Phase Changes in the Daily Variation of the Cosmic Ray Nucleonic Component

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Abstract

Results of the analysis of solar daily variations in the cosmic ray nucleonic component at nine stations during the International Geophysical Year are presented.

Examination of month to month phase behaviour leads to the conclusion that there is an important component variation synchronized in Universal Time at all stations, and its origin is discussed. Its effects on inferences about the primary anisotropy responsible for the main part of the daily variation and on various characteristics of the observed variation are also discussed.

1. Introduction.

It is well known that the average time of maximum of the solar daily variation in cosmic ray intensity, measured by recorders at ground level, undergoes long term changes. The results of THAMBYAHPILLAI and ELLIOT (1953), SARABHAI et al. (1954), VENKATESAN and DATTNER (1959), and others, have shown that these long term (e.g. year to year) changes are associated with the cycles of solar and geomagnetic activity, although these associations are not entirely consistent and do not give a clear indication of the mechanisms producing and directly controlling the daily variation.

Its local time dependence, together with other features, suggest strongly that the major part of the daily variation arises from an anisotropic distribution of the primary radiation entering the geomagnetic field region. This interpretation is now fairly generally accepted, as is also an explanation of the long term phase shifts in terms of changes in the mean direction of the primary anisotropy.

A recent discussion of probable and possible causes of such an anisotropy has been given by DATTNER and VENKATESAN (1959) and it seems clear that several separate effects may contribute, subject to more or less independent modulation by changing conditions in interplanetary regions. We shall not be concerned here directly with this problem but rather with an examination of the degree of agreement between different recording stations on the direction of the effective anisotropy and on changes in this direction inferred from observed phase changes in the daily intensity variation.

Several authors have examined records of the meson component and shown that there is a high degree of correlation between the phase trends in yearly mean diurnal variations at different stations (cf. VENKATESAN and DATTNER, 1959). With reasonable assumptions about the energy dependence of the anisotropy, sufficiently accurate allowance can be made for deflections of primaries in the geomagnetic field, to produce fair agreement on the mean direction of the anisotropy in different years (cf. DORMAN, 1957). However, the agreement between stations concerning shorter term (e.g. month to month) phase changes is not as satisfactory. In many cases the apparent inconsistencies are considerably greater than could be expected from the relatively larger statistical errors inherent in the shorter term measurements. A similar situation exists for the amplitude of the observed daily variation.

In the case of the meson component to which most of the published results refer it is tempting to attribute much of the inconsistency to important residual atmospheric contributions. Adequate correction for the influence of changing temperature-height distributions in the atmosphere cannot be made at present because of our very limited knowledge of these changes throughout each day. In periods as short as one month these unknown residual effects could add an important component to the daily variation. Such a component is certain to differ considerably between stations in any one month and to change from month to month, thus seriously affecting phase and amplitude correlations.

Such influences however may not account fully for the inconsistencies. By examining records of the nucleon instead of the meson component these difficulties can be almost completely overcome since in this case the only significant atmospheric effect is due to total pressure changes for which correction can be accurately made. There is a further advantage in that the amplitude is in general larger than for the meson component and the accuracy of phase determinations is correspondingly greater. As will be evident from results for the nucleonic component presented in a later section, month to month phase changes at different stations remain rather poorly correlated, indicating that disturbing effects of non-atmospheric origin must also play a significant role.

It is customary to resolve the observed daily variation into its harmonic components. The first two (diurnal and semidiurnal) usually suffice to give a reasonably close fit to the observed variation although it cannot be inferred that these have independent physical significance. For an anisotropy of any particular form the actual course of the variation will depend on the directional acceptance pattern projected outside the geomagnetic field for each recorder, and several harmonic components will in general be required to describe this course accurately. The relative magnitude of the harmonics will also differ from station to station. However, in the great majority of cases the diurnal component is found to be the largest and must reflect the existence of a single main "core" of the anisotropy. Its time of maximum will then in general give a good indication of the direction in asymptotic longitude of this "core". It has often been demonstrated (e.g. VENKATESAN and DATTNER, 1959) that the diurnal component does in fact exhibit much more consistent behaviour than the smaller semidiurnal component and we shall confine our attention mainly to it.

In what follows we shall present results of analysis of the daily variation in nucleonic component intensity at nine stations covering the period of the International Geophysical Year (July 1957—December 1958). A procedure will be described by which a significant general improvement can be made to the phase agreement between stations on a month to month basis. The hypothesis is made that the observed daily variation contains a diurnal component arising from synchronized Universal Time variations effecting all stations. In separate monthly periods such a U.T. component is determined (by relatively crude methods) which on subtraction from all stations yields the best possible improvement in phase agreement. The relative success of this procedure suggests that the U.T. component is genuine, and its effects on inferences from the observed daily variation will be briefly discussed.

2. Analysis of nucleonic component records

Choice of stations and selection of data

For any comparison of the mean daily variation at different stations, particularly when averages over periods as short as one month are considered, it is very desirable that exactly the same days should be used for all stations. Considerable changes in the form of the variation occur from day to day and inclusion of some days for which data are not available for all stations can only detract from the value of the comparison. On the other hand if a comparison is attempted between too many stations, one finds relatively few days with complete records available from all stations. Thus in the present case the analysis is limited

Table 1. Stations used in the analyses.

