Rocket Measurements of the Geomagnetic Field

Above Woomera, South Australia

by

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ABSTRACT

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Two British Skylark research rockets, each carrying a proton magnetometer, were flown from the Woomera Rocket Range, South Australia, in March 1964.

The first flight merely recorded an approximately inverse cube law variation of magnetic field with height but on the second flight a magnetic discontinuity, of approximately 24 gammas amplitude, was recorded. These results are consistent with ground observations at the times of the two flights and they establish experimentally the existence of an electric current system in the E-region of the ionosphere over South Australia. The height and vertical thickness of the current are, however, not in close agreement with theoretical predictions.

Author

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INTRODUCTION

The generally accepted basis for the explanation of the observed daily variations in the earth's magnetic field is to be found in the dynamo theory, first postulated by Balfour Stewart in a famous article in the 1882 edition of the Encyclopaedia Britannica. His suggestion arose from the observation that the amplitude of the daily variations increased by a factor of two or more during a sunspot maximum, as compared with that during a sunspot minimum. Since this large factor could not be explained in terms of any known physical changes near the surface of the earth, he concluded that the source of the variations must lie in the upper atmosphere and must, therefore, be an electric current. Schuster (1908), Chapman (1919) and other workers later elaborated the dynamo theory and, using magnetograms recorded at various observatories throughout the world, they were able to represent the complex and changing array of magnetic variations by a relatively simple system of horizontally stratified sheet currents, stationary relative to the sun, but, relative to an observer on the earth, continuously moving westwards and varying in intensity with a predominantly twenty-four hour period.

According to the dynamo theory the electric currents are initiated and maintained by a combination of the action of solar tidal winds and the effects of solar radiations on the upper atmosphere. As charged particles are transported across the lines of force of the earth's magnetic field electromotive forces deflect the positively charged particles in the opposite direction from the negative ones, thereby generating a current. This current rapidly sets up polarization at the boundaries of the conducting region and the electric fields associated with this polarization further modify the current pattern. This current system is identified by the symbol Sq to differentiate it from other proposed currents responsible for lunar (L) variation and storm-time (D) variation. Since the source of the charged particles is to be found in the horizontal layers of the ionosphere it follows that, on a world-wide scale, the current system must be predominantly horizontal. The current density at any point then depends on the velocity of the tidal winds producing the electromotive forces, on the conductivity of the ionized gases and on the strength and direction of the earth's magnetic field.

Using routine observatory magnetograms it is possible to estimate the total current flowing above any part of the earth but a detailed analysis is not possible from ground data alone. In particular it is difficult to assess such features as the height, vertical thickness and any possible stratification of the currents.

With the advent of high altitude sounding rockets in 1946, direct in-situ measurements of atmospheric properties became possible and Vestine and others (1947) first suggested that rocket-borne magnetometers could be used to investigate the distribution of these electric currents with height. Accurate determinations of the current density as a function of height at several geographical locations would then test the validity of the dynamo theory and assist in its further development.

Assuming for the moment, that the electric currents are located in the ionosphere, it follows that their horizontal dimensions must be large compared with their height and hence, to an observer on the ground, the Sq current system can be approximated by an infinite sheet current. The magnetic field associated with a current of this nature is $2\pi j$ gauss, where j is the current density in absolute amps per centimeter, and it is independent of the height of the current sheet. Thus, if a rocket vehicle is used to carry a magnetometer, which is designed to measure F, the total scalar geomagnetic field, it should detect a discontinuous change of approximately $4\pi j \cos I \sin\theta$ in passing through the current, where I is the inclination of the geomagnetic field below the horizontal and θ is the angle between the direction of the current flow and the local magnetic North.

In addition to the measurements of various atmospheric current systems, rocket-borne magnetometers could be used to obtain more detailed information on the morphology of the earth's main magnetic field and secular variations and to check the validity of the various attempts which have been made to describe the geomagnetic field in terms of a spherical harmonic analysis.

A comprehensive summary of the various circumstances in which worth-while magnetic measurements should be carried out from rockets has been given by Chapman (1954). In addition to his recommendations for flights during magnetic disturbances he further suggests that measurements of the current systems be undertaken in low and middle latitudes during periods of magnetic calm in order to confirm the existence of the Sq current system and to investigate its morphology.

The first in-situ detection of an ionspheric current was made, in a pioneering rocket flight, by Singer, Maple and Bowen (1951). They installed a total-field fluxgate magnetometer in an Aerobee rocket, which reached a height of 105 Km at a point very close to the magnetic equator, and succeeded in detecting a magnetic discontinuity of 400 ± 50 gamma.

Cahill (1959) has reported a further series of equatorial flights using rockoons which were instrumented with proton magnetometers and were launched from ship-board. In particular two flights from the vicinity of Jarvis Island reached heights of 120 and 130 Km and detected anomalous departures from a dipole field of -150 gamma and -300 gamma respectively, the experimental error in the observations being ± 20 gamma. The second flight also indicated some stratification of the electrojet into two layers, though the upper layer was not completely penetrated.

