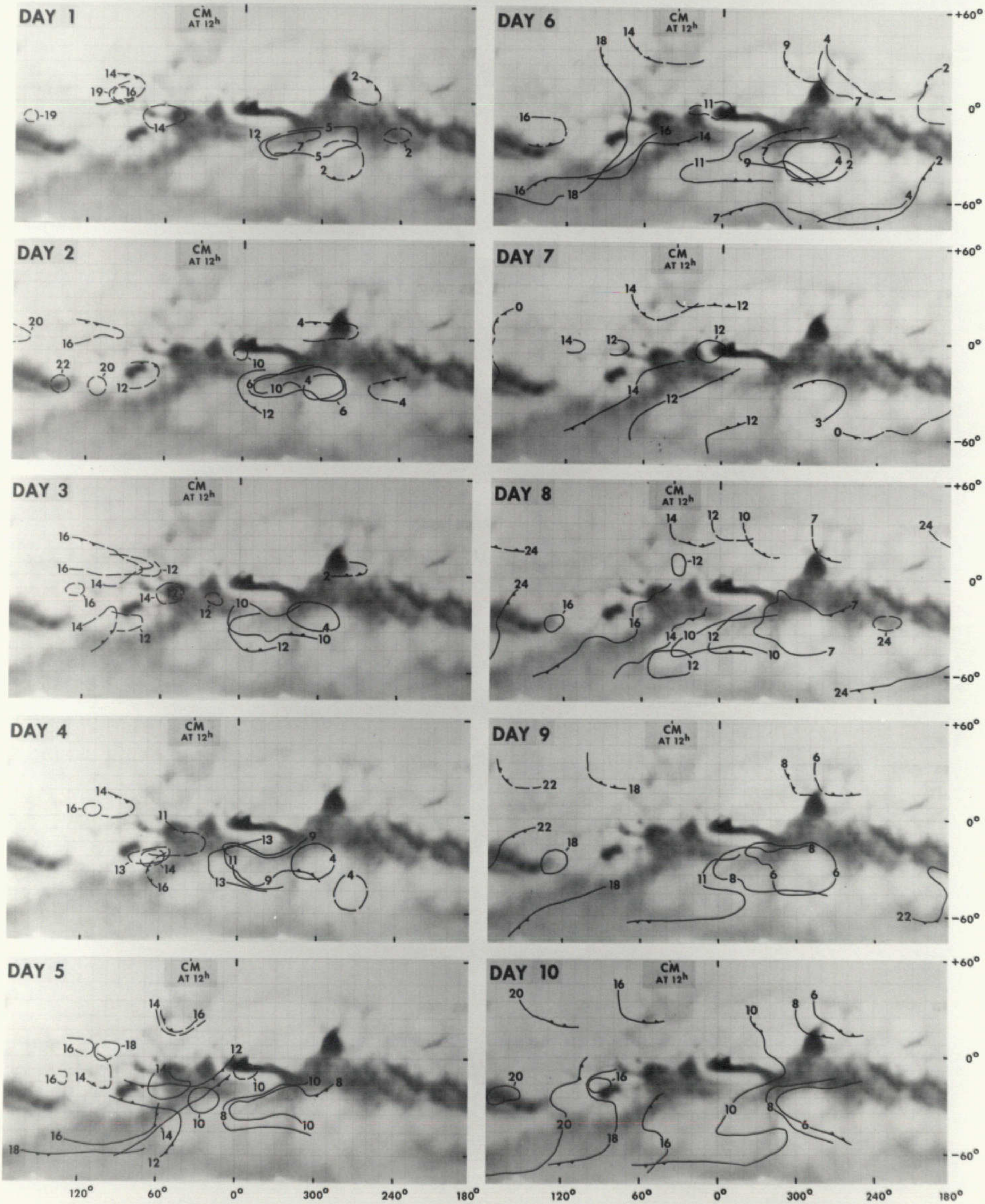

DAY 1
DAY 2
DAY 3
DAY 4
DAY 5
DAY 6
DAY 7
DAY 8
DAY 9
DAY 10
CM AT 12h
+60°
0°
-60°
120°
60°
0°
300°
240°
180°

Figure 6.