Station	Geographic		Geomagnetic		Alt. (m)	Date used for months
	Lat.	Long.	Lat.	Long.		
Hobart	—42° 55′	147° 14′ E	—51.5°	225°	725	7/57—12/58
Uppsala	+59° 51′	17° 55′ E	+58.6°	106°	S.L.	7/57—12/58
Leeds	+53° 49′	1° 33′ W	+56.3°	83°	100	7/57—12/58
Mawson	—67° 36′	62° 53′ E	—73.1°	104°	S.L.	7/57—12/58
Murchison Bay	+80° 03′	18° 15′ E	+72.2°	137°	S.L.	9/57—12/58
Ottawa	+45° 24′	75° 54′ W	+56.8°	351°	100	7/57—12/58
Sulphur Mt.	+51° 12′	115° 36′ W	+58.2°	300°	2283	7/57—12/58
Berkeley	+37° 52′	122° 18′ W	+44.1°	298°	S.L.	7/57— 9/58
Resolute	+74° 41′	94° 54′ W	+82.9°	289°	S.L.	7/57—12/58

to nine stations for which I.G.Y. records are relatively free of breaks in continuity and for which the counting rates of the neutron monitors ensure reasonably small statistical errors. Table I lists the stations selected, together with their geographic and geomagnetic coordinates.

By regarding as permissible the interpolation of no more than two missing bihourly figures to complete at any station an otherwise acceptable day, the total number of days of simultaneously available records found in the eighteen separate months ranges from 18 to 31, yielding satisfactory statistical accuracy. Interpolations have been made where necessary by fitting values to the general trend shown by adjacent bihourly figures.

Harmonic analyses carried out

The analyses for each station have been carried out using the facilities of the BESK electronic computer in Stockholm. The basic data fed to the computer for each analysis consisted of thirteen consecutive bihourly count totals. The thirteenth value was obtained by considering each day to extend from 00 hrs to 24 + 2 hours. The computer automatically corrected for the difference in the 1st and 13th values on the assumption that it represents a linear secular intensity change over the mean day. The programme was arranged to yield the amplitude in per cent and the times of maximum of both the diurnal and semidiurnal components, the usual procedure of least squares fitting being followed. All analyses were based on days commencing at 00 hrs Greenwich Mean Time, and used pressure-corrected data.

Two main sets of analyses were made; the first used data from all available days of simultaneous records and will be referred to as the "all selected days" analysis, while the second used data from only those selected days remaining after exclusion of "disturbed" days and will be called the "quiet selected days" analysis. The classification of days as disturbed has been based on visual inspection of plotted records and not on any strict criterion. In general the disturbed days are those including the onset and decreasing phase of Forbush-type decreases and perhaps one or two following days, together with any other days on which marked anomalous primary intensity changes occurred.

The grand totals for each station over the whole period have also been analysed both for "all selected days" and "quiet selected days" as have also the totals for the 46 days classified as disturbed.

Figures 1 and 2 present the results for the diurnal component plotted in the conventional manner on vector summation dials for the "all selected days" and "quiet selected days" cases respectively. For each station the whole vector summation plot has been rotated clockwise through an angle which brings all plots approximately parallel and in the general direction of 12 hrs G.M.T. on the dial. This facilitates comparison of phase changes at the different stations. These angles of rotation are as follows.

Hobart	99°	Murchison Bay	335°
Resolute	175°	Mawson	338°
Berkeley	182°	Leeds	344°
Sulphur Mt.	188°	Uppsala	346°
Ottawa	241°		

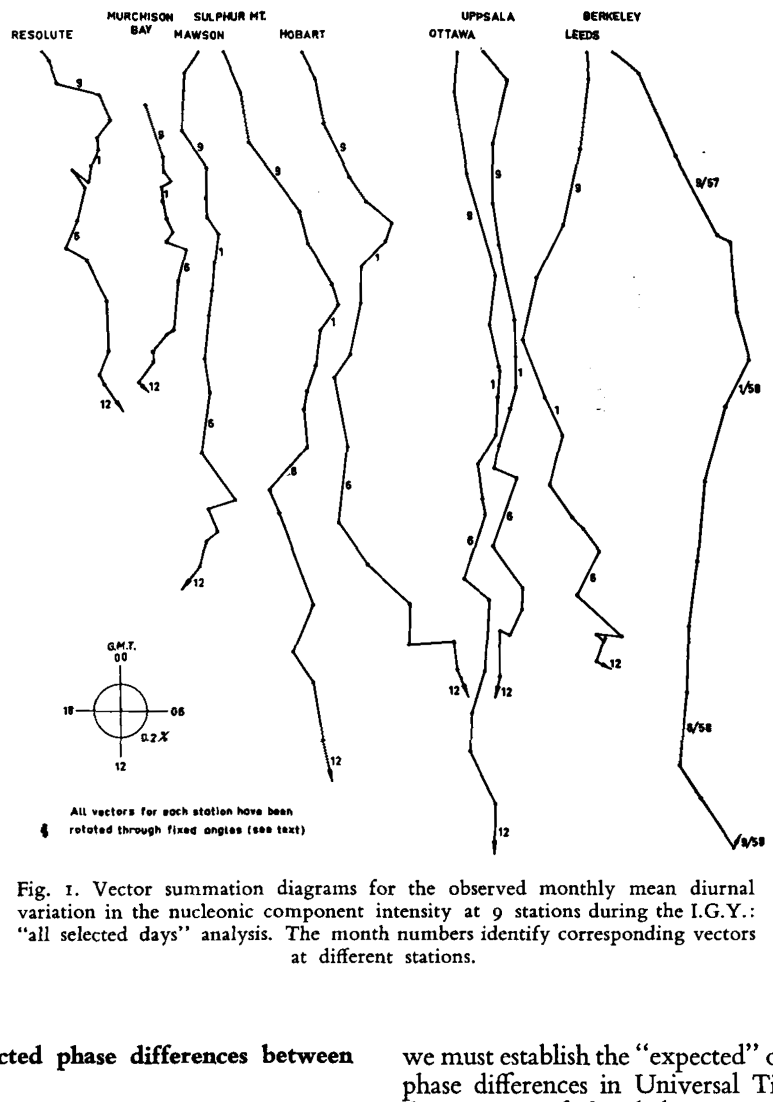

Fig. 1. Vector summation diagrams for the observed monthly mean diurnal variation in the nucleonic component intensity at 9 stations during the I.G.Y.: "all selected days" analysis. The month numbers identify corresponding vectors at different stations.

