J. Astrophys. Astr. (1981) **2,** 201–212

Long Term Variations in Solar Flare Activity

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Received 1981 April 4; accepted 1981 June 8

Abstract. A statistical analysis of the contemporary (1954–1975) solar flare particle events has been made for the parameters F (integrated, proton fluence in cm^{-2} in an event with kinetic energy above 10 MeV) and R_0 (the characteristic rigidity). These data are compared with the long-term averaged values determined from stable- and radio-nuclide measurements of lunar samples. The analysis shows that the ancient solar flare proton spectrum was harder (higher R_0 values) compared to that observed in contemporary flares. A similar analysis can not be made for the mean long-term averaged flux ($\bar{J}$, cm^{-2} s^{-1}), since the contemporary averages suffer from an uncertainty due to the statistics of a single event. However, the average flux estimates for time durations $\langle T \rangle$ exceeding 10^3 yr, are free from such uncertainties. The long-term averaged $\bar{J}$ values obtained over different time scales (10^4 – 10^6 yr) suggest a possible periodic variation in solar flare activity, with enhanced flux level during the last 10^5 yr. The available data rule out the occurrence of giant flares, with proton fluence exceeding 10^{15} cm^{-2} during the last million years.

Key words: solar flares—solar activity—long term variations

1. Introduction

The variability in the solar output of matter and radiation as also in the magnetic fields associated with solar active regions is of considerable importance in the studies of aeronomy, meteorolgy, atmospheric physics as well as stellar land solar physics. The most commonly used indicators of solar activity are sunspots, flares, plages and related phenomena. These phenomena, in one way or the other, are related to solar magnetic fields and hyperthermal processes. Our knowledge of the basic processes involved is still poor in spite of the facts that the 11 yr sunspot cycle was recognized about a hundred and fifty years ago, that the corroborating records exist from the seventeenth century and that the solar flare events have been studied in great detail during the last three decades (Schwabe 1843; Webber *et al.* 1963; McDonald, Fichtel and Fisk 1974; Eddy 1976). An important supplement to direct observations is a study of the behaviour of the Sun over long periods of time. This would be of great importance for the following reasons. First, the sunspot activity itself has been recognised as exhibiting a multiple periodicity over and above the 11 yr cycle, which extends to the duration of the record itself. Second, direct observations of solar electromagnetic processes are restricted to only a few sunspot cycles. Besides the 11 and 22 yr cycles, periodicities of 55 and 90 yr seem to be well established (Wittmann 1978). In the absence of direct observations extending over long periods of time, a near constancy of the sun has been assumed although theoretical models and scanty experimental data have questioned this off and on. Only recently, Eddy was able to bring forth a rather conclusive evidence that even on the time scale of three centuries for which sufficient direct solar measurements and indirect evidence relating to solar phenomena exist, the Sun can not be called a constant star (Eddy 1976,1977). He showed that the envelope of the 11 yr solar activity has been fluctuating considerably. He was able to extend the studies to variations in solar activity over time periods of about 7000 yr B P by tying on to the ^{14}C tree ring chronology (Eddy 1977). He hypothesised that the Sun has had sustained periods of high and low activities of duration of the order of a century, back to 7000 yr B P. These periods have been designated by him as Grand Maxima and Grand Minima. An example of the latter is the Maunder minimum during 1645–1715 A D. How can a variation in the solar activity change the ^{14}C tree ring record? This question was recently considered in detail by Castagnoli and Lal (1980) and it could be shown that Eddy's hypothesis is tenable since changes in solar activity produce modulation in galactic cosmic ray intensity which is adequate to account for the observed ^{14}C deviation in tree rings. Thus although there seems to exist a strong case for Maunder minimum type of solar minima, one must look for additional evidence.

In this paper, we present an intercomparison between the contemporary flare data (1956-1973) based on rocket and spacecraft experiments and the long term ($> 10^4$ yr) averaged solar flare data, based on stable- and radio-nuclide studies of lunar samples.