Magnetic anomalies, of several hundred gamma amplitude, associated with localized intense electric currents in aurorae have also been detected (Meredith et al 1958). A number of other rocket flights have taken place in latitudes away from the geomagnetic equator but the successful detection of the Sq current system, in these latitudes, has not been reported (Maple et al 1950, Heppner et al 1958, Marks and Conley 1959, Conley 1960, Hutchinson and Shuman, 1961).

In a consideration of the dynamo theory the magnetic equator constitutes a special case in which electric-fields, caused by polarization effects in the ionosphere, result in a considerable enhancement of the current density during the middle daylight period, in a band approximately 3^o of latitude wide; this results in a magnetic discontinuity of magnitude several hundred gamma as detected by a rocket-borne magnetometer. In mid-latitudes, however, the Sq magnetic variations are much smaller and hence the problem of detecting the postulated ionospheric-currents is more difficult.

ESTIMATED GEOMAGNETIC EFFECTS

A rough estimate of the amplitude of a discontinuity, which might be expected in the total scalar force in passing through the postulated electric current above Woomera, can be made as follows.

The rocket launching site at Woomera, from where British Skylark rockets are normally fired, is situated at Lat. 30^o 56'S, Long. 136^o31'E, Geomagnetic Lat. -41.0^o.

Fig. 1 shows the position of Woomera, at local midday and midnight, relative to the Sq current system, as given by Chapman and Bartels (1940). It is immediately evident that the focus of the Southern pattern passes very close to Woomera. In fact the magnetograms recorded at Gnangara, in Western Australia (Lat. 31· 47'S), indicate that the focus passes to the north of that observatory on about 60% of days, to the south on about 10% and overhead on about 30% (Private communication from P. M. McGregor, Mundaring Geophysical Observatory, Western Australia). Normally, therefore, Z, the vertical component of F, shows the greatest diurnal variation at ground level. Z is, however, continuous in passing through the current sheet and so cannot contribute appreciably to any discontinuity. Fig. 2 shows the mean monthly variations in X and Y, the horizontal components of F, for quiet days during 1938 at the Watheroo Magnetic Observatory (30°19'S, 115°53'E, geomagnetic Lat. -41·8° Long. 185·6°). Since the observatory at Watheroo (now removed to Gnangara) was at approximately the same magnetic latitude as Woomera it is reasonable to assume that the magnetograms from an observatory at Woomera would be very similar at corresponding local times. In Fig. 2, Y, the E-W component, shows maximum variation but, since this component is almost normal to F, it will contribute very little and hence it is the variation in X which can be expected to be mainly responsible for any discontinuous change in F. The maximum value of ΔX occurs at 09.00 ± 1 hours in August, when its value is about 20 gamma different from the night-time value. Since at least 25% of this will be due to induced earth currents, the actual discontinuity in X will be roughly 0.75 x 2 x 20 = 30 gamma and this leads to an estimated discontinuity in F of 30 cos 63 = 14 gamma, since the inclination at Woomera is 63°. Thus the average discontinuity which might be expected in passing through the Sq current over Woomera is about an order of magnitude less than that which has been detected at the geomagnetic equator. The actual effect which might be encountered on any given day could, of course, vary considerably according to the precise location of the focus of the current system and the magnetic conditions prevailing at the time.

INSTRUMENTATION

The magnetometer and data processing technique which was used for these flights has been discussed in detail, together with the results of an instrument proving flight (Burrows 1964). Although a horizontal component magnetometer would have simplified the problem of detecting an Sq current discontinuity the Skylark rocket cannot yet be stabilized to the degree required for useful measurements of magnetic components; a total force instrument was therefore developed using the principle of nuclear free precession (Packard and Varian 1954, Waters and Francis 1956, Waters and Francis 1958, Burrows 1959). The data of this instrument are in the form of damped sine-waves the frequency of which is an analogue of the total scalar magnetic force; it produces approximately one absolute determination of F per second.

In view of the small anticipated magnetic discontinuity it was essential to remove the sensing head well out of range of the magnetic field perturbations due to various other rocket instrumentation.

In a standard Skylark rocket the two principal sources of magnetic interference are the mild steel tube of the Raven motor and the magnet of the 6 cm magnetron used in the "Missile Tracking System". Accordingly the M.T.S. magnetron was enclosed inside a magnetic shield and the magnetometer sensor was mounted on the end of a flexible pneumatic probe.

During the rockets ascent through the atmosphere the probe was folded inside a 12" diameter canister mounted in the main body of the rocket.

After the rockets had passed through the dense atmosphere the spent motor tube was ejected, by means of three pneumatically operated plungers, and the probe was deployed to its full length of 20 feet, at which range the residual magnetic fields associated with the rocket were negligible. This technique considerably simplified the problem of maintaining adequate magnetic cleanliness in other rocket instrumentation.

