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SYNOPTIC PLANETARY IMAGING
WITH THE LST HIGH-RESOLUTION CAMERA

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ABSTRACT

The value of synoptic imaging of the planets is illustrated. The advantage of the Large Space Telescope, as compared with ground-based telescopes and planetary orbiters and flybys, is discussed. Desirable LST camera parameters and observing strategies are considered from the standpoint of synoptic imaging.

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Decades of ground-based observations have shown that our neighboring planets in the solar system are very dynamic bodies. Astronomers have long been fascinated by the recurring clouds, occasional dust storms, and the ever-changing polar caps and hoods on Mars. Faint atmospheric markings and spectroscopically variable regions circulate around Venus, while Jupiter displays continuously varying patterns of belts, zones, and spots. Because of the limited resolution of ground-based images, comparatively little is known about dynamical processes on Saturn, Uranus, and Neptune, but it is unlikely that these planets are completely devoid of change. Transitory spots have, in fact, been detected on Saturn.

Despite the severe limitations of ground-based observation, synoptic programs have yielded a lot of information and will continue to do so for a long time to come. Planetary photographs, now being collected at ten times the rate of a decade ago, provide unprecedented continuity and homogeneity in the material available for analysis (Baum, 1973). Spectroscopic campaigns, such as the recent study of Venus by Young (1973), are also beginning to delve into the character of time variations in planetary atmospheres. Synoptic polarimetry (Bowell, 1973) is beginning to reveal interesting variations, and I suspect that photometry and spectrophotometry of planets could benefit from a more synoptic approach than has thus far been applied. In the present paper, however, I shall confine remarks to the rationale for synoptic imaging.

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There is no hope of understanding the changes which we see occurring on planets if observations are taken only once or at long intervals. Consider the global 1971 dust storm on Mars (Capen and Martin, 1972), whose development is illustrated in Figure 1. Within a month the planet went from its normal appearance to a totally featureless disk. A few good photographs appropriately spaced like those in Figure 1 would, of course, have revealed that a dust storm had occurred, but synoptic observations of the type being produced by the International Planetary Patrol Program (Baum, 1973) are required if anything is to be said about the way in which the storm developed. Figure 2 shows the first ten days of the storm as observed on Patrol photographs taken in red light (Martin, 1973). Outlines represent the extent of storm-brightened areas at two-hour intervals each day, the times being labelled in terms of a Martian analog of apparent solar time at Greenwich (i.e., twenty-fourths of a Martian day counting from midnight at 0° longitude). One can see that the dust storm went through a daily cycle of regeneration, advancing farther each day than it did the day before.

In 1971 a major disturbance also occurred on Jupiter, and its development is shown in Figure 3. In the space of less than a week, the disturbance grew from a tiny ultraviolet spot in the south equatorial belt to a bright splotch comparable in size to the Red Spot (Baum, 1971). Here again the value of synoptic observations is evident.

The features that we observe in ultraviolet light on Venus are less distinct than those observed on Mars and Jupiter. Variations in these features and their circulation around Venus have been studied by several investigators, including Boyer and Guérin (1969) and Caldwell (1972). Not only do the features appear to move around the planet in a retrograde sense with a period of about four days, but they also fade and revive in an unpredictable manner.

These are only a few of the more striking examples of dynamic processes occurring on other planets to illustrate the value of synoptic observations, and I shall mention some others later. Let us now turn to the question of the value of synoptic planetary observations from the Large Space Telescope as compared with synoptic observations from planetary flybys and orbiters or from the ground.

Planetary orbiters permit short-term glimpses of local detail, but do not provide planetwide synoptic coverage. Few people realize how limited a view can be had with a planetary orbiter. Figure 4 illustrates the best of a preliminary set of candidate orbits around Mars for the first Viking orbiter in 1976. The figure represents a Mercator map of the planet, and the outlines indicate the areas that are adequately illuminated and that can be seen with reasonable viewing geometry by the orbiter instruments during the early days of the mission. The actual fields of view for single exposures with the orbiter cameras (and associated instruments) are very small patches within these areas of access. Labels on the outlines identify hours preceding and following periapsis. The dot labelled "P" identifies the sub-spacecraft point at the time of periapsis. On each outline, part of the boundary represents the minimum sun elevation angle (i.e., a line parallelling the terminator), while the rest of the boundary represents the maximum acceptable obliquity of view. It turns out, in fact, that vertical viewing will be possible only from about two hours before periapsis until a few minutes after.

Suppose, for example, that we wish to monitor what is going on in the vicinity of Sinus Meridiani, 0° latitude and 0° longitude. That area will be within view for only about an hour each Martian day, ten hours before periapsis. At that time the spacecraft is quite far out in its orbit, and the viewing is highly oblique. There will be no choice in the viewing angle, in the field of view, nor in the time of day at the site being observed. There is no possibility, for example, of watching the development of a cloud at different times during a Martian day. Most of the planet cannot be viewed at all while the orbit remains synchronous.

If the orbit is desynchronized during limited time intervals as now planned, other parts of the planet will come into view, but only on preselected hours and dates, and with severe viewing angle constraints. Although an orbiter mission can do a beautiful job of geological mapping, as the Mariner 9 mission has recently demonstrated, it provides only limited opportunity for investigating atmospheric phenomena. The only way that good synoptic coverage could be provided by orbiters would be to have six or eight of them distributed in an equatorial ring around each planet, and the cost of such a program would certainly be very high.