2. Contemporary solar flare data

Direct measurements at high altitudes and latitudes provided the first insight into the composition and the energy spectrum of solar flare radiation. Pioneering work in this field was carried out by the Goddard group (Biswas and Fichtel 1965; McDonald Fichtel and Fisk 1974) which exposed nuclear emulsion detectors using rockets and balloons over a decade (1960–1972). For other investigations contributing to information about solar flare events, reference is made to Webber *et al.* (1963), McDonald (1963), Weddel and Haffner (1966), Crawford *et al.* (1975) and Biswas (1972). In the present paper we make use of these basic data which also allow one to make cumulative estimates for each event. Such estimates have been made by Webber *et al.* (1963) and Weddel and Haffner (1966) for events during solar cycle 19 (1954–1964). For solar cycle 20(1965-1975) much more reliable information is available based on the counting rate data obtained by the Solar Proton Monitor Experiment (SPME) on the satellites IMP-4, 5, and 6 (Bostrom *et al.* 1967–1973). An intercomparison was made between the four sets of data and a mutual consistency in event integrated fluxes found to be better than 25 per cent (King 1972).

All available information on solar flare events, some of which has been briefly summarised above, was carefully considered by Reedy (1977) who has compiled fluences (F) of all solar events during solar cycles 19 and 20, for events with total proton fluence exceeding 10^7 cm^{-2} and kinetic energies exceeding 10 MeV. He has also given fluence data separately for energies above 30 MeV and 100 MeV, and above 30 MeV and 60 MeV respectively for solar cycles 19 and 20. We will use these data as a representative sample of contemporary solar flare events. We will also confine ourselves to the method of representing the differential energy spectrum on an exponential rigidity basis

$$dN/dR = K \exp(-R/R_0), \quad (1)$$

where R is the rigidity in MV and R_0 the characteristic rigidity in MV. Here dN/dR denotes the omni-directional (4π) differential rigidity flux and K is a constant. Such a representation describes the energy spectrum fairly well in the interval 5-100 MeV n^{-1} for both singly and multiply charged particles (Lal 1972). Typical values of R_0 lie between 50 and 100 MV.

3. Ancient solar flare data

There are not many ways of studying long term (prehistoric) characteristics of solar flares. For this study one has to find some vestigial records of flare particles of which nuclear effect is the only known example. Fortunately, there exist extensive studies of two flare particle-induced nuclear effects in extraterrestrial samples: (i) Production of isotopes in the target matrix, both stable and radioactive, due to nuclear interactions, and (ii) solid state damage of the crystalline structure of the constituents in the target matrix as a result of ionisation losses suffered by charged particles.

In the case of the former, stable products *e.g.* He and Ne isotopes, and radioactive isotopes, *e.g.* ^{14}C, $^{26}A1$, ^{53}Mn, ^{59}Ni and ^{81}Kr, have been detected. In the case of the latter, etch tracks and thermoluminescence effects have been studied. Although these flare effects could be detected in meteorite samples (Amin *et al.* 1969; Lal and Rajan 1969; Pellas *et al.* 1969) quantitative studies of flare effects began only after the acquisition of the first lunar samples (Shedlovsky *et al.* 1970; Lai *et al.* 1970; Crozaz *et al.* 1970). For a review of the studies of extraterrestrial rock samples conducted with a view to determining prehistory of cosmic radiation, both galactic and solar, reference is made to Lal (1972).

In this paper we concern ourselves only with the long term averaged proton fluxes and spectra, based on the studies of radionuclides ^{14}C, $^{26}A1$,^{53}Mn and ^{81}Kr (Wahlen *et al.* 1972; Boeckl 1972; Bhattacharya and Bhandari 1976; Kohl *et al.* 1978; Yaniv, Marti and Reedy 1980) and stable nuclide ^{3}He (Venkatesan *et al.* 1980) in lunar samples. The radioactive isotopes provide flux and energy spectra of protons, averaged over time periods (10^4 yr to ~ 5 Myr) comparable to their mean lives. The presently available ^{3}He data also cover a similar range since the exposure ages of the two rocks studied are about 1 Myr.

A convenient way to express the solar proton spectrum is to characterise it by two parameters: (i) characteristic rigidity R_0, and (ii) the integrated omni-directional (4π) flux above 10 MeV kinetic energy J (> 10 MeV).

The long term averaged values for J (> 10 MeV) and R_0, inferred from lunar data, lie in the range of 70 to 200 cm^{-2} s^{-1} for J, and 100-150 MV for R_0.

4. Comparison of contemporary and ancient flare data

We will now compare the ancient and the contemporary flare data. However, before we proceed, we will evaluate the general features in the distribution of the flare particle energy spectra and fluences in different events for the contemporary data. Such an analysis is necessary because the contemporary data are limited to the past three decades, and it is important to evaluate the nature of fluctuations between the events to assess the meaning of possible differences between the two sets of data.