3. The expected phase differences between stations.

It is evident in both Figures 1 and 2 that the month to month phase changes at the various stations are not well correlated. The changes are less irregular in Figure 2 than in Figure 1 indicating that the exclusion of disturbed days improves the general agreement, even though purely statistical errors are made relatively larger, but the detailed changes are still not very well correlated. However it is clear that over the whole 18 month period no really pronounced semipermanent changes in direction of the primary anisotropy occurred.

In order to judge the measure of phase agreement between stations in any one month we must establish the "expected" or "standard" phase differences in Universal Time between the stations. If the daily variation were due entirely to an anisotropy in the primary radiation entering the geomagnetic field, then apart from the uncertainty introduced by statistical errors, we would expect to observe quite specific fixed intervals between the intensity maxima at different stations. In principle we could calculate these intervals from a knowledge of the energy dependence and spatial form of the anisotropy, the trajectories of primaries traversing the earth's field, the complete directional sensitivity pattern at the top of the atmosphere for each recorder, and the geographic coordinates of the recording

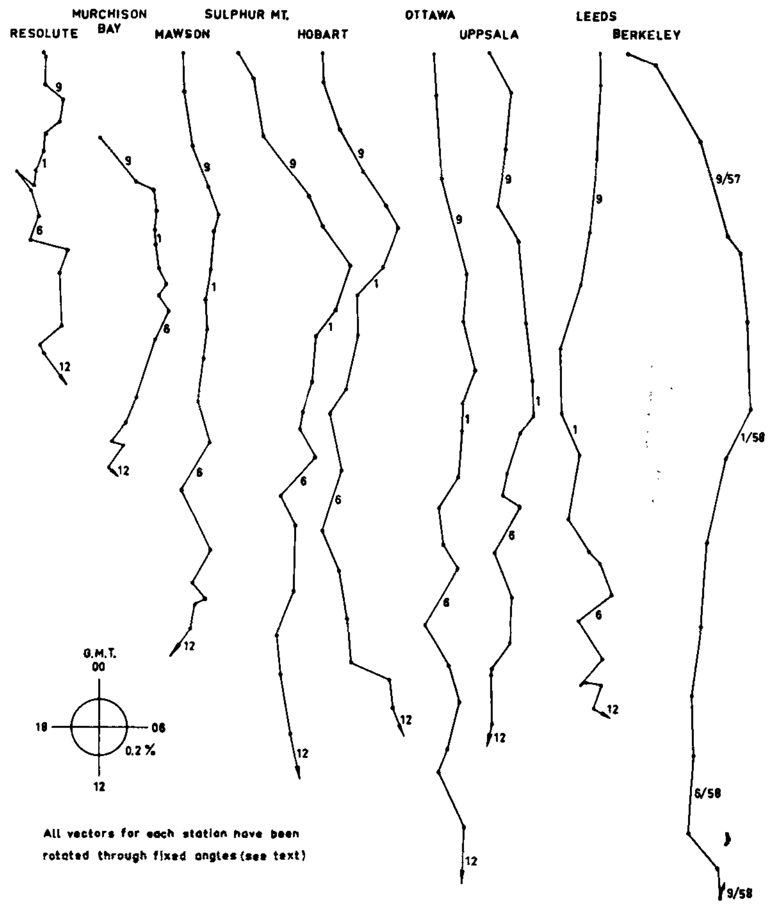

Fig. 2. Vector summation diagrams for the observed monthly mean diurnal variation: "quiet selected days" analysis.

stations. However as we can only infer the properties of the anisotropy from our ground level observations, it seems more satisfactory and practical to assume for our present purpose that the "expected" U.T. intervals are those exhibited by the mean daily variations over a relatively long period.

Table 2 A sets out the phase angles of the long term (12 and 18 month) mean diurnal variations determined by different methods (see description with the Table). The phase angles quoted are values of f_1 appearing in the expression $R_1 \sin (\Theta + f_1)$ for the diurnal component, with the time zero, $\Theta = 0$, at 00 hrs G.M.T. Table 2 B lists the corresponding differences in phase angle between stations arranged approximately in the order in which the maxima occur ($15° = 1$ hour). These differences are quite similar for the various cases. However in order to minimize any effects of possible annual or seasonal variation in amplitude and the effects of inclusion of disturbed days, we have chosen to determine the "standard" phase differences from the two overlapping 12-month quiet day periods (columns g and h) for which we have strictly comparable records for all 9 stations. The phase determinations in these cases have been made directly from the vector plots of Figure 2, as the phase angle of the resultant, or mean, of the appropriate 12 vectors. An average is chosen from the two 12-month periods and the accepted standard phase differences are given in the final column of Table 2 B.

Table 2.

2 A Phase angles of long term mean diurnal variations in the nucleonic component.
(Phase angle f_1^0, in the expression $R_1 \sin(\theta + f_1)$ for the diurnal component with $\theta = 0$ at 00 G.M.T.

