THE SOLAR DAILY VARIATION OF COSMIC RAY MESON INTENSITY AT $\lambda=52$ °S. AND $\lambda=73$ °S.

By N. R. PARSONS*

[*Manuscript received April* 15, 1957]

Summary

Some preliminary results are given of an investigation of solar daily variations recorded by vertically directed meson telescopes at Hobart, Tasmania (geomagnetic latitude $\lambda=52$ °S.) and at Mawson, Antarctica ($\lambda=73$ °S.). Long-term trends in phase of the variation are found to be similar to those reported by observers in the northern hemisphere. However, a substantial and fairly consistent phase difference in local time is apparent between the two stations, and its origin is discussed. A brief discussion of pressure-correction procedures is also given.

I. INTRODUCTION

Investigations of the solar daily variation of cosmic ray meson intensity have been carried out over many years at stations in the northern hemisphere, but few comparable records are available from the southern hemisphere. Many of the characteristics of the daily variation, particularly of the observed short- and long-term changes in form, are assumed to be " world-wide " in nature, and observations at southern stations should provide valuable information to assist in the interpretation of these phenomena.

Continuous recording, using a vertically directed counter telescope of high counting rate, was commenced at Hobart, Tasmania (geographic coordinates 42° 50′ S., 147° 20′ E.; geomagnetic coordinates 52 °S., 224 °E.) in September 1953. In April 1955 similar equipment was installed at the Australian National Antarctic Research Expedition station at Mawson, Antarctica (geographic coordinates 67° 36′ S., 62° 53′ E.; geomagnetic coordinates 73° S., 104 °E.). The purpose of this paper is to present some preliminary results obtained at these two stations.

Records have also been obtained over the same period using telescopes inclined to the vertical, and these will be discussed in a subsequent paper.

II. THE RECORDING TELESCOPES

All results presented have been obtained with Geiger counter telescopes of identical design. A detailed description of the equipment, prepared together with operating instructions and other relevant material as an equipment manual, has been published elsewhere (Parsons 1957). Briefly, the telescopes consist of three equally spaced square trays of counters, each tray having a sensitive

* Antarctic Division, Department of External Affairs, Melbourne; present address: Physics Department, University of Tasmania, Hobart.

TABLE 1

FIRST AND SECOND HARMONICS OF BIMONTHLY MEAN DAILY VARIATIONS OF MESON INTENSITY

Bimonthly Period	Hobart				Mawson			
	1st Harmonic		2nd Harmonic		1st Harmonic		2nd Harmonic	
	Amplitude (%)	Time of Maximum (L.M.T.)	Amplitude (%)	Time of 1st Maximum (L.M.T.)	Amplitude (%)	Time of Maximum (L.M.T.)	Amplitude (%)	Time of 1st Maximum (L.M.T.)
Sept.-Oct., 1953 ..	0·128	0656	0·053	0948				
Nov.-Dec.	0·199	0652	0·099	0852				
Jan.-Feb., 1954 ..	0·249	0748	0·131	0910				
Mar.-Apr.	0·184	0948	0·097	1124				
May-June	0·159	0848	0·041	0918				
July-Aug.	0·249	0424	0·071	0928				
Sept.-Oct.	0·177	0340	0·039	1146				
Nov.-Dec.	0·166	0708	0·009	0728				
Jan.-Feb., 1955 ..	0·112	0600	0·067	1044				
Mar.-Apr.	0·137	0836	0·116	0832				
May-June	0·140	1052	0·045	0958	0·121	1336	0·050	0156
July-Aug.	0·241	1024	0·051	1126	0·109	1220	0·042	0216
Sept.-Oct.	0·102	0624	0·019	0020	0·073	1000	0·014	0240
Nov.-Dec.	0·120	0720	0·045	0124	0·085	1420	0·016	0130
Jan.-Feb., 1956 ..	0·093	1400	0·054	0020	0·104	1748	0·047	0330
Mar.-Apr.	0·227	1220	0·047	0116	0·138	1552	0·105	0526
May-June	0·253	1112	0·095	0140	0·095	1252	0·082	0538
July-Aug.	0·196	1208	0·087	1038	0·107	1648	0·037	0232

area of 1 by 1 m, the separation of extreme trays being 1·5 m. Between the lower two trays is 10 cm of lead absorber. The Geiger tubes are of the external cathode type, 4 cm in diameter and of 1 m sensitive length. The associated electronic circuits record the threefold coincidence rate (approx. 85,000/hr) with a resolving time of 2·5 μsec. Scale factors of 2^7 are employed, and hourly count totals are recorded on Post Office type electromechanical registers.