Planetary flybys during their "observatory" phases (i.e., approach and departure) can provide planetwide views, but these periods are necessarily of limited duration. The probability that a flyby will arrive at the planet during a particularly interesting period of activity is rather low. There is the further problem that flybys will not generally occur when planets are favorably situated for simultaneous observation from the Earth. For example, the Mariner Venus-Mercury spacecraft will fly by Venus in early 1974 at a time when the cloud pattern cannot be seen from the Earth, so there will be no way of connecting the Mariner findings with the range of Venus cloud conditions that have been observed with ground-based telescopes. Similarly, Pioneer 10 will pass Jupiter in December of 1973, more than four months after opposition. When the Viking spacecraft reach Mars in June of 1976, the planet is almost as far away from Earth as it can be.

The merit of the Large Space Telescope, as compared with planetary orbiters or flybys, is that the LST can view large areas of the planet, sometimes nearly the whole disk, on a much more flexible schedule. Furthermore, it can do this with only gradual changes of lighting and viewing geometry over periods of months.

The advantages of the LST over ground-based telescopes are (1) an order of magnitude improvement in spatial resolution and (2) a broader range of accessible wavelengths. In the ordinary optical range, the LST will enable us to observe features on a planet 100 times smaller in area than can now be done under the very best conditions with ground-based telescopes, and almost 1000 times smaller in area than must be dealt with on average in typical ground-based synoptic programs.

What can we expect to learn with this improved resolution? Of course, totally unexpected phenomena beyond the reach of ground-based telescopes may very well be discovered. Such discovery of the unexpected should certainly be a major goal of the Large Space Telescope. Leaving aside the unknown, however, there are many known phenomena for which an improved understanding of physical processes can be expected from LST synoptic observations.

An example is Jupiter's Great Red Spot. This long-lived feature is undoubtedly one of the major enigmas in all of astronomy. Several models have been suggested to explain the Spot (Peek, 1958; Hide, 1961; Smoluchowski, 1970; Kuiper, 1972), and most of the models make specific predictions concerning the flow pattern around the Spot, the interchange of material between the Spot and its surroundings, and the vorticity within the Spot itself. Unfortunately, with ground-based resolution, interactions between the Spot and other features are rarely seen, so the critical flow patterns are not known with certainty. Observations of the Great Red Spot with the LST camera over a sufficient time interval may provide the missing key to its nature.

In addition to the question of the Great Red Spot, the problem of the overall atmospheric dynamics of Jupiter could benefit greatly from the improved resolution of the LST. It has been known for a long time that the circulation pattern of Jupiter's atmosphere is complicated. Measurements of the longitudinal motion of features, such as the recent analysis of Patrol photographs by Inge (1973) shown in Figure 5, reveal abrupt discontinuities with latitude and also with time. Observations with the LST will make it possible to achieve greater latitudinal resolution in rotational profiles, thereby better defining the extent of the shear zones between currents. It should also become possible to measure north-south velocities in the cloud layers. These are rarely observed at ground-based resolution, but the detection of them is needed to identify the instability mechanisms operating in Jupiter's atmosphere (Stone, 1973).

On Mars, typical ground-based resolution is several hundred kilometers, and only the grossest manifestations of atmospheric activity can be observed. The much smaller detail revealed by the LST camera will be a great help in understanding the formation of clouds, the progress of dust storms, and the advance and regression of the polar caps in terms of topography, elevation, winds, and local albedos.

The broader wavelength window available from the LST as compared with telescopes below the Earth's atmosphere brings several possible camera investigations to mind. Access to the near ultraviolet may permit image detection and monitoring of the Martian airglow (Barth et al., 1972). The detectability of the ultraviolet features in the Venus cloud deck should be improved, so that variations of contrast and detail can be investigated. Ultraviolet features on Jupiter, such as the SEB disturbance in Figure 3, will be of interest to look for at shorter wavelengths and with higher resolution. Imaging of

Jupiter and Saturn in the infrared methane band at 8870 Å will make possible studies of the variations in the height and/or tenuosity of cloud features as a function of position and time at much higher resolution than can be done from the ground. And, of course, one would want to take a similar look at Uranus and Neptune.

During the decade between now and the launching of the LST, our choice of synoptic camera programs and priorities will doubtless change. To some extent, however, we shall probably want to pursue synoptic studies that are extensions in resolution and wavelength over those that are being carried out today with ground-based telescopes.

Taking the examples of ground-based synoptic planetary observations for reference, let me suggest some desirable LST camera parameters and some possible strategies for the synoptic observation of the principal planets. I would like to focus attention first on Jupiter, partly because it may offer the highest potential for fundamental findings and partly because it puts higher demands on camera performance than Mars or Venus do.

If the whole disk of Jupiter is to be recorded without serious degradation of the optical transfer function of the telescope at visual wavelengths, it has to fill a detector having at least 2500 x 2500 pixels, so that the image sampling interval will be about half the limiting spatial wavelength. On the other hand, if the limb of the planet is not included in the recorded image, there will be no zenocentric reference against which the positions of moving cloud features can be measured. They can, of course, be measured relative to one another within a smaller pixel format that does not include the limbs, and such a compromise may be satisfactory if the detector spans at least 1000 x 1000 pixels. Mosaic coverage of the image with still smaller detector arrays, such as 256 x 256 pixels, will be rather unsatisfactory unless the piecing together of the mosaic can be done with extremely high precision so that coordinate continuity across the junction is good to less than half a pixel. The same holds true, of course, for the relative positional stability of pixels within a larger array that spans the full disk. Image smear due to Jupiter's rotation should be held to a similar limit and therefore sets the maximum exposure time at about one second. Danielson (1973) has shown that one second is sufficient to produce a good signal-to-noise ratio with ordinary filter bandwidths at visual wavelengths, but that longer exposures with image motion compensation would be required to do well in the ultraviolet.