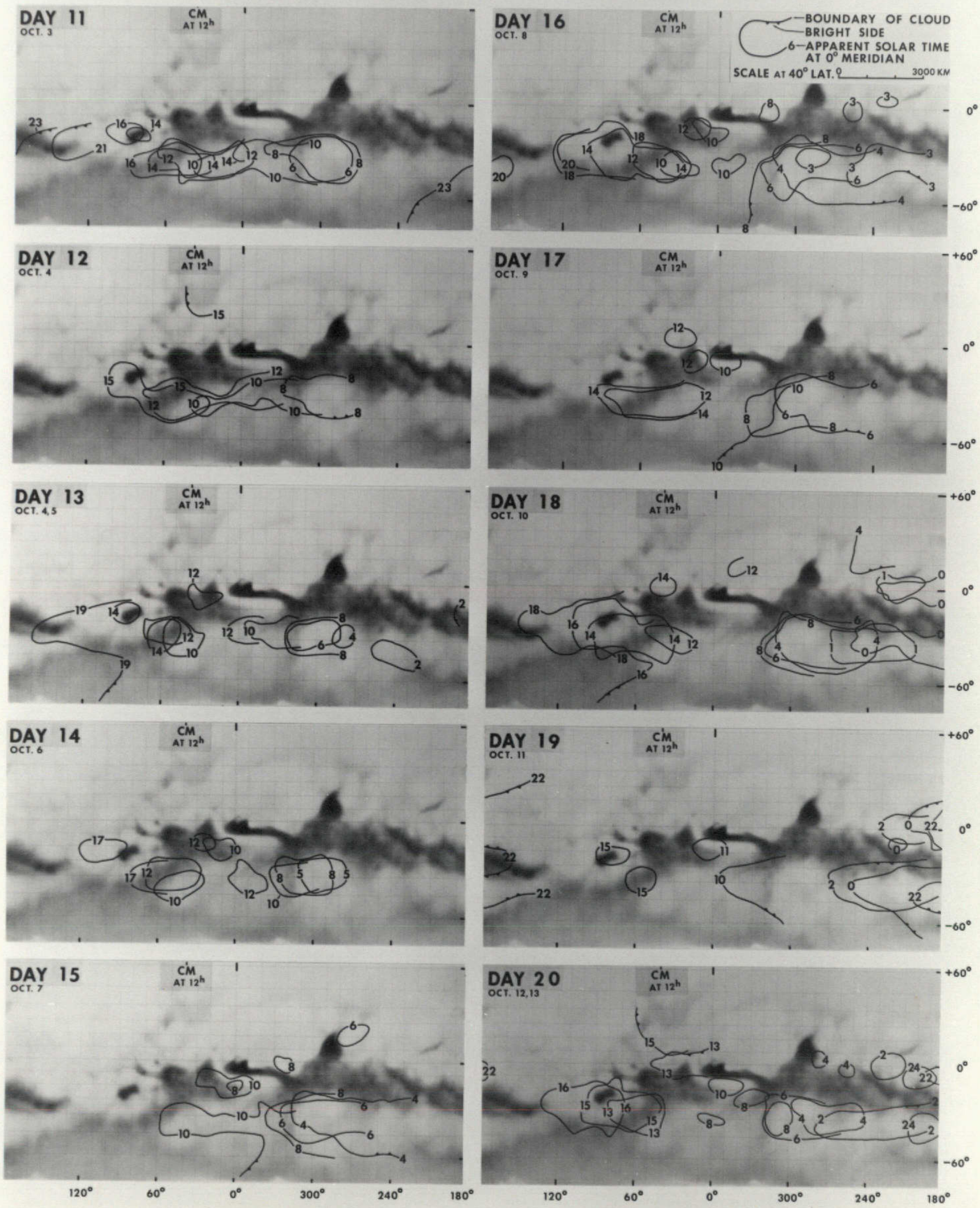

DAY 11
OCT. 3
DAY 16
OCT. 8
BOUNDARY OF CLOUD
BRIGHT SIDE
6—APPARENT SOLAR TIME AT 0° MERIDIAN
SCALE AT 40° LAT. 0 3000 KM
DAY 12
OCT. 4
DAY 17
OCT. 9
DAY 13
OCT. 4,5
DAY 18
OCT. 10
DAY 14
OCT. 6
DAY 19
OCT. 11
DAY 15
OCT. 7
DAY 20
OCT. 12,13
CM AT 12h
+60°
0°
-60°
120°
60°
0°
300°
240°
180°

Figure 7.