At both stations the recorders are situated at an elevation of 15 m above sea-level.

III. Treatment of Data

The mean daily intensity variations have been calculated for successive bimonthly periods, and are represented by 12 bihourly intensity figures expressed as percentage deviations from the mean. These figures have been obtained after correction using a standard barometer coefficient of $-2 \cdot 31$ per cent. per cm Hg (see discussion in Appendix I) and after correction for residual secular change (assumed to be linear over the mean day). The final figures have been subjected to harmonic analysis by standard methods and the mean daily variation expressed as the sum of the 24- and 12-hr components of best fit.

It is interesting to note that the mean daily pressure variation, although contributing substantially to the observed intensity variation at Hobart, is very small at Mawson, and correction in the latter case affects the original figures very little. Moreover, at Hobart the pressure variation is almost entirely semi-diurnal in character whereas the small variation at Mawson is largely diurnal.

IV. Summary of Results

Table 1 summarizes the results of harmonic analysis of both the Hobart and Mawson data, taken in bimonthly groups. These results are plotted in Figures 1 and 2 to display the long-term changes in both amplitude and phase and to facilitate comparison of these changes at the two stations.

In Figure 1 are also included some results from other stations to allow comparison of the observed phase changes. The Tokyo data include results up to December 1954 published by Miyazaki (1955) and these results have been extended up to December 1955 by an examination of pressure-corrected bihourly data kindly supplied by Maeda (1955–56). These records are from a Nishina type ionization chamber, under a 10 cm lead shield and 40 cm concrete roof and situated near sea-level. The Manchester and London results are as published by Possener and van Heerden (1956) and refer to relatively wide-angle unshielded counter telescope measurements. Up to the end of June 1954 averages of simultaneous north and south measurements at 45° to the vertical are used. The authors show these to be comparable with the later vertical measurements made at London. The separate time groups to which the plotted average times of maximum refer are indicated in the diagram. The Hafelekar results are taken from Steinmaurer and Gheri (1955). They are from measurements at an elevation of 2300 m with an ionization chamber under a 10 cm lead shield. Quarter-yearly mean times of maximum are given.

The data from each of the three northern stations are corrected only for pressure variations, using experimentally determined total barometer coefficients.

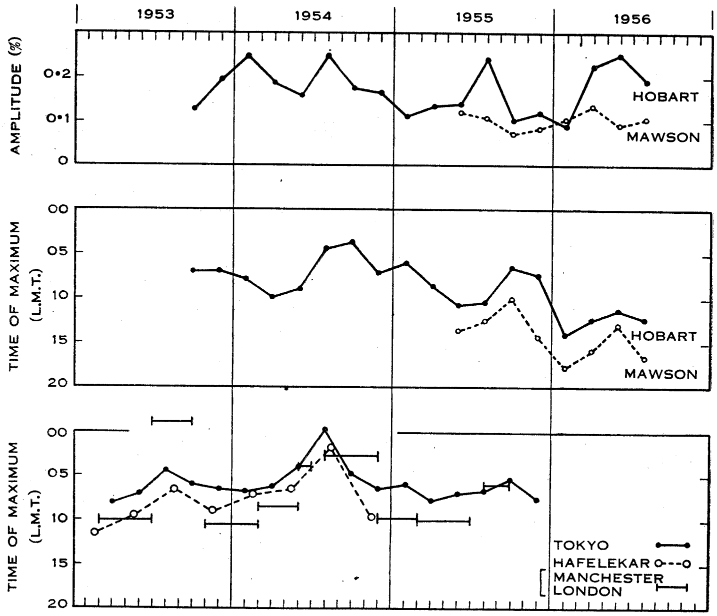

Fig. 1.—The 24-hr component of the daily variation of meson intensity, showing changes in mean amplitude and phase at Hobart and Mawson, and changes in phase observed at northern stations.