If all sides of Jupiter were to be observed by the LST on an uninterrupted patrol schedule for a desirable length of time, it would be incompatible with other astronomical programs competing for LST time. A reasonable proposal would therefore be to record about 60 images of a particular side of Jupiter at regular intervals, either each rotation period (every 9.9 hours) or each alternate rotation period (every 19.8 hours). If the selected interval is one rotation, a 60-image program would last 25 days. Since the images would have to be acquired within about ±30 minutes of the ideal times, this program could be a difficult one to schedule. On the basis of present patrol experience, however, such an LST program can be expected to yield an accuracy better than 0.2 meter per second in the velocity field of the Jovian cloud pattern--enough to identify dynamic modes very well. If the program is successful, it would probably be desirable to repeat it several times at two- or three-year intervals.

Any pixel format or mosaicking method that is satisfactory for Jupiter should also be satisfactory for Mars, Venus, or Saturn. An ideal program for Mars would include two different observing schedules, one for studying diurnal effects and the other for following changes that occur in the course of days and weeks.

The diurnal study of Mars would require hour-by-hour imaging, preferrably for a full rotation, several times (perhaps once or twice per month) during a Martian apparition. Diurnal effects include known contrast variations, which doubtless have much smaller scale structure than we see in ground-based Patrol photographs and which put demands on on the photometric performance of the LST camera. As illustrated for a particular location and time period in Figure 6, the contrast between a light area and a neighboring dark area tends to change in an asymmetric way during the Martian day, in the sense that the light area seems to become intrinsically brighter in the afternoon. If data for various time periods are averaged and if a symmetric Minnaert function is subtracted, one obtains the residual afternoon brightening curve shown in Figure 7. Any LST study of diurnal effects will require good stability in the relative sensitivities of pixels, so that subtle contrast changes can be detected. In this regard, I hope that the LST camera detector can approach fundamental limits (set by photoelectron statistics) connecting contrast threshold and spatial frequency.

Day-to-day changes (as distinct from diurnal effects) probably cannot be followed on all sides of Mars without imposing an undue burden on LST observing time, so I would propose imaging a particular side (perhaps around CM = 340°) once each rotation (24.6 hours) for about two months near favorable oppositions. Specifically, this would mean about one set of images per day through June and July of 1986 and through September and October of 1988. The latter will probably include the developing stages of a major dust storm.

On Venus a selected "side" of the atmospheric cloud pattern should be monitored by the LST in ultraviolet light. This would require an image (or set of images) about once every 4.3 days, on an adjustable schedule, for two four-month intervals bracketing an eastern and a western elongation.

With the LST, it would be desirable to do all synoptic planetary imaging in a sequence of several colors. The present ground-based Patrol successfully employs four broad-band filters that approximate the UBVR system used in astronomical photometry. With the addition of another band in the ultraviolet, this system would also be a good choice for LST imaging. Narrow-band filters might be helpful in diagnosing the presence of particular surface minerals or cloud constituents, but may be of limited value in a synoptic mode. The total range of sampled wavelengths should be as broad as possible so as to optimize the possibility of interpreting the phase angle dependence of contrast changes in terms of particle size populations. Thus, a broad range of sensitivity from the ultraviolet to near infrared will be desirable.

In summary, the synoptic use of the LST high-resolution camera will make major contributions to our understanding of variable atmospheric phenomena on planets, particularly Jupiter, Mars, Venus, and Saturn.

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FIGURE CAPTIONS

Figure 1. The development of the planetwide dust storm on Mars in 1971 as seen on International Planetary Patrol photographs in red light.

Figure 2. Maps showing the red-light outlines of the 1971 Martian dust storm at two-hour intervals during the first ten days. Numbers labelled on the outlines represent apparent solar time at the 0° meridian. (Martin, 1973).

Figure 3. Planetary Patrol photographs in ultraviolet light showing the growth of a major disturbance in the south equatorial belt of Jupiter. (Baum, 1971).