In the two rocket flights discussed in this paper the proton magnetometer was classed as a secondary experiment, the primary object of the flights being the measurement of the flux of gamma rays in the primary cosmic radiation (Southampton University). The rockets also carried sporadic E detectors (University College, London), x-ray cameras (Leicester University) and, for attitude and performance determination, sun slits, fluxgates, rate gyroscopes and accelerometers (Royal Aircraft Establishment, Farnborough).

In conjunction with the rocket flights a ground proton magnetometer (Burrows 1963) was operated to record the diurnal variation in F and a fluxgate instrument, kindly loaned by the Bureau of Mineral Resources, Melbourne, recorded H, the horizontal component. H was selected as being that component of the Sq variation field which is discontinuous in passing through the postulated current sheet as discussed above.

In flight the rockets were tracked by means of kine-theodolites, radar type FPS16 and the M.T.S. beacon transmitter, all standard range facilities at Woomera. Each rocket was powered by a combination of a Raven solid fuel motor and a "cuckoo" booster. A full description of the Skylark sounding rocket has been given by Hazell and Dorling (1959).

DATA PROCESSING

During flight the proton precession signals were relayed via the standard Skylark "465" telemetry system (Rae, 1946) and recorded, together with a standard 50 Kcps reference signal and timing code, on an "Ampex" multi channel tape recorder.

During play-back the signal/noise ratio of the raw data was improved by means of a manually controlled tracking filter and the signals were mixed with a suitable reference frequency derived from the 50 Kcps standard recorded on the same tape. By this means variations in precession frequency, due to tape speed variations, were, to a first order, compensated.

A full description of the apparatus and the data reduction technique employed has been given by Burrows (1964).

Fig. 3 shows a sample of the beats derived from flight SL 129 obtained by this method recorded together with a 1mS timing code.

The precession frequencies, and hence magnetic-field readings, were computed manually by counting the number of beats in a time, measured from the timing code, and adding the beat frequency, thereby derived, to the accurately known reference frequency. The advantage of this manual technique over a fully automatic approach is that, where the signal is of amplitude comparable with noise or interference, the regular beats can be seen and random noise rejected.

RESULTS

A) Ground Data

Fig. 4 shows the records of the diurnal variation in F which were obtained from the ground proton magnetometer at Woomera for seven consecutive days, starting on the date of the first rocket flight. The instrument measures the period of 1024 cycles of the precession signals in units of 10^{-5} second and records the last two digits; in the ambient field at Woomera this corresponds to a full scale deflection of 143 gamma. Since the first three digits were invariant at 413 the absolute value of the total force of the geomagnetic field was typically, 58,210 gamma. In making the records of Fig. 4 the instrument was set to take one reading per five minutes. It should be noted that all seven records are similar, in general form and amplitude of the peak diurnal variation; indeed all the records taken, on magnetically undisturbed days, during the three months the instrument was in operation at Woomera are similar in character to those reproduced in Figure 4.

Fig. 5 shows the H magnetograms recorded by the fluxgate magnetometer, at Woomera on the 10th and 12th March 1964, the days of the two rocket flights.

A comparison of figures 4 and 5 indicates that, on the 10th and 12th March the diurnal variations in F were very similar in amplitude (21 gamma and 24 gamma respectively) whereas there was a much larger negative variation in H on the second day. This suggests that on the 10th March the focus of the Sq current pattern passed nearly overhead at Woomera whereas on the 12th March it was situated at a significantly lower latitude. The 12th March was, therefore, a much more suitable day for the detection of a magnetic discontinuity at Woomera.

FLIGHT DATA

Skylark SL 129 was fired at 02.06 hrs. U.T. (11.36 hrs. Australian Central Standard Time) on the 10th March 1964; it reached a height of 175 Km and impacted at a point 77 Km down range on a bearing of 326.6°T relative to the launcher. Skylark SL 128 was fired at 02.07 hr U.T. (11.37 hr. A.C.S.T.) on the 12th March 1964; it reached a height of 175 Km and impacted at a point 77 Km down range on a relative bearing of 285.7°T, approximately 54 Km from the impact point of SL 129. On both flights the proton magnetometers functioned satisfactorily and produced data continuously from the time of probe deployment until the sensing head was torn off as the rockets re-entered the earth's atmosphere.

The accuracy of each reading depends on the attitude of the rocket at the time, as a consequence of the variation of signal amplitude with the angle between the axis of the sensing head and the geomagnetic vector, (Burrows 1964); hence, as the rockets tumbled in flight, the scatter of the readings about the mean values varies from less than 1 gamma to a maximum of about 10 gamma. All the readings which were obtained have, however, been used in the computations and discussions which follow. The first one or two readings of each flight are of dubious value as, at this time, the probes were still being inflated and the sensing heads were probably still under the influence of the rocket's magnetic fields.

It is well known that rotational motions of a proton sensing head introduce a frequency modulation in the precession signal (Bloom 1955, Hall 1962). In practice, however, the fluxgate data showed that Skylarks 129 and 128 precessed with periods of 23 seconds and 35 seconds respectively; the errors from this cause, whilst non-the-less detectable, are small and have been neglected.