2 B Differences in phase angle. These are reckoned positive clockwise on a U.T. dial.

a) From analysis of grand totals for 18 months, all selected days
b) » » » » » » 18 », quiet selected days
c) From mean of 18 monthly vectors, all selected days
d) » » » 18 » », , quiet selected days
e) » » » 12 » », 9/57—8/58, all selected days
f) » » » 12 » » » 10/57—9/58, » » »
g) » » » 12 » » » 9/57—8/58, quiet selected days
h) » » » 12 » » » 10/57—9/58, » » »
i) The adopted standard phase differences (approximate means from columns g and h)

2 A	a	b	c	d	e	f	g	h	i
Hobart	22	15	23	16	19	16	10	8	
Uppsala	256	256	257	256	259	258	257	255	
Leeds	255	256	256	255	255	259	253	254	
Mawson	245	245	247	247	252	249	248	248	
Murchison Bay					251	243	250	240	
Ottawa	154	153	154	153	153	149	153	149	
Sulphur Mt.	104	101	106	103	106	97	102	94	
Berkeley					97	95	93	91	
Resolute	96	86	99	89	98	87	88	83	
2 B									
H →U	126	119	126	120	120	118	113	113	113
U →L	1	0	1	1	4	—1	4	1	2
L →M	10	11	9	8	3	10	5	6	6
M →MB	} 91	} 92	} 93	} 94	1	6	—2	8	3
MB→O					98	94	97	91	94
O →SM	50	52	48	50	47	52	51	55	53
SM→B	} 8	} 15	} 7	} 14	9	2	9	3	6
B →R					—1	8	5	8	7
R →H	74	71	76	73	79	71	78	75	76

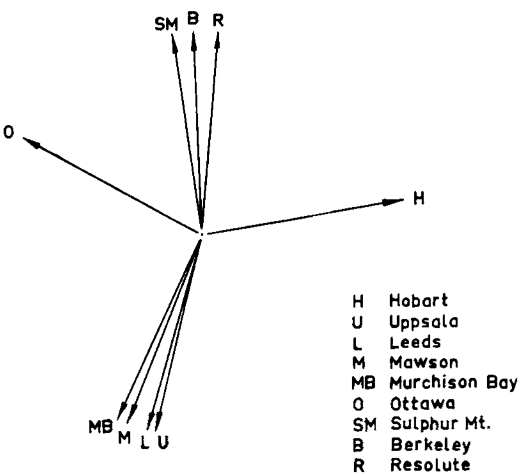

Fig. 3. 24-hour dial showing the adopted "standard" or expected phase relationships between the diurnal variations at different stations in Universal Time. The phase differences in angular measure are given in the final column of Table 2.

Figure 3 shows the standard phase intervals on a 24-hour U.T. dial. We are at present interested only in the phase differences, i.e. the relative and not the absolute positions of the vectors, and thus the time scale is arbitrary.

4. Determination of a U.T. component of the diurnal variation.

Having established expected phase differences in U.T. between the stations, we can proceed as mentioned in Section 1 to see whether for each month separately, we can improve the agreement between the observed and expected phase intervals.

We commence with the hypothesis that the monthly mean diurnal variation contains a component arising from synchronized variations in U.T. affecting all stations. The maximum of this component would thus occur at the same U.T. at all stations. We make the simplifying assumption that it has the same amplitude for all stations considered. This seems justified in view of the fact that such transient and approximately simultaneous world-wide primary intensity changes as Forbush-type decreases produce almost the same percentage changes at all stations above the knee of the latitude curve. The possibility of making this simple assumption has led to our choice only of relatively high latitude stations for the investigation.

We shall examine the results of the "all selected days" analysis. For a particular month the nine station diurnal vectors are drawn on a single U.T. dial on transparent paper. This is then placed over the standard dial of Figure 3 so that the origin points coincide. In most months quite marked differences from the standard phase intervals are evident and the fit is poor no matter into what relative positions the two dials are rotated. However by such relative rotation about the origin point it is possible in general to find a position where subtraction of a single fixed vector of suitable amplitude from each of the experimental ones will alter their phase angles in a manner resulting in considerably improved agreement with the standard intervals. Although the method is rather crude, the appropriate vector and orientation of the dial giving best improvement are not difficult to find, and more elaborate fitting methods are not warranted. We call the vector found the U.T. vector for the month considered. (It applies of course only to the mean diurnal variation for the limited number of days used in this analysis and cannot be considered applicable for any other selection of days from the month.) It should be pointed out that if we

Table 3. The monthly mean U.T. diurnal components determined for the "all selected days" analysis, $R_1 \sin(\theta + f_1)$ with $\theta = 0$ at 00 G.M.T.