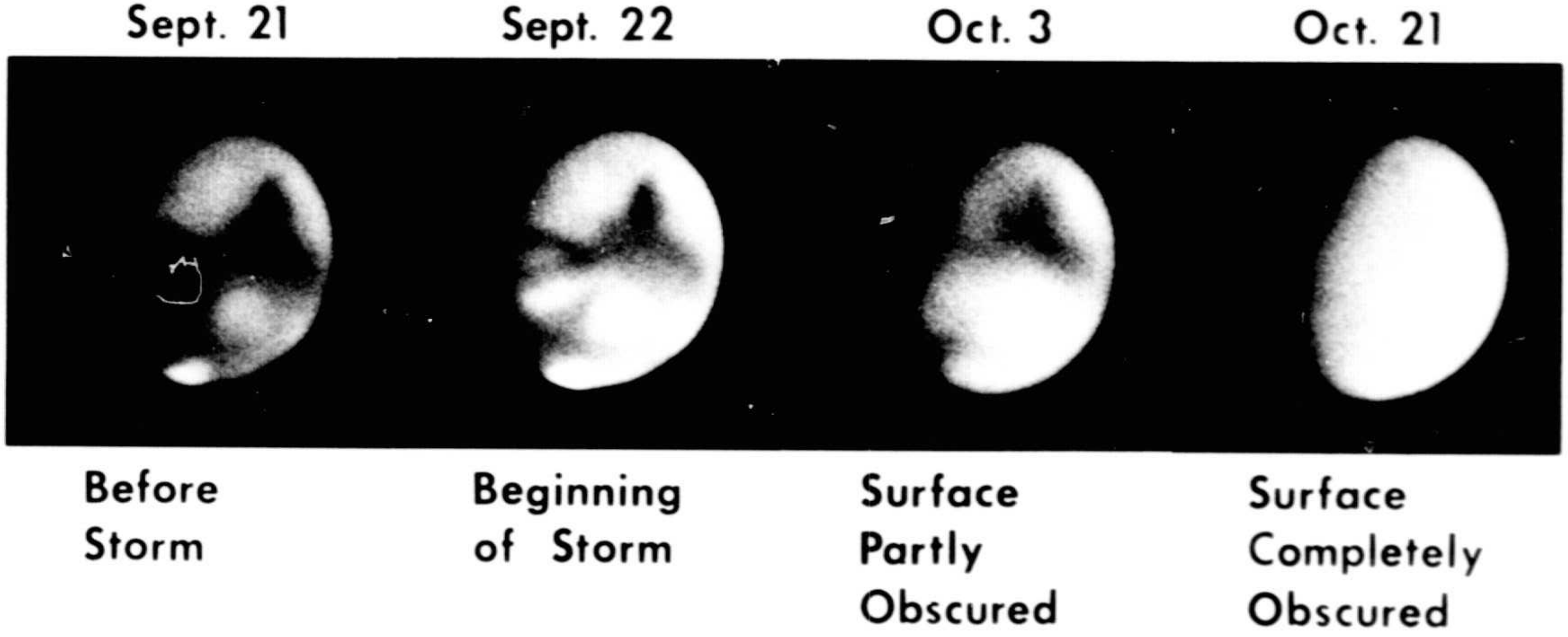
Figure 4. Mercator map of Mars showing the areas that can be viewed by Viking orbiter cameras during the early days of the mission.

Figure 5. Observed rotation periods of cloud features on Jupiter as a function of latitude in 1970, 1971, and 1972. (Inge, 1973).

Figure 6. Ratio of the blue surface brightness of a light area (Xanthe) on Mars to that of the neighboring dark area (Nilokeras), plotted against the local time of day in that region. These data are for one of three calendar intervals studied during the 1971 Mars apparition. (Thompson, 1973).

Figure 7. Diurnal change in the intrinsic albedo ratio of two neighboring areas on Mars, based on subtracting a Minnaert function from raw data, like those in Figure 6, for three calendar intervals in 1971. (Thompson, 1973).

MARS 1971 — YELLOW STORM



International Planetary Patrol Program
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Flagstaff, Arizona

Figure 1.