The magnetometer data have been compared with values of magnetic total force calculated on the basis of spherical harmonic analyses using coefficients derived by Leaton and Evans (1964) and by Cain et al (1962, 1964a, 1964b). The differences between measured values and values obtained from two of the reference fields are shown in figures 6 and 7.

The agreement between measured and computed fields depends mainly on the coefficients used but also there is a second order difference between the upward and downward sections of each flight. Thus when April '64 coefficients are used there is close agreement between the two sections of the flight of SL 128 but a large scatter in flight SL 129; on the other hand using Leaton and Evans coefficients leads to a better agreement in the case of SL 129 whereas the upward and downward flights can now be resolved in flight SL 128. (cf. figs. 6 and 7). As noted earlier, the trajectories of the two rockets were significantly different and these secondary discrepancies must reflect the different gradients of the errors of the two computed fields along the tracks of the two rockets.

In order to provide a quantitative comparison between the abilities of the various reference fields accurately to describe the earth's main field at the particular location of Woomera, the values of measured field minus computed field (defined as DEL), at the apogee of flight SL 128, are listed below:

Coefficients		DEL
Leaton and Evans	(1964)	+44 ± 3 gamma
Vanguard A	(Cain et al, 1962)	-75 ± 3 gamma
April 64	(Cain et al, 1964a)	-118 ± 3 gamma
Vanguard B	(Cain et al, 1964b)	-992 ± 3 gamma

In spite of these differences in detail, as between the flight results using different reference fields, the general form of the variation of DEL with height is consistent, regardless of which coefficients are used in calculating the reference fields.

IONOSPHERIC CURRENTS

As stated above, fig. 5 shows that the flight of SL 129 took place when the focus of the Sq current system was close to overhead at Woomera and the value of ΔH recorded at the time of the flight is close to the mean value. It is not therefore surprising that the flight data (Fig. 7 (left)) do not show any significant discontinuity, which could with confidence be attributed to a current sheet.

The flight of SL 128 however occurred when the magnetic conditions at Woomera were much more favorable for the detection of a discontinuity. As discussed above, at the time of the flight the fluxgate magnetometer recorded a significant departure from the nighttime value (Fig. 5). The Kp index for the appropriate 3 hour period was 4 (Lincoln 1964) but the proton magnetometer record shows that, at Woomera, the diurnal magnetic variation was normal and undisturbed except for minor fluctuations (Fig. 4). The reduced data from the rocket-borne magnetometer show an unmistakeable change in slope at a height of about 104 Km followed by a return to the original slope at about 115 Km (Fig. 7 (right)). This indicates that, during this time, the rocket passed through an electric current and the sign of the discontinuity confirms that the current was flowing in a direction having a westerly component. This anomaly is recorded on both the upward and downward portions of the flight. The absence of any similar discontinuity during the rest of the flight up to apogee indicates that no other current system, of comparable magnitude, was flowing in this height range at the time of the rocket flight.

In order to measure the amplitude of the magnetic discontinuity and to compare it with that which would be anticipated on the basis of ground data the upward and downward flight data are each plotted separately in Fig. 8, since they constitute two independent measurements. The mean relative displacement of the upper and lower portions of the curves is 24 $\pm$ 3 gamma. This experimental figure can be compared with one calculated on the basis of the ground data, as described above. At the time of the flight the deviation of H from the undisturbed nighttime value was -35 $\pm$ 2 gamma, the uncertainty being due to the difficulty in selecting the undisturbed value. This leads to an expected discontinuity in F of between 23 and 26 gamma, making the approximations and on the assumptions discussed above.

The magnetic discontinuity, which was observed in flight therefore agrees very closely, both in amplitude and in sign, with what would be anticipated on the basis of the ground observations at the time. This lends support to the belief that, at the latitude of Woomera, the currents responsible for the normal diurnal magnetic variations are concentrated almost entirely in a single layer, extending from approximately 104 Km up to approximately 115 Km, in the E region of the ionosphere; futhermore on the basis of the assumption that 25% of the observed diurnal variations are due to induced earth currents, these results also imply that any nighttime ionospheric currents must be much smaller than those which have been demonstrated to flow during the daytime.

Many attempts have been made to calculate the way in which the electrical conductivity of the ionosphere should vary with height at different geomagnetic latitudes using a variety of simplified models of the atmosphere (Baker and Martyn 1952, Fejer 1953, Chapman 1956, Ratcliffe and Weekes 1960, Maeda and Matsumoto 1962). By neglecting any vertical gradients of tidal wind velocity these theoretical results can be used to make a rough estimate of the vertical distribution of current density which might be encountered. The heights of the currents in the equatorial electrojet, which were detected by the earlier flights of Singer et al and Cahill, agreed reasonably well with the theoretical calculations as they applied to the special conditions at the geomagnetic equator.