Month	R_1 %	f_1^0	Month	R_1 %	f_1^0
7/57	.100	120	4/58	.050	300
8	.100	180	5	.120	0
9	.200	180	6	0	—
10	.100	140	7	.080	325
11	.050	90	8	.250	125
12	0	—	9	.100	65
1/58	.150	305	10	.200	125
2	.025	150	11	.080	195
3	.100	75	12	.100	100

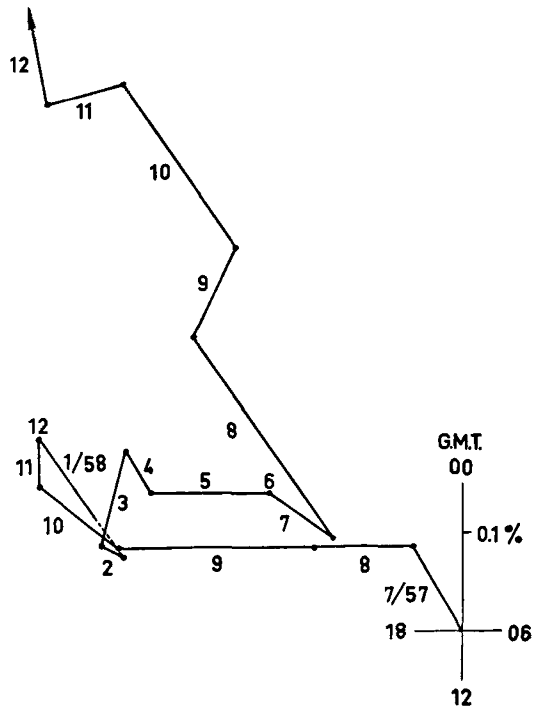

Fig. 4. Summation diagram for the monthly U.T. vectors the subtraction of which produces the most improved inter-station phase agreement.

were considering only two or three stations it would be possible to determine a unique vector which would produce exact agreement. For more than three stations we can find a vector which on subtraction gives only the most improved general agreement.

Details of the U.T. vectors found are given in Table 3 and the vectors are plotted on a summation dial in Figure 4. Although the accuracy of the method used is not great, it is clear that in many cases the amplitude of the U.T. vector is relatively large and its subtraction can therefore make very appreciable changes to both the relative amplitudes and phases of the original vectors. An example illustrating these effects for the month August 1958 is shown in Fig. 5. Figure 5 A shows the original vectors together with the U.T. vector to be subtracted. This is a case in which the original phase intervals are greatly different from those of the standard dial in Fig. 3. Fig. 5 B shows the resultant vectors, and the direction marked H_s is that for the Hobart vector on the standard dial. It indicates

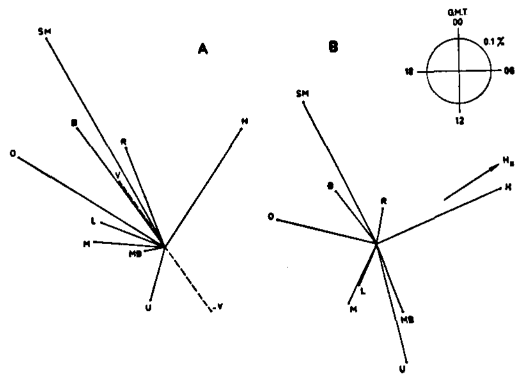

Fig. 5. Harmonic dials for August 1958, illustrating the possible large effects of subtraction of a U.T. component common to all stations. The station vectors are identified as in Fig. 3. 5 A: original vectors. 5 B: after subtraction of the vector *V*. The direction marked *Hs* (=Hobart standard) indicates the orientation of the standard dial of Fig. 3, giving best phase fit to the resultant vectors.

the orientation of the standard dial which gives best fit to the corrected vectors. The fit in this case is still far from perfect but a considerable improvement has certainly been made.

Fig. 6 shows the summation dials for the "all selected days" analysis after correction for the effects of the U.T. vectors, and is to be compared with Fig. 1. It is clear that the month to month phase changes are now much more consistent at the various stations as one would expect if the vectors now describe much more accurately the diurnal component arising from a primary anisotropy alone.

The degree of consistency in Fig. 6 is even more satisfactory than that in Fig. 2 (for the "quiet selected days"). By following a similar procedure month by month for the quiet day

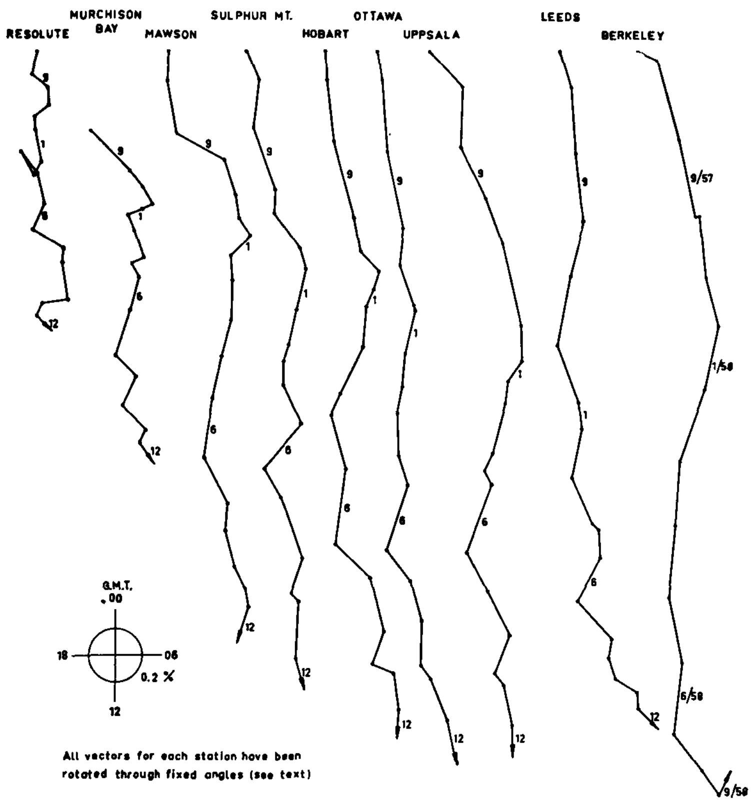

Fig. 6. Vector summation diagrams for the monthly mean diurnal variation: for the "all selected days" analysis, after subtraction of monthly Universal Time components common to all stations. (Note that in July 1957 the Resolute vector has almost zero amplitude.)

case, U.T. vectors of appreciable amplitude, often similar to those for the "all selected days" case can still be found but the statistical accuracy is somewhat less. Thus the U.T. component is not a feature of the disturbed days only.