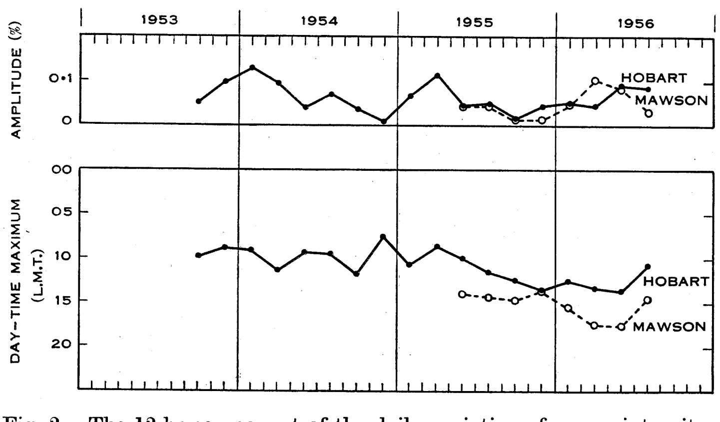

Fig. 2.—The 12-hr component of the daily variation of meson intensity, showing changes in amplitude and phase at Hobart and Mawson.

V. Discussion

(a) *Long-term Changes*

The main characteristic of the daily variation at both Hobart and Mawson is the occurrence of a single broad maximum. However, departures from a simple sinusoidal form are significant and, although the variations in most cases can be fairly closely approximated by the sum of 24- and 12-hr sine waves, distinct physical significance cannot necessarily be attached to these. Nevertheless, because of the predominantly diurnal character of the variation, the fitting of such curves does provide a convenient method of demonstrating long-term changes in phase and amplitude.

A further point relevant to the interpretation of daily variations averaged over many days is that these are not characteristic of all days within the period considered. Standard errors of the harmonic coefficients may be estimated from the total number of particles counted for each bihourly period, on the assumption that departures of single corrected bihourly readings from the mean fitted wave are due only to statistical fluctuations. By such a method, one finds in the present results that standard errors of the calculated bimonthly mean amplitudes vary between $0 \cdot 01$ and $0 \cdot 02$ per cent., depending on the available number of complete days' records in each period. However, an examination of the variation on individual days indicates a degree of variability far in excess of that expected from statistical fluctuations alone. Physical significance must therefore be attached to this variability, and the implication is that long-term changes apparent in the mean daily variation arise from the variable frequency of occurrence of different forms of individual daily variations. An examination of the day-to-day variability exhibited by the present records will be reported in a future paper.

Figure 1 shows that significant changes have occurred since 1953 in both the amplitude and time of maximum of the mean diurnal (24-hr) component. During the period for which the Hobart and Mawson records overlap, the changes in phase at the two stations are closely parallel although the amplitudes are not well correlated. Further, the results from the three northern hemisphere stations show phase changes of a broadly similar nature. There is thus further evidence for the world-wide nature of this phenomenon and for its origin in the primary radiation. Similar evidence has been presented by several investigators from records prior to 1954, e.g. Sarabhai, Desai, and Venkatesan (1954), who show that the changes occur at the equatorial station Huancayo and must therefore involve primary particles of energies greater than 10^{10} eV. We would expect the phase changes observed at different stations to be not highly correlated because of statistical uncertainties, breaks in record continuity, different instrumental arrangements, and the variability of unknown residual atmospheric effects in different localities and seasons. However, the degree of similarity which does exist in the phase changes suggests that the atmospheric components remaining after correction are not larger than the diurnal variation due to other causes.

The fitted semi-diurnal components (Fig. 2) are in general smaller than the diurnal components, but there is some evidence here also for significant long-term changes in both amplitude and phase, and for some degree of similarity in behaviour at the two stations.

(*b*) *Phase Difference in L.M.T. between Hobart and Mawson*

It is apparent from Figure 1 that a fairly consistent phase difference in local mean time, averaging some 3–4 hr, exists between the 24-hr components at Hobart and Mawson. A similar behaviour is evident in the 12-hr component. In both cases the time of maximum is later in the day at Mawson than at Hobart. It does not seem possible to attribute this to uncorrected atmospheric effects, and we discuss below possible sources of this phase difference.

Brunberg and Dattner (1954) have suggested that the daily variation arises from an anisotropy of primary particles within the energy range $2\text{–}4\times10^{10}$ eV entering the Earth's field, the direction of the anisotropy lying roughly in the plane of the ecliptic. However, examination of particle trajectories in the field (Brunberg and Dattner 1953) seems to indicate that the anisotropy must involve particles from a wide range of asymptotic latitudes with no strong concentration near the equatorial belt if the observed lack of any marked change in amplitude with latitude is to be explained.