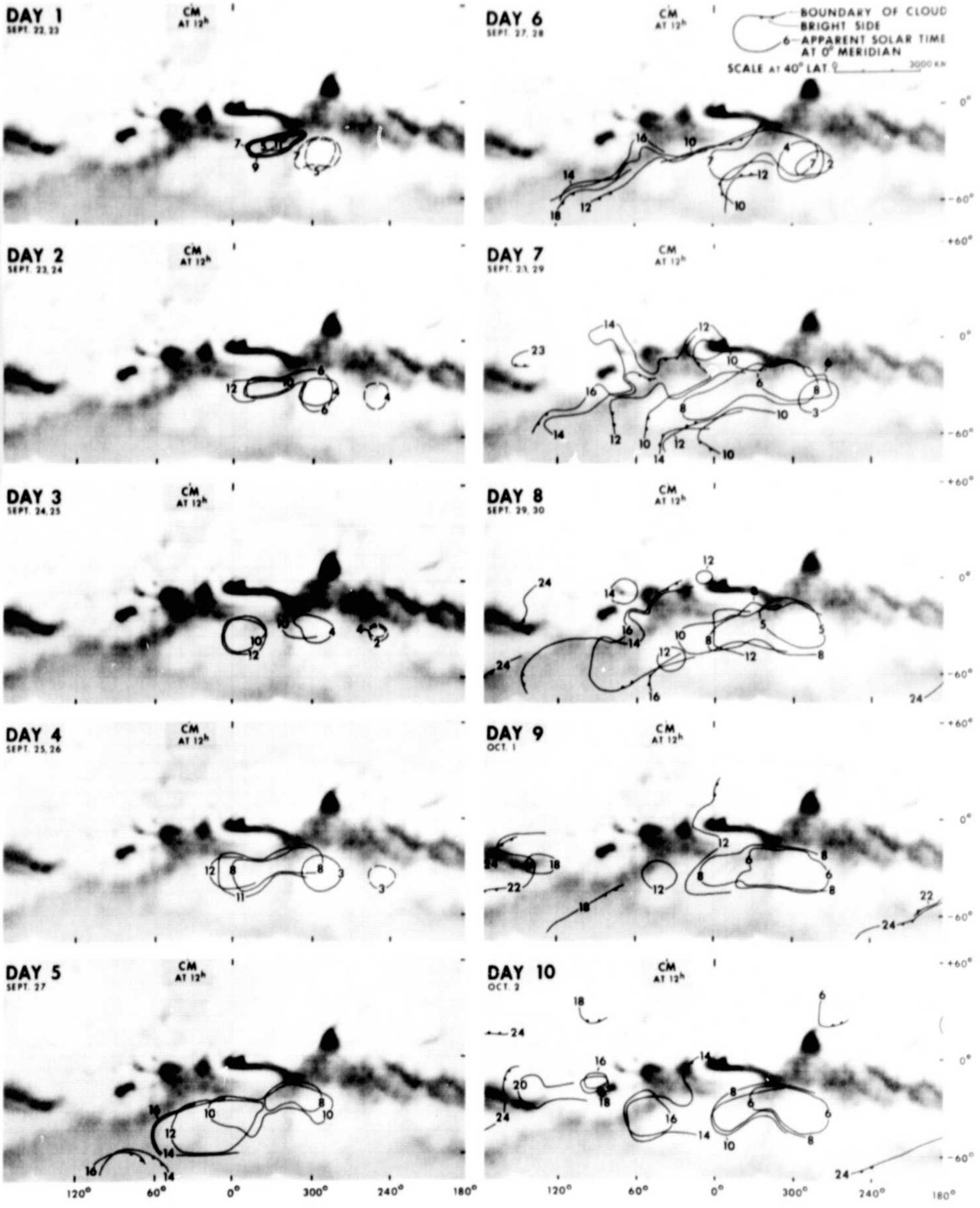
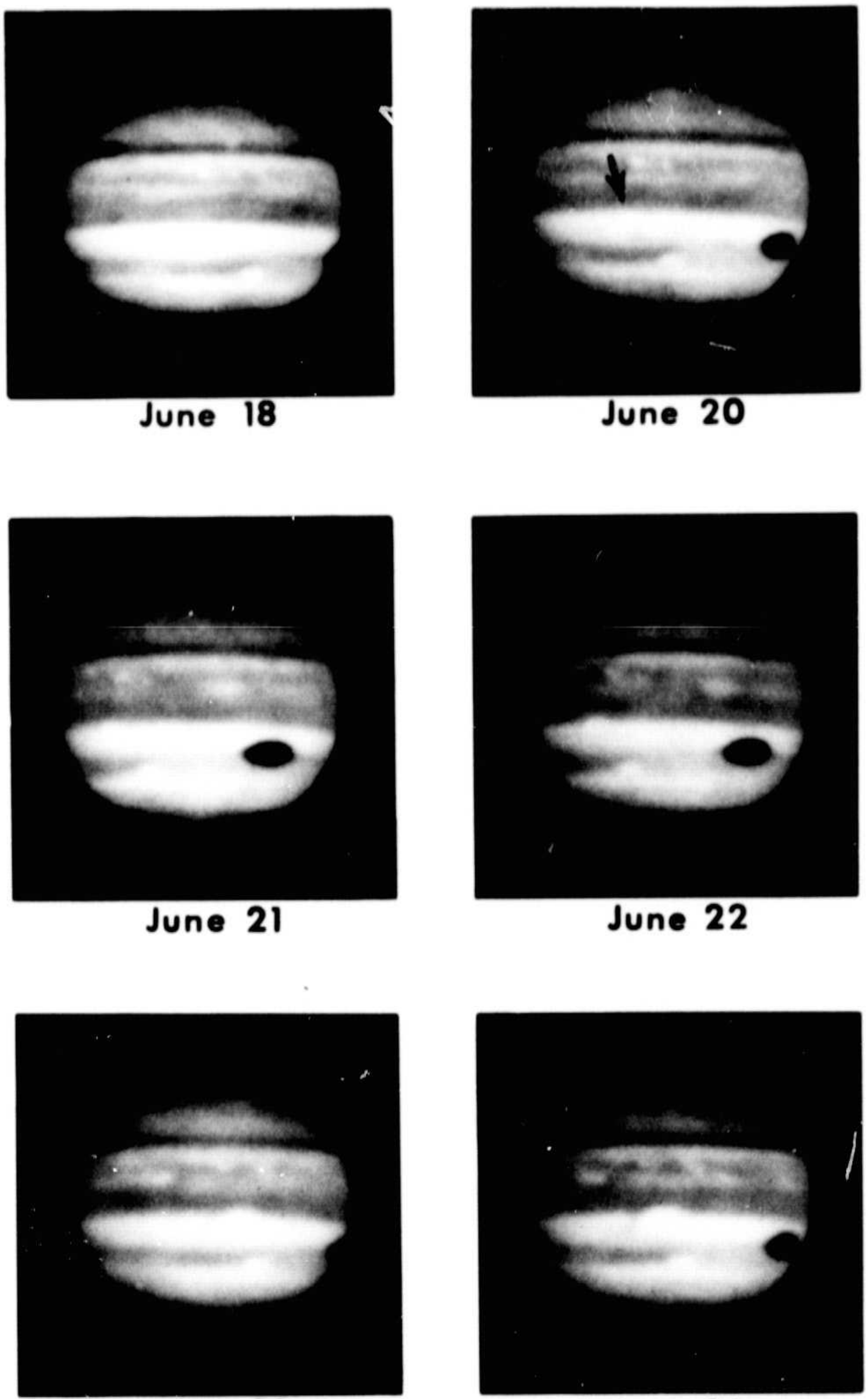

DAY 1
SEPT. 22, 23
CM AT 12h
DAY 2
SEPT. 23, 24
DAY 3
SEPT. 24, 25
DAY 4
SEPT. 25, 26
DAY 5
SEPT. 27
DAY 6
SEPT. 27, 28
DAY 7
SEPT. 28, 29
DAY 8
SEPT. 29, 30
DAY 9
OCT. 1
DAY 10
OCT. 2
BOUNDARY OF CLOUD
BRIGHT SIDE
6 — APPARENT SOLAR TIME AT 0° MERIDIAN
SCALE AT 40° LAT. 0 3000 KM
+60°
0°
-60°
120°
60°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

Figure 2.

1971 SEB DISTURBANCE



June 18

June 20

June 21

June 22

June 23

June 24

International Planetary Patrol

Figure 3.