5. Changes in direction of the primary anisotropy.

If the U.T. component found is a genuine effect which shifts the phase of the diurnal variation arising from a primary anisotropy alone, then the positions of the corrected vectors on the U.T. dial and not those of the original vectors will be directly related to the direction of the primary anisotropy. Further, the month to month changes in the optimum orientation of the standard vector dial with respect to U.T. will determine the changes in direction of anisotropy with which the 9 stations best agree. That is, we obtain an average determination based on records from 9 stations.

We may take for example changes in the phase angle of the standard Hobart vector as our best estimate of changes in the direction of anisotropy. The month by month phase behaviour of this vector is shown in Fig. 7, which has been drawn as a summation dial with all vectors given an arbitrary fixed amplitude. Except for a constant additive angle the plot of Fig. 7 shows directly the changes in the effective direction of anisotropy. Clockwise changes in vector direction indicate that the direction of maximum intensity has shifted further from the earth-sun line in the sense of the earth's rotation.

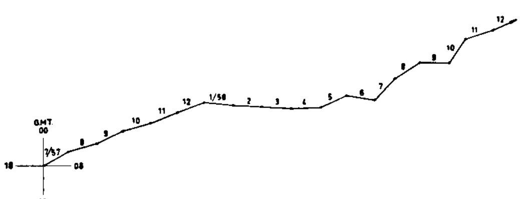

Fig. 7. Showing the month by month changes in direction of the primary anisotropy, deduced as described in Section 5. The actual direction of the anisotropy in space relative to the earth-sun line would be obtained by adding a constant angle to the phase angle of each vector. A clockwise change in vector direction corresponds to a shift in the direction of anisotropy in the sense of the earth's rotation.

We conclude from this Figure that the direction of maximum intensity remained virtually constant from July to December 1957, then changed by about 25° for the next few months before becoming rather variable until the end of 1958, although the mean direction for the latter half of 1958 was approximately the same as that for the similar period in 1957. Attention should be drawn here to Figure 4 which shows that marked changes in the phase trend of the U.T. vectors also occurred at about the same times as changes in the direction of anisotropy (Fig. 7). It is also interesting to notice that December 1957 coincided approximately with the lowest primary intensity reached during the present solar cycle. The existence of some degree of quasi-persistent behaviour in the U.T. vectors as shown in Figure 4 and the possible associations with the direction of anisotropy and the mean level of primary intensity may be significant, but the present evidence does not justify further speculation here.

Although we have not been concerned with the absolute direction of the primary anisotropy nor with the actual mean deflections in geographic longitude suffered by the primaries affecting each station, it is nevertheless of interest to determine the relative deflection angles. For instance if we represent the deflection angle measured eastwards for Hobart by Ψ, then from our standard phase intervals and the geographic longitude of the stations, we deduce that the effective mean deflection angles are as follows.

Resolute	$\Psi - 42°$
Mawson	$\Psi - 37°$
Sulphur Mt	$\Psi - 8°$
Berkeley	$\Psi - 8°$
Hobart	Ψ
Ottawa	$\Psi + 5°$
Murchison Bay	$\Psi + 5°$
Uppsala	$\Psi + 16°$
Leeds	$\Psi + 34°$

These estimates are of course based on the observed mean time of maximum of only the diurnal component and will remain valid only if the energy dependence of the primary anisotropy remains substantially constant. It will be interesting to compare these relative values with theoretical predictions when these become available.

6. Origin of the U.T. component.

The apparent existence of a diurnal variation synchronized in U.T. at all stations does not necessarily imply that the primary radiation undergoes world-wide pulsations with a true solar-day periodicity. There are few ways in which world-wide modulation of primary intensity could conceivably be controlled directly by the earth's rotation—one could perhaps envisage that the rotation of the eccentric geomagnetic dipole field in a nonuniform medium might produce small periodic changes in a geocentric electric field. However it is unlikely that any such effects would be consistent with the large phase changes shown by the diurnal U.T. variations found (Table 3).

It must be remembered that in determining the expected phase intervals due to a primary anisotropy alone, we made the implicit assumption that any disturbing effects would approximately cancel in an annual mean for quiet days. If there were any tendency over a long period for a U.T. component to exhibit a preferred phase, this assumption would be unjustified. It would therefore be valuable to have theoretical estimates of the phase intervals to compare with the experimental values used here. Mc Cracken (private communication) has made estimates for some stations which do in fact agree fairly well with the intervals used here. For instance he has predicted (Mc Cracken, 1959) that although Mawson is 45° (3 hours) east of Uppsala, the latter should record a maximum in the diurnal variation of the nucleonic component some 20 minutes (5°) earlier in U.T. than Mawson. This compares favourably with the lead of 8° used in the present investigation.

Thus it seems likely that the U.T. component exhibits no long term persistent features, and in a monthly period may arise from irregular primary intensity changes unrelated to the earth's rotation. We shall briefly examine some possibilities.

The pressure corrected bihourly intensity $I(t)$ measured by a neutron monitor during a day may be represented as the sum of several time-variable functions, e.g.,

$$I(t) = \bar{I} + a(t) + b(t) + c(t) + d(t)$$

$a(t)$ is a function containing all harmonics describing the daily variation arising purely from a primary anisotropy. It is essentially a local time phenomenon.