It is now possible to draw some general qualitative conclusions about the vertical morphology of the current pattern, at the mid-latitude location of Woomera, as they apply at least at the time of the flight of SL 128, and to compare these empirical results with the theoretical predictions. As noted above it appears that the electric currents were concentrated in a single layer of the E region of the ionosphere and the upper and lower boundaries of this layer were both quite sharply defined. The layer was, however, considerably thinner and was located somewhat lower in altitude than would be predicted on the basis of the calculations. This conclusion implies that either the models, which have been used to calculate the conductivity profiles, do not describe the physical conditions sufficiently accurately at mid-latitudes or, more likely, that there existed above Woomera at the time of the flight a significant vertical gradient of the tidal wind velocity and this must be taken into account in any calculations of the vertical morphology of the ionospheric electric currents ; gradients of this nature have been observed during several nighttime rocket flights using sodium vapour techniques (Kochanski, 1964) but no reliable wind measurements, during the mid-daylight hours at the heights of the observed current layer, have been reported.

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FIGURE LEGENDS

Fig. 1. The position of Woomera relative to the Sq current system for the equinox of a sunspot minimum, (left) at mid-day as viewed from the sun and (right) at mid-night as viewed from the night hemisphere (after Chapman and Bartels). The flow between adjacent current lines is 10,000 A.

Fig. 2. Hourly means of ΔX and $\Delta \gamma$ for quiet days at Watheroo, 1938.

Fig. 3. Sample record of beats obtained by processing of raw data. (Duration of record approximately 0.5 second)

Fig. 4. Ground Proton Magnetometer Records, 10th - 16th March 1964, Woomera. Full scale deflection of each record = 143 gamma. Timing marks are local time at Woomera (= U.T. +9½ hours).

Fig. 5. Variation of H on the days of the rocket flights (field strength decreasing upwards). Timing marks are local time at Woomera (=U.T. + 9½ hours).

Fig. 6. Comparison of measured values of total force with computed values as a function of height, Left-SL 129; Right-SL 128, Leaton and Evans coefficients.

Fig. 7. Comparison of measured values of total force with computed values as a function of height, Left-SL 129; Right-SL 128, April 1964 coefficients. (Cain et al, 1964)

Fig. 8. Magnetic discontinuity detected by Skylark SL 128. Left-upward flight; Right-downward flight.