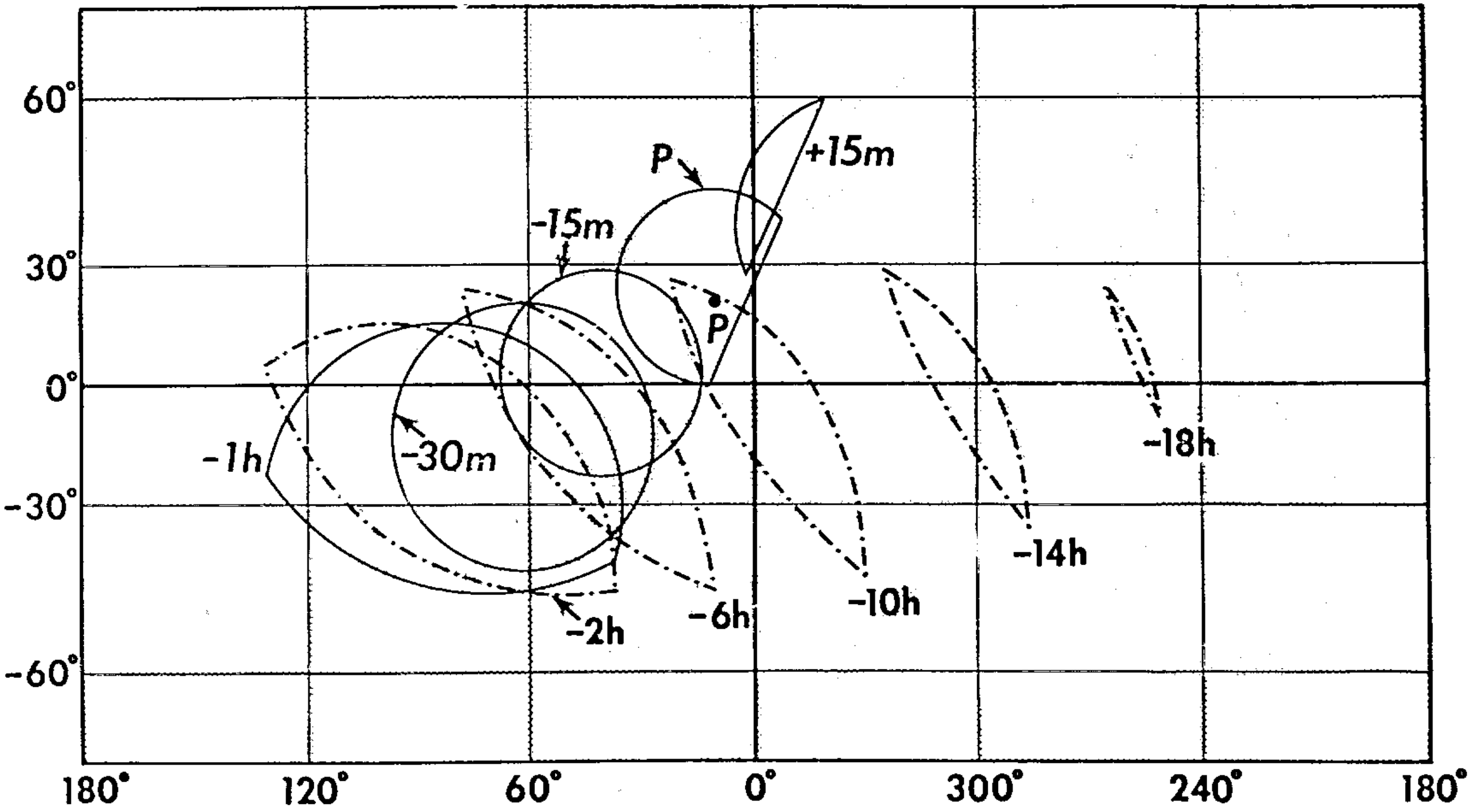

60°
30°
0°
-30°
-60°
180°
120°
60°
0°
300°
240°
180°
P
+15m
-15m
P
-1h
-30m
-2h
-6h
-10h
-14h
-18h

Figure 4.