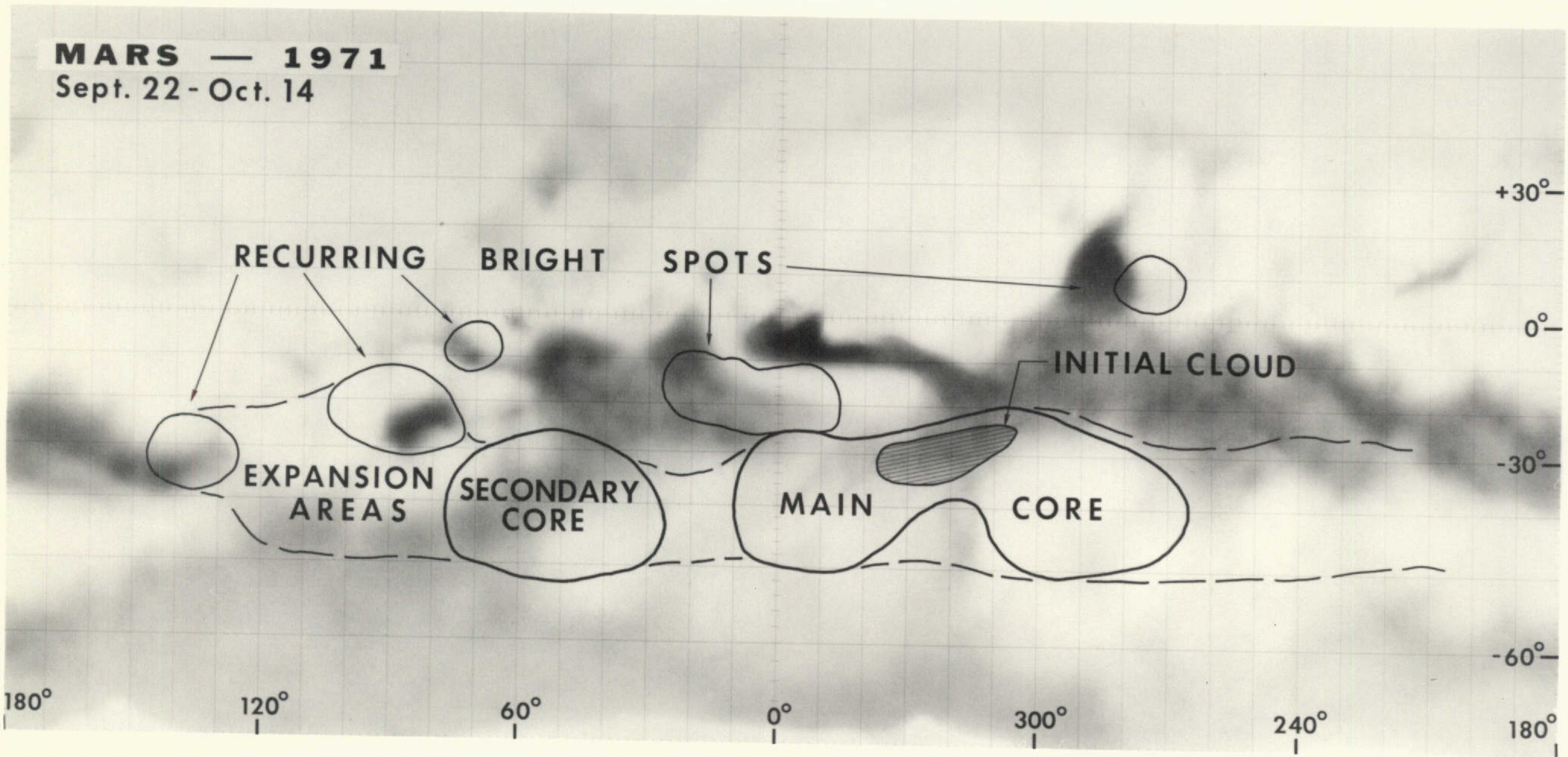


Figure 8.

53

ATTACHMENT B

51

ATTACHMENT C

A COMPARISON OF MARTIAN ALBEDO FEATURES WITH TOPOGRAPHY A73-44551

JAY L INGE AND WILLIAM A BAUM

PLANETARY RESEARCH CENTER LOWELL OBSERVATORY FLAGSTAFF ARIZONA 86001