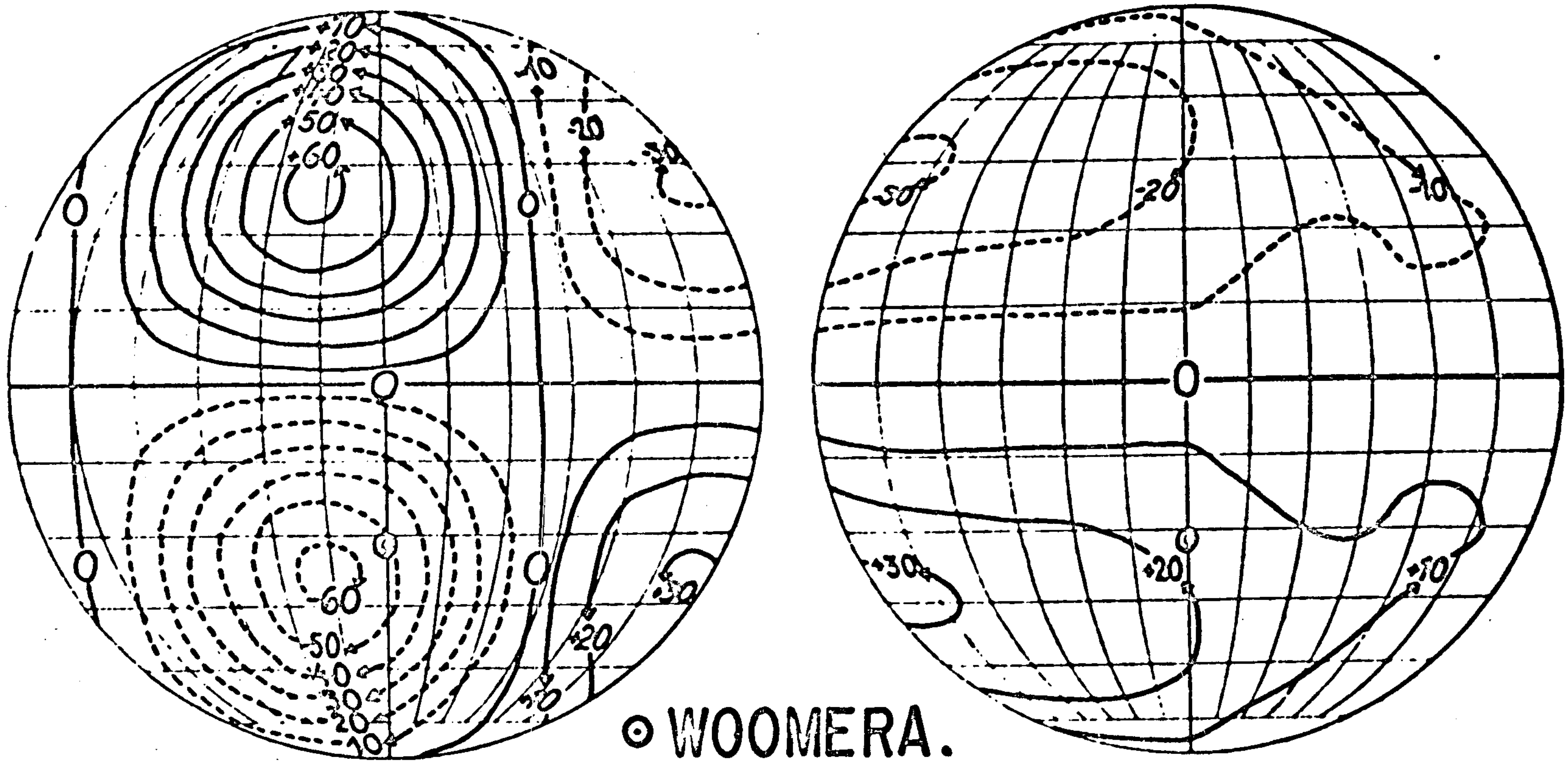
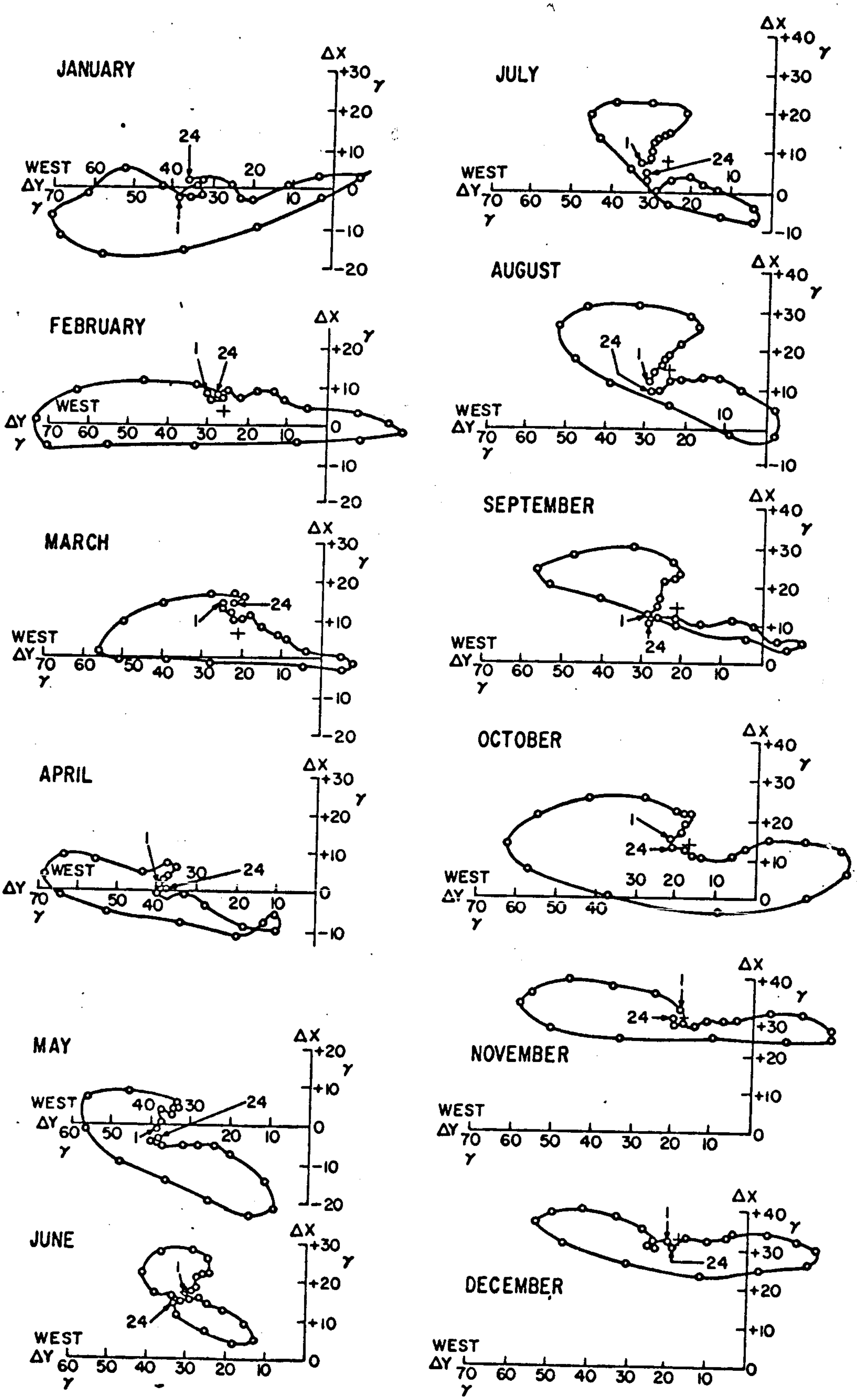