$b(t)$ is a function describing purely statistical fluctuations, independent at different stations.

$c(t)$ describes the contribution made by relatively long term secular changes (e.g. the 27 day and month to month changes in mean intensity level).

$d(t)$ describes non-random but irregular short term variations of a quasi-persistent character, leading to serial correlation of consecutive bihourly intensity values. These may be due to rather localized effects or to synchronized world-wide variations (e.g. small Forbush decreases and solar flare effects would be of this type).

Only the functions $c(t)$ and $d(t)$ need be considered as possible sources of an apparent U.T. diurnal variation in a monthly average. The function $c(t)$ could produce such a component as a result of the general mean curvature of changes of intensity level occurring in a 27-day type of variation. This type of "curvature effect" has been discussed by Chapman and Bartels (1951). Depending on its sense on the majority of days in the period considered, the general curvature will introduce a component to the mean daily variation with either maximum or minimum at the centre of the daily period chosen. Moreover the phase of this component will be independent of the choice of starting point for the daily intervals. Since the 27-day variations are world-wide this effect would produce a diurnal variation synchronized in U.T. at all stations. The magnitude of this curvature effect may be determined simply in any particular case. Inspection of a plot of daily mean intensity values shows that the month in our analysis likely to contain the greatest curvature effect is August 1957, although it is far from an ideal case. In this month actual calculation of the amplitude of the diurnal component introduced by the curvature effect shows it to be less than 0.005 per cent.

Since the curvature effect is negligible, we are left then with only the function $d(t)$ as a possible source of our U.T. component. That approximately synchronized world-wide intensity variations of this type occur at least on some days is certain. Forbush decreases are obvious examples, but other less prominent cases may be readily seen when data plots for many stations are compared. Quite small variations of a world-wide character are difficult to recognize since they would be partly masked by the local time dependent and purely random fluctuations present simultaneously. Nevertheless it seems reasonable to assume that a high proportion of days will be affected to some extent in this way. This assumption is strongly supported by the fact that significant and highly correlated changes occur at different stations in daily mean intensity values. In order to estimate the possible amplitude of the U.T. diurnal component arising from this type of intensity fluctuation we may consider an artificial model which nevertheless simulates quite well the typical pattern of quasi-persistent variations actually observed.

Suppose we have a long time series consisting of equally spaced independent values of a random normal variable whose standard deviation is σ, and that we then form from it a new series consisting of the running sums of 4 consecutive values. The new series will have standard deviation 2σ but will possess the property of quasi-persistence, with each value being independent only of those four or more on either side of it. If σ is suitably chosen, trials show that such a series does in fact resemble quite strikingly the type of irregular fluctuations actually observed in bihourly cosmic ray intensity figures, although in the cosmic ray case the range of the fluctuations may change considerably from day to day.

If we take independent samples of 12 consecutive values from the original random series and fit a first harmonic to each sample, it can be shown that its root mean square amplitude will be $0.577\,\sigma$ (Ch. 16, CHAPMAN and BARTELS, 1951). If we now repeat this procedure using similar samples from the derived quasi-persistent series the root mean square amplitude will be $1.752\,\sigma$. Suppose now that we examine the effect in the mean over N samples (corresponding to N days in the cosmic ray case). In the case of the original random series the root mean square amplitude in repeated selection of N samples will then be $0.577\,\sigma/\sqrt{N}$. In the case of the quasi-persistent series the expected amplitude will depend on whether the N samples are consecutive in the series (in which case they are not independent), or whether they are independent and not adjacent in the series. (In the cosmic ray case there are usually some missing days in an otherwise consecutive group). If the N samples are independent the root mean square amplitude in repeated selection of groups of N will be $1.752\,\sigma/\sqrt{N}$, whereas if all the samples are consecutive the value is slightly higher, and is given by

$$1.414\,(1.866\,N - 0.331)^{\frac{1}{2}}\,\sigma/N.$$

To relate these figures to the cosmic ray case we must choose a value for σ which yields quasi-persistent fluctuations of a reasonable magnitude not inconsistent with the observed type of intensity variations. $\sigma = 0.3\ \%$ is such a reasonable choice. It is in fact less than the statistical standard error of bihourly intensity values ($\sim 0.4\ \%$) for typical recorders considered in this paper. For a typical "monthly" mean we may take $N = 25$. These values would yield a root mean square amplitude for a fitted diurnal variation of between 0.105 % and 0.115 % (for the non-consecutive and consecutive-day cases respectively).

Obviously these values would become still larger if either σ or the persistence period were increased slightly. However the example chosen is sufficient to show clearly the relatively large contribution which such variations could make to the observed daily intensity variation. Moreover since we are considering them to represent approximately synchronized intensity variations at all stations their contribution to the diurnal variation would have the same time of maximum in U.T. at all stations, and the phase would naturally be subject to large erratic changes from month to month. As the U.T. components found in our analysis (Section 4) have an average amplitude of about 0.1 % it seems that they could be explained quite well by irregular short-term modulation of the world-wide intensity.

7. Conclusion.

The evidence presented suggests that a Universal Time component plays an important role in determining the form of the observed daily intensity variation. Subtraction of such a component from monthly mean diurnal variations observed at different stations leads to more consistent month to month phase behaviour at the various stations and considerably improved interstation agreement on the direction of the primary anisotropy responsible for the principle component of the daily variation.