We assume, then, that the daily variation results from such an anisotropy and that the Earth's field is of dipole form, described at the Earth's surface by the geomagnetic coordinate system in current use. Then the time of maximum intensity recorded at any station will be determined by the deflections suffered in this field by the incoming particles. We expect the maximum for a vertical telescope to be recorded when the initial approach direction of vertically incident particles makes its minimum angle with the direction of maximum primary intensity.

The initial direction of approach of a particle of given energy may be read from the curves of Brunberg and Dattner (1953). It is specified by two angles: Φ, the angle which the direction makes with the geomagnetic equatorial plane, and Ψ_E, a geomagnetic longitude angle measured eastwards from the geomagnetic meridian plane through the recording station. The difference in Ψ_E at two stations for particles of energy equal to the mean energy of those involved in the anisotropy has been assumed by several authors to give a measure of the expected phase difference in L.M.T. at the two stations. However, because the relationship between geomagnetic and geographic coordinates is not the same at different places on the Earth, this approximation is not good enough, particularly at high latitudes.

If the origin of the daily variation is as suggested, we may calculate the expected phase difference as follows. We assume first a mean energy of 2×10^{10} eV for the particles involved. Then at Hobart (H) and Mawson (M) for vertical incidence, we find

$$\Phi(H)=15\ ^\circ\text{S.} \qquad \Psi_E(H)=42^\circ$$
$$\Phi(M)=56\ ^\circ\text{S.} \qquad \Psi_E(M)=29^\circ$$

We now imagine the Hobart station to be transposed $\Psi_E(H)$ eastwards in geomagnetic longitude and to a new geomagnetic latitude of $\Phi(H)$. A vertical telescope at this new position H' (geomagnetic lat. 15 °S., geomagnetic long. 226 °E.) would, in the absence of a field, record particles from a direction exactly parallel with the initial direction of field-influenced particles which arrive vertically at Hobart. A maximum in the daily vertical intensity variation will thus be recorded at Hobart when the Earth's radius through H' makes its minimum angle with the direction of maximum primary intensity, i.e. when this latter direction lies in the geographic meridian plane through H'. Suppose the Mawson station is also appropriately transposed to a new position M' (geomagnetic lat. 56 °S., geomagnetic long. 133 °E.). The geographic coordinates of H' and M' are respectively (13 °S., 194 °E.) and (47 °S., 74 °E.). We see then that the actual difference in recorded times of maximum in universal time should be given by the geographic longitude difference between H' and M', in this case 120°. If we subtract from this the geographic longitude difference between Hobart and Mawson (84°) we obtain the expected phase difference in local mean time (36°=2 hr 24 min). The results of such calculations for several mean energies of the anisotropic primary particles are set out in Table 2. The geomagnetic-geographic coordinate transformations have been made according to McNish (1936). Also included in the table for comparison are the corresponding simple differences in Ψ_E between the two stations.

TABLE 2

EXPECTED PHASE DIFFERENCES BETWEEN DAILY VERTICAL INTENSITY VARIATIONS AT HOBART AND MAWSON

Mean Energy of Anisotropic Primaries (eV)	Expected Phase Lag at Mawson (L.M.T.)	Ψ_E (Hobart)—Ψ_E (Mawson)
$1\cdot5\times10^{10}$	2 hr 40 min (40°)	15°
$2\cdot0\times10^{10}$	2 hr 24 min (36°)	12°
$3\cdot0\times10^{10}$	1 hr 44 min (26°)	7°
$4\cdot0\times10^{10}$	1 hr 16 min (19°)	5°

It is clear from Table 2 that the error committed in assuming Ψ_E to represent a solar time displacement is quite large.

Brunberg and Dattner (1954) have concluded that the mean energy of the primary particles responsible for the daily variation is in the region $2\text{–}4\times10^{10}$ eV. The assumption that lower energies are involved meets with serious difficulties (cf. Elliot and Rothwell 1956). We see then from Table 2 that the observed phase difference in L.M.T. of 3–4 hr between Hobart and Mawson is only partly explained by the different locations of the stations.

The above discussion is based on the assumptions that the daily variation arises from an anisotropy outside the Earth's field region, and that the particles suffer deflection in a dipole field described by the surface coordinates in current use. The evident discrepancies suggest that either of these assumptions may be incorrect.