FIG 1


JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
WEST
ΔY
ΔX
γ
1
24
+40
+30
+20
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0
-10
-20
70
60
50
40
30
20
10

FIG-2

Figure 3. in preparation:
Will look like:-

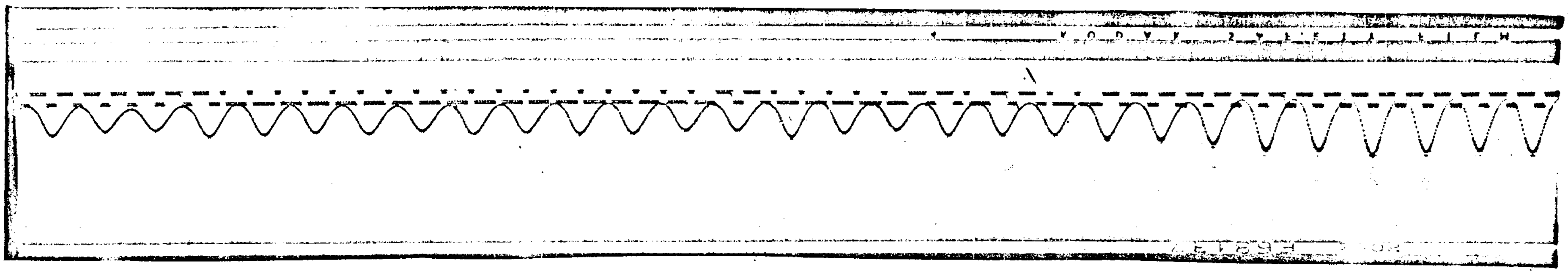
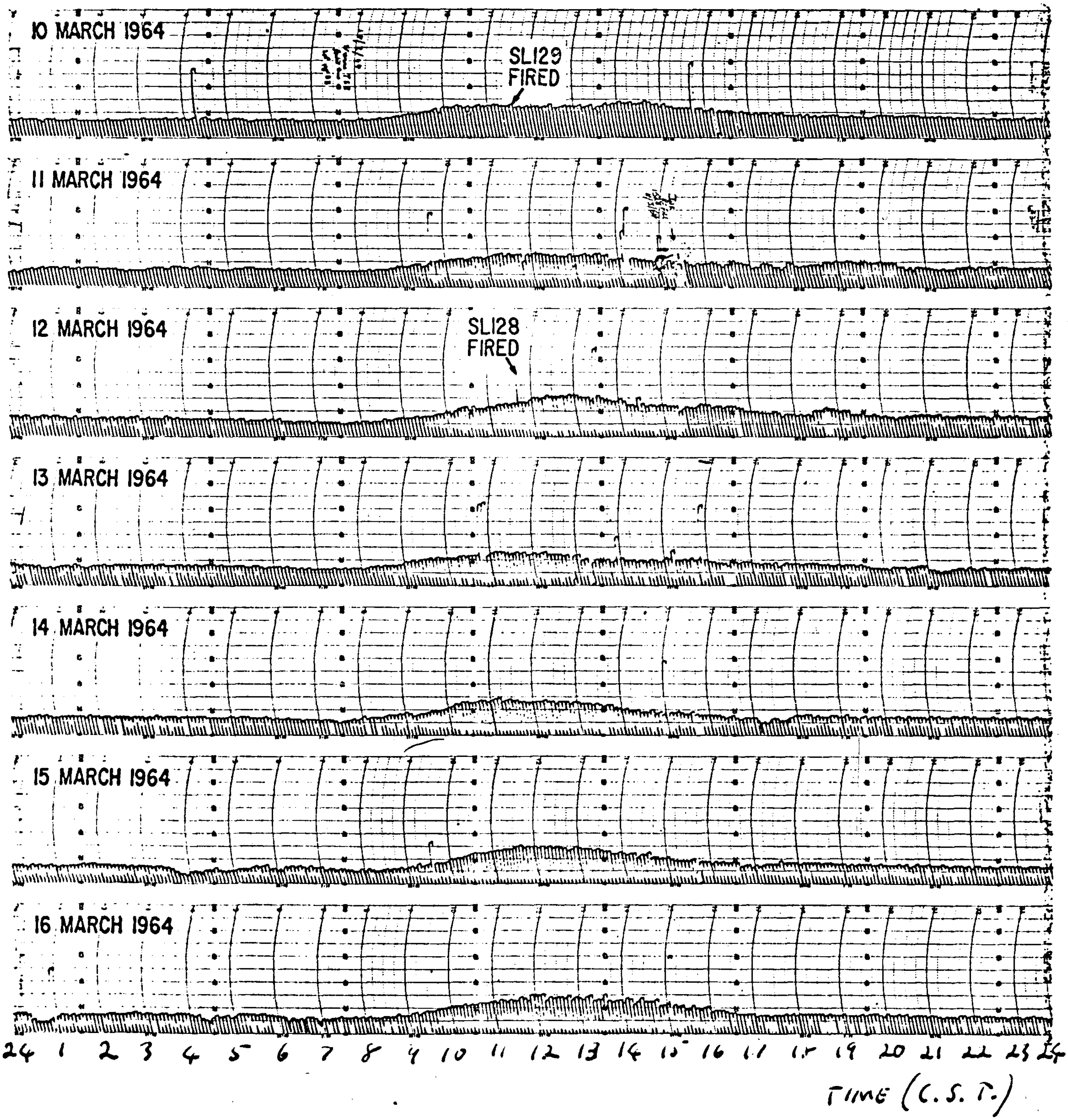