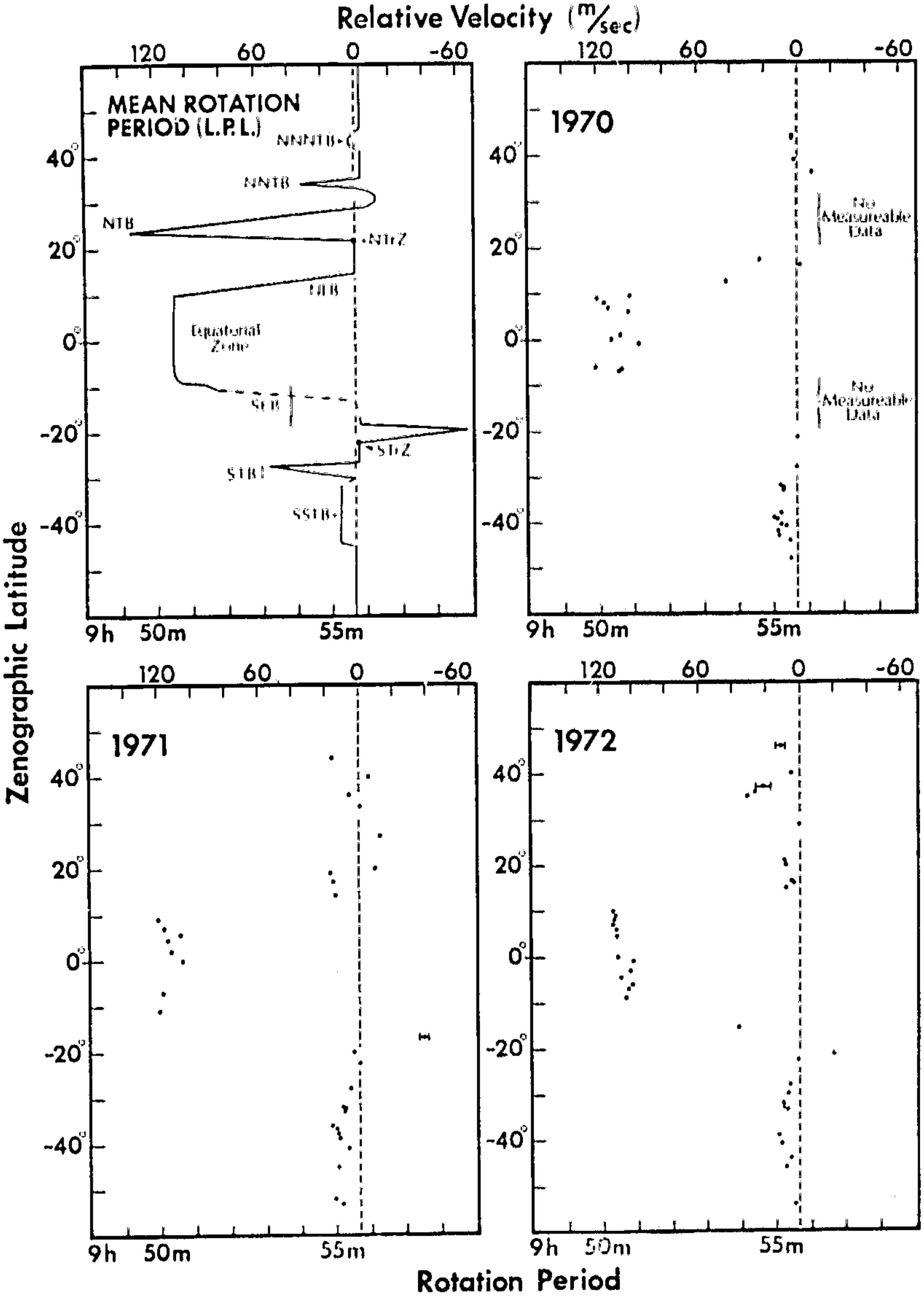

Relative Velocity (m/sec)
120
60
0
-60
MEAN ROTATION PERIOD (L.P.L.)
NNNTB+C
NNTB
NTB
NTrZ
NEB
Equatorial Zone
SEB
STrZ
STB
SSTB+
1970
No Measureable Data
No Measureable Data
1971
1972
Zenographic Latitude
40°
20°
0°
-20°
-40°
9h
50m
55m
Rotation Period

Figure 5.