Considerable evidence has recently been obtained (e.g. Simpson *et al.* 1956) indicating that the magnetic field effective in determining trajectories of cosmic ray particles differs appreciably from the dipole field fitted to magnetic measurements made at the Earth's surface. Distortions of the field pattern are expected owing to the rotation of the inclined field with the Earth in the highly conducting interplanetary medium now known to exist, and to the orbital motion of the Earth through this medium. It seems then that use of the trajectory data of Brunberg and Dattner in conjunction with the previously accepted geomagnetic coordinates of observing stations, may give seriously misleading results. The errors may be sufficiently large to account for many reported discrepancies in daily variation results. It may not for instance be necessary to discount the existence of an external anisotropy as Elliot and Rothwell (1956) suggest.

If we assume the effective field to be of inclined dipole form, but rotated westwards through about 45° as suggested by the results of Simpson *et al.* (1956), we find that in the new geomagnetic coordinate system Hobart is about 9° further north and Mawson 5° further south. We may make a new calculation of the expected phase difference between the two stations in the same manner as before, but using Φ and Ψ_E values appropriate to the new geomagnetic latitudes. This calculation shows that the expected phase differences in L.M.T. listed in Table 2 are substantially increased. For particles of energy $1 \cdot 5 \times 10^{10}$ eV, the lag at Mawson becomes roughly 3 hr 40 min instead of 2 hr 40 min, and for particles of energy $2 \cdot 0 \times 10^{10}$ eV it becomes 2 hr 48 min instead of 2 hr 24 min. At higher energies the expected lag is less, as before. We see then that, if relatively low energies are involved, the observed phase difference of 3–4 hr is not inconsistent with the interaction of an external anisotropy with an effective dipole field of the modified orientation.

On the other hand, if as suggested by Elliot and Rothwell (1956) we are to envisage an origin of the daily variations purely in some modulation mechanism within the field region, it is possible that times of maximum should be related basically to the local geomagnetic time scale and not to solar time. If the time of maximum were to depend on local geomagnetic time, this alone could account for a phase lag in L.M.T. at Mawson of approximately $2\frac{1}{2}$ hr. If such a dependence could be substantiated by examining comparable results from many different stations, it would be difficult to avoid the conclusion that the daily variations do indeed have their origin within the region occupied by the Earth's field.

Whichever interpretation is correct, it seems reasonable to expect that the observed long- and short-term changes in the daily variation may be caused by density fluctuations of the interplanetary medium presumed responsible for field distortion and that the changes would thus be related indirectly to solar activity.

VI. Acknowledgments

Acknowledgment is due to Dr. A. G. Fenton and members of the cosmic ray research group within the University of Tasmania for valuable discussions during the preparation of this paper, and to Professor A. L. McAulay for valuable criticism of the draft. The assistance of Mrs. P. James with some of the computational work has been greatly appreciated.

The author also expresses thanks to his colleagues of the 1955–56 Australian National Antarctic Research Expedition party at Mawson whose cooperation in many ways assisted in the successful prosecution of the cosmic ray programme at the station.

VII. References

BRUNBERG, E. A., and DATTNER, A. (1953).—*Tellus* **5**: 135, 269.
BRUNBERG, E. A., and DATTNER, A. (1954).—*Tellus* **6**: 73.
ELLIOT, H., and ROTHWELL, P. (1956).—*Phil. Mag.* (8) **1**: 669.
FENTON, K. B. (1952).—Ph.D. Thesis, University of Tasmania.
McNISH, A. G. (1936).—*Terr. Magn. Atmos. Elect.* **41**: 37.
MAEDA, K. (1955–56).—Monthly Reports of Cosmic Ray Data, Nos. 46–57. Scientific Research Institute (Japan).
MIYAZAKI, Y. (1955).—*J. Sci. Res. Inst., Tokyo* **49**: 267.
OLBERT, S. (1953).—*Phys. Rev.* **92**: 454.
PARSONS, N. R. (1957).—Aust. Nat. Antarctic Res. Expedition Interim Rep. No. 17.
POSSENER, M., and VAN HEERDEN, I. J. (1956).—*Phil. Mag.* (8) **1**: 253.
SARABHAI, V., DESAI, U. D., and VENKATESAN, D. (1954).—*Phys. Rev.* **96**: 469.
SIMPSON, J. A., FENTON, K. B., KATZMAN, J., and ROSE, D. C. (1956).—*Phys. Rev.* **102**: 1648.
STEINMAURER, R., and GHERI, H. (1955).—*Naturwissenschaften* **42**: 294.
TREFALL, H. (1955*a*).—*Proc. Phys. Soc. Lond.* A **68**: 625.
TREFALL, H. (1955*b*).—*Proc. Phys. Soc. Lond.* A **68**: 893.
TREFALL, H. (1955*c*).—*Proc. Phys. Soc. Lond.* A **68**: 953.