A number of useful analyses of contemporary flare data have been made earlier with a view to assessing the effects of solar flare radiation due to exposures near Earth as well as during interplanetary flights on both man and hardware (Webber *et al.* 1963; Modisette, Vinson and Hardy 1965; Weddel and Haffner 1966, Divine 1973; King 1974; Kolomenskii *et al.* 1978). Primary emphasis in these investigations has been on deducing the probability of getting a total fluence which exceeds a certain specified value during a mission of specified duration. We will however be more concerned with the details of the distribution of fluence F, and characteristic rigidity R_0, and the relationship between them in order to deduce expected long term averaged flare spectra. Analyses reported here is more detailed than those of the earlier workers; the gross features are however similar to those obtained earlier.

4.1 *Statistical Analysis of Contemporary Solar Flare Data*

As mentioned earlier, we adopt the compilation of Reedy (1977) for solar flare events during 1954–1975, encompassing solar cycles 19 and 20. This compilation lists 65 flare events with fluence exceeding 10^7 cm^{-2} for protons of kinetic energy above 10 MeV. A statistical analysis of these events leads to three important conclusions.

1. The F and R_0 values both follow a lognormal distribution. As an illustration, we show in Figs 1 and 2 the observed distribution and the log-normal fits for F and R_0 respectively.
2. Flare events of the solar cycles 19 and 20 are all statistically very similar with respect to the R_0 values (Table 1). The F values are however appreciably different (Table 2). This difference may be genuine, but in view of the difference of three orders of magnitude in the measured F values, the difference in μ_n and σ_n values may not be statistically significant (μ_n = mean of In x's and σ_n = standard deviation of In x's; Aitchison and Brown 1957). The imprecise determination of the statistical parameters for F, however, is not of any serious consequence as discussed later.
3. Non-parametric test shows that there is no correlation between F and R_0 in individual events *i.e.* in any given event of a particular fluence F_1, all values of R_0 are equally probable. We checked by setting up a contingency table the null-

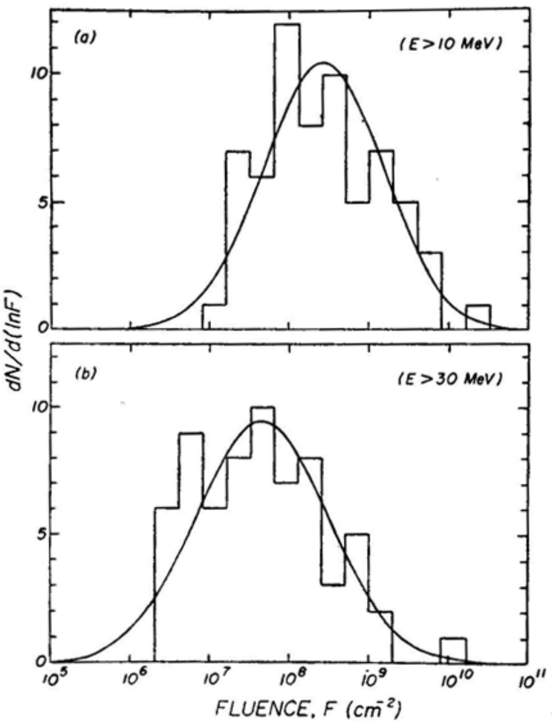

Figure 1 Frequency distribution of cumulative omni-directional (4π) proton fluence (cm^{-2}) in 65 solar flare events (during 1954–1975) for protons of kinetic energy above 10 MeV (a), and 30 MeV (b) All events of fluence above 10^7 protons cm^{-2} of $E > 10$ MeV are considered. Data are from compilation by Reedy (1977). The smooth curve represents the best fit log-normal distribution to the data.

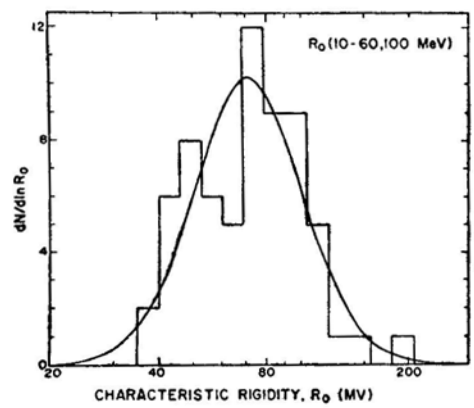

Figure 2 Frequency distribution of the characteristic rigidity (R_0) values for all events considered in Fig. 1 for the energy interval (10-60, 100) MeV. R_