It has been shown that the U.T. component may result from the existence of irregular world-wide primary intensity changes of the short term quasi-persistent type and it may not be necessary to postulate daily periodic modulation of the primary intensity caused directly by the earth's rotation. Nevertheless examination of further experimental data in the light of these suggestions is required.

We have considered only the diurnal variations. In principle we could follow an exactly similar procedure for the semidiurnal or higher harmonics since each harmonic is formally independent of the others. However statistical uncertainties are too great in these cases to make this worth while. It should however be pointed out that the proposed origin of the U.T. variation would produce a semidiurnal component of mean amplitude similar to that for the diurnal component. Its effects would therefore be relatively greater on the phase and amplitude of the smaller semidiurnal variation (see Fig. 8) and may provide an explanation of the very erratic

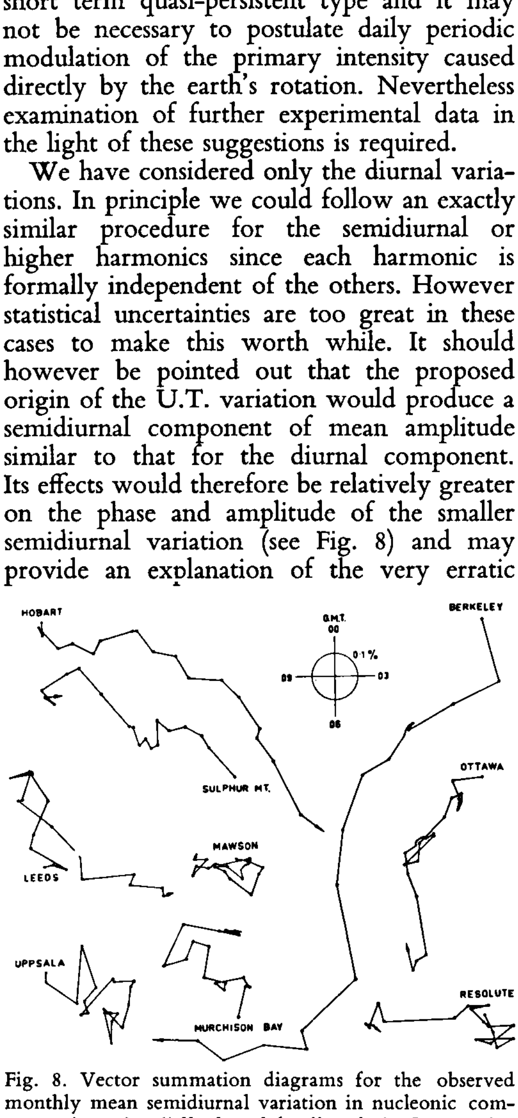

Fig. 8. Vector summation diagrams for the observed monthly mean semidiurnal variation in nucleonic component intensity: "all selected days" analysis. Consecutive vectors are for months 7/57—12/58 for all stations except Berkeley (7/57—9/58), and Murchison Bay (9/57—12/58)

and inconsistent behaviour of this variation at different stations.

In a similar way the presence of short term irregular world-wide intensity variations unrelated to any primary anisotropy could provide at least a partial explanation of the high degree of day to day variability in the observed daily variation and the difference in behaviour at different stations. Such an explanation could remove some of the difficulties inherent in attempts to explain the variability in terms of rapid changes in an anisotropy of complex form.

Other features of the daily variation in which inconsistent behaviour has been observed are the changes related to the degree of geomagnetic activity. In the majority of published results, increased amplitudes and earlier times of maximum are reported to accompany increased geomagnetic disturbance but the reverse is occasionally observed at some stations. In the present analysis for instance, on comparing the 18-month mean diurnal variations for "quiet" days with the mean variations on the 46 days classified as disturbed (excluding Murchison Bay and Berkeley for which we have less than 18 months data) we find the differences to be rather inconsistent at the various stations. Although the disturbed days were not selected on a magnetic disturbance criterion they nevertheless do correspond in almost all cases with enhanced geomagnetic activity. By following the same procedure with the mean diurnal components for the disturbed days as that used for monthly means, a U.T. component of amplitude 0.20 per cent and suitable phase has been found which on subtraction from all station vectors produces a very marked improvement in agreement with the standard phase intervals between stations. Whereas compared with the corresponding quiet day variations the original disturbed day diurnal components show maxima ranging from 3 hours earlier (Hobart) to 0.5 hours later (Leeds) with only small insignificant differences for Uppsala, Mawson, and Ottawa, the resultant vectors after subtraction of the U.T. component all exhibit maxima between 1.1 and 2.1 hours earlier.

The various effects discussed show clearly that the possible influences of a U.T. component chould not be overlooked in any interpretation of experimental observations of the daily intensity variation. In particular, care should be exercised when conclusions about the direction of primary anisotropy are drawn from the phase of the daily variation observed at single stations.

It must be stressed that the reality, relative importance and origin of the component have not been firmly established, and although the success of the hypothesis is strongly suggestive, independent methods of testing it are required. From the discussion of Section 6 it is clear that if world-wide short-term intensity fluctuations occur, even if small and somewhat intermittent, they must give rise to a component of the daily variation. They undoubtedly occur on some days, but could well occur on many others, partly masked by local time dependent and statistical fluctuations. Perhaps the best method of separating them for study would be to average intensity data in Universal Time for a number of neutron monitor stations suitably situated at roughly the same latitude but different longitudes so that the averaging process would eliminate the local-time variations caused by a primary anisotropy.

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NOTE

The detailed numerical results of the harmonic analyses described in Section 2, together with the statistical standard errors of estimate of amplitudes and times of maximum can be made available in tabulated form to those wishing to make use of them.

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