Appendix I

Barometric Correction Procedure

Some comment is required on the procedure referred to in Section III for barometric correction of the observed mean daily meson intensity variations. Accurate barometric pressure records are readily obtained but, unfortunately, at all recording stations insufficient knowledge of daily atmospheric temperature fluctuations is available to allow adequate correction for their effects. The practice of many investigators has been to " correct " for mean daily pressure variations by using a total barometer coefficient obtained by simple two-variable linear regression analysis of a set of daily mean intensity and pressure figures. Often such a coefficient obtained from a long series of data is adopted as a standard throughout, but sometimes different coefficients have been derived from, and applied to, separate time groups of data. It is well known that total barometer coefficients derived in this manner at different stations, or at the same station from different time groups of data, vary over a relatively wide range. A large part of this variability arises from the variable extent to which day-to-day barometric and temperature changes are correlated. Attempts are sometimes made to estimate the possible magnitude of temperature contributions to the residual " corrected " daily variations, but this is rendered more uncertain since an unknown and variable partial correction for temperature effects is already included in the barometric correction.

Discussions of the complex atmospheric effects on cosmic ray meson intensity have been given recently by Olbert (1953), Trefall (1955*a*, 1955*b*, 1955*c*), and others. In particular Trefall (1955*c*) has derived the theoretical total barometer coefficient for the vertical meson component as a function of recorder cut-off momentum under conditions of constant atmospheric temperature distribution. He has pointed out that total barometer coefficients calculated from experimental data over long periods approximate fairly closely to the theoretical values, indicating that the average correlation between day-to-day barometric and temperature changes over a long period is slight.

It is suggested here that Trefall's work provides a basis for more uniform and satisfactory correction procedures, at least in daily variation studies, and that the value of the theoretical total barometer coefficient appropriate to the particular recorder in use be taken from curve *C* of Figure 1 in Trefall's paper (1955*c*). Such a procedure corrects for the total effects which would be produced by the known barometric changes only if the atmospheric temperature distribution remained constant. Nevertheless, it seems preferable to leave the effects of temperature changes present in full rather than include a poor, partial, unknown, and variable degree of correction by adopting experimentally determined total barometer coefficients.

The cut-off momentum of the present recorders is $2 \cdot 3$ mμc, and the corresponding theoretical coefficient for vertically incident radiation at sea-level is $-2 \cdot 31$ per cent. per cm Hg. Because of the finite opening angle of the telescopes, the inclusion of inclined radiation could render this coefficient inapplicable if the theoretical coefficient varied significantly with inclination to the vertical. Fenton (1952) has reviewed the available experimentally determined total barometer coefficients for vertical and inclined telescopes and finds no convincing evidence for a significant dependence on inclination. Concurrent with the present vertical telescope measurements, continuous records were also obtained at Mawson with a telescope of identical design inclined 45° to the vertical and rotating automatically to give successive hourly count totals in geographic north, east, south, and west headings. Calculations based on 6 months' daily means at Mawson yield a total barometer coefficient of $-2 \cdot 31 \pm 0 \cdot 18$ per cent. per cm Hg for the vertical telescope and $-2 \cdot 18 \pm 0 \cdot 18$, $-2 \cdot 19 \pm 0 \cdot 18$, $-2 \cdot 22 \pm 0 \cdot 19$, and $-2 \cdot 27 \pm 0 \cdot 19$ per cent. per cm Hg for the inclined telescope at the various headings respectively. (The errors given are 95 per cent. fiducial limits.) The inclined values do not differ significantly from one another or from the vertical value, and none of the values differs significantly from Trefall's theoretical value of $-2 \cdot 31$ per cent. per cm Hg for vertically incident radiation. It thus seems that no serious error would be committed by considering this value as applicable to the present vertical telescopes.

Correction has therefore been made using this value throughout, and each observed bimonthly mean daily variation has been corrected to the mean pressure for the bimonthly period.