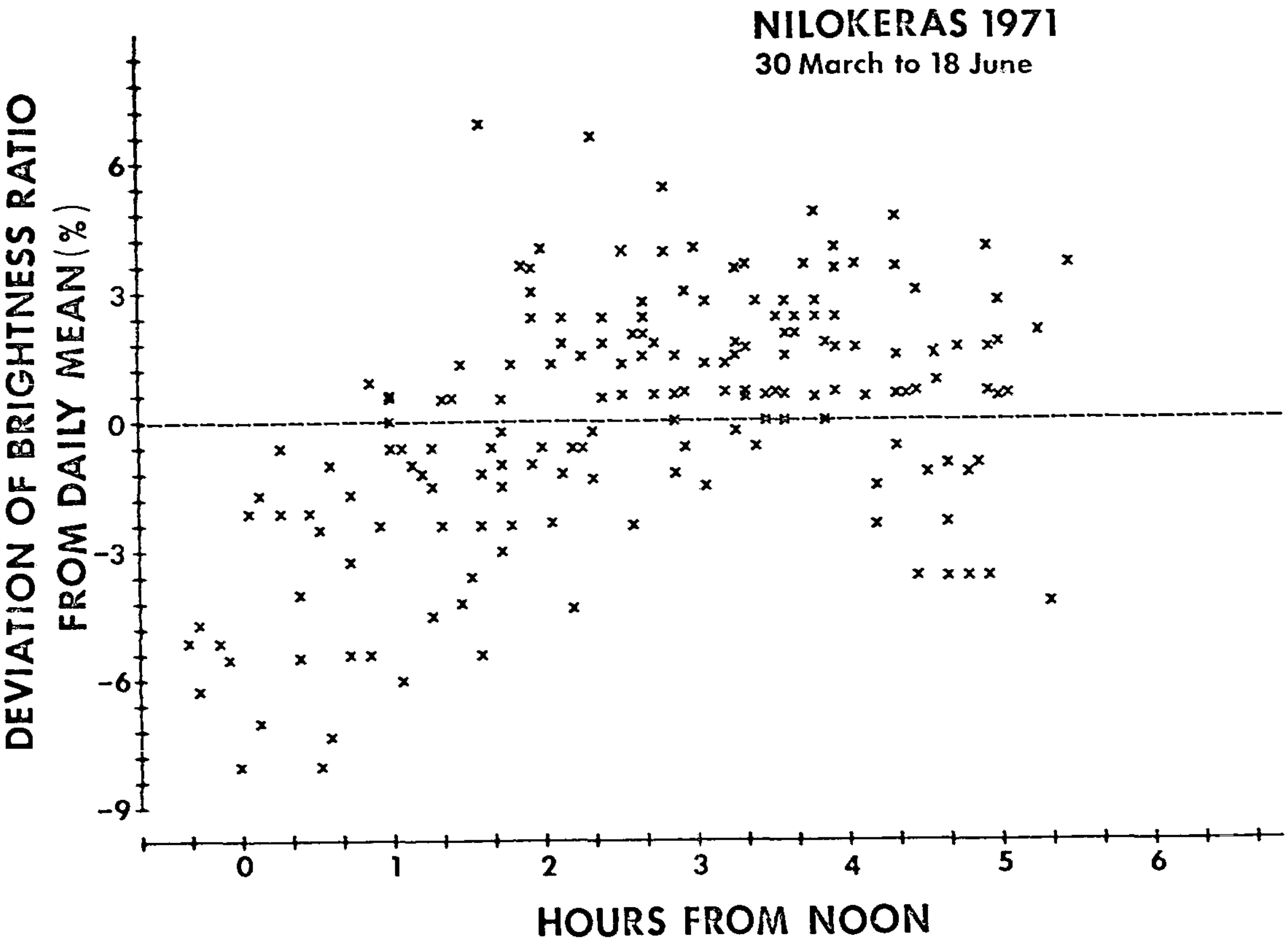

NILOKERAS 1971
30 March to 18 June
DEVIATION OF BRIGHTNESS RATIO FROM DAILY MEAN (%)
6
3
0
-3
-6
-9
0
1
2
3
4
5
6
HOURS FROM NOON

Figure 6.

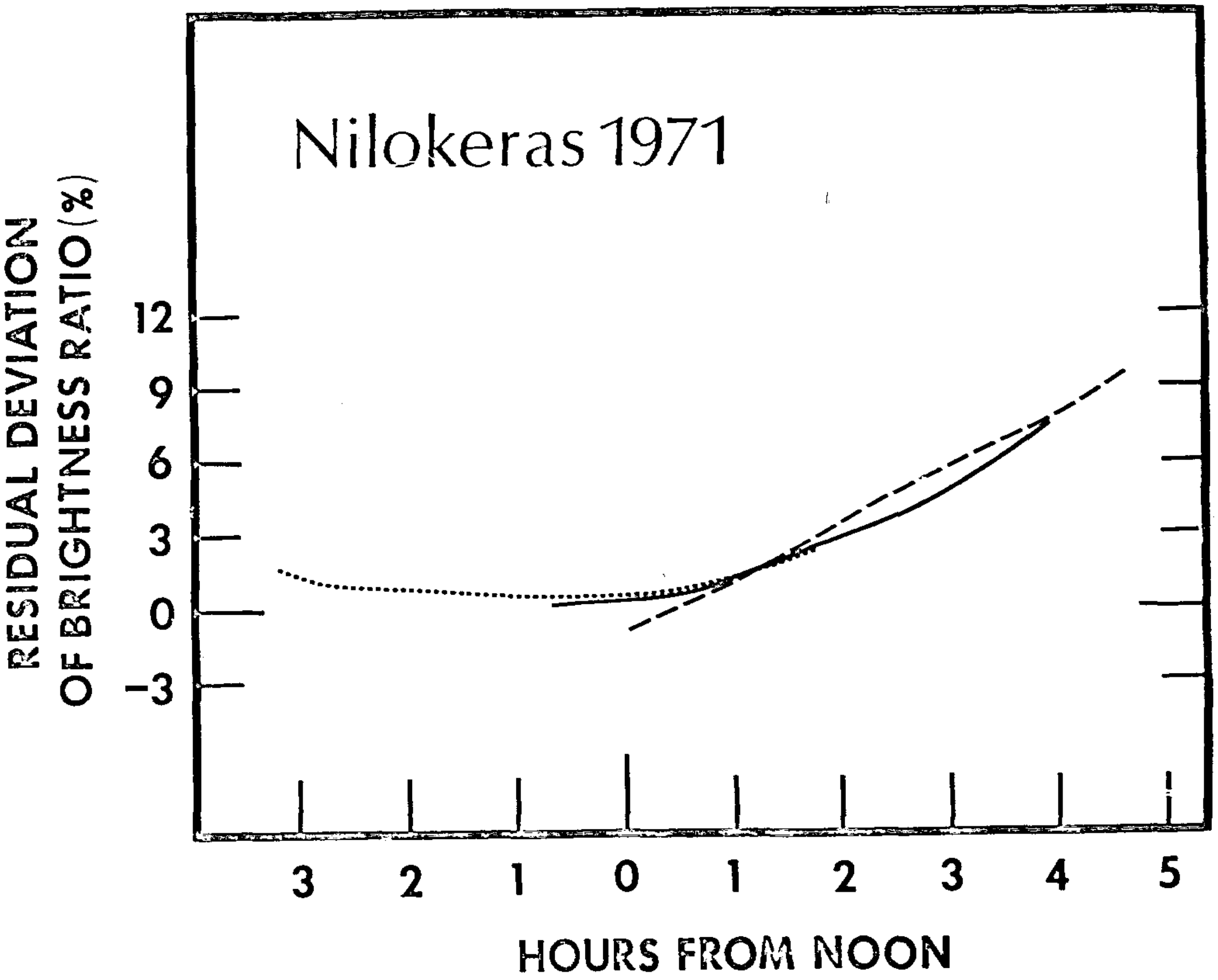
Nilokeras 1971
RESIDUAL DEVIATION
OF BRIGHTNESS RATIO (%)
12
9
6
3
0
−3
3
2
1
0
1
2
3
4
5
HOURS FROM NOON

Figure 7.