FIG. 3.


10 MARCH 1964
SL129 FIRED
11 MARCH 1964
12 MARCH 1964
SL128 FIRED
13 MARCH 1964
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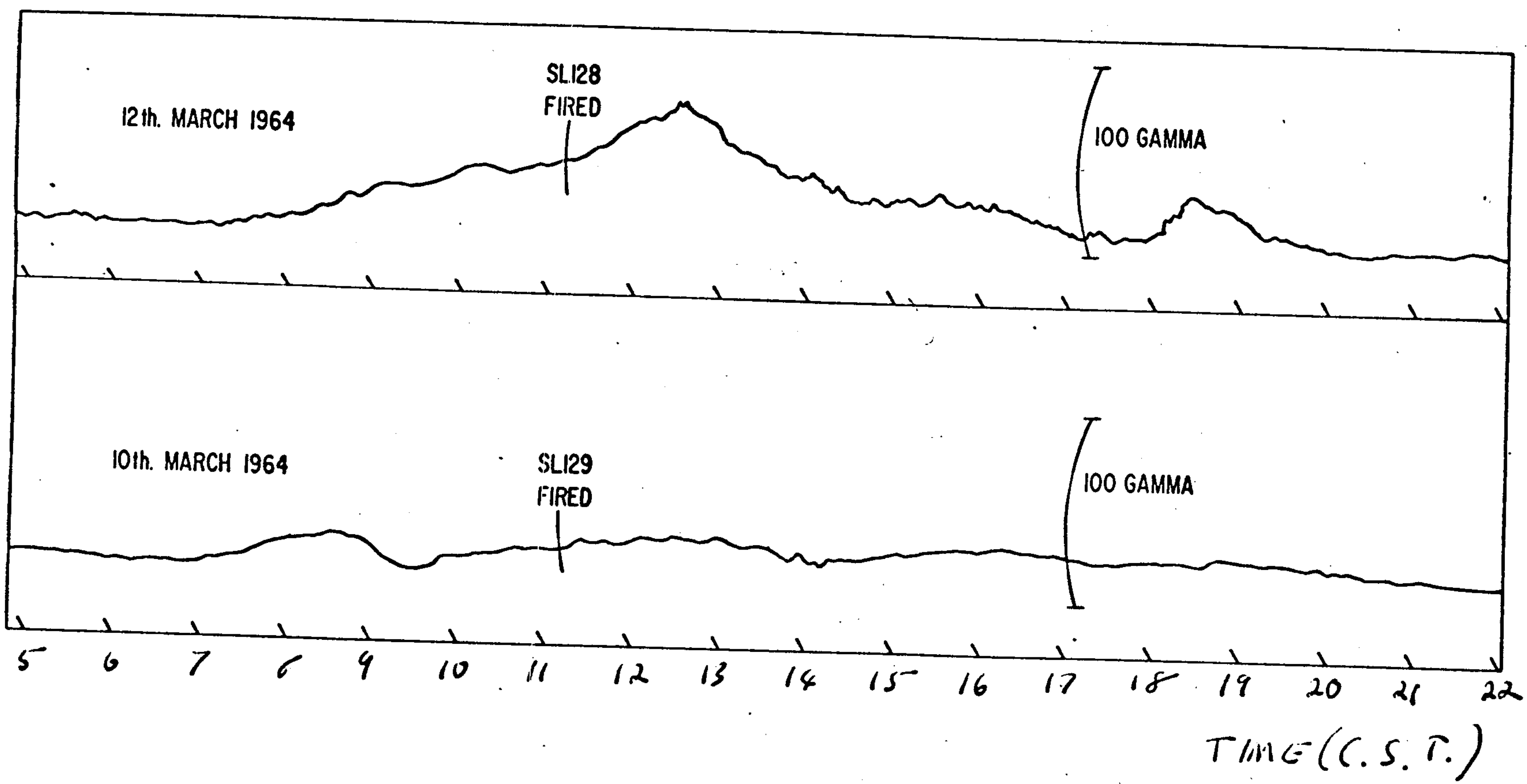
16 MARCH 1964
24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
TIME (C.S.T.)


12th. MARCH 1964
SL128
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10th. MARCH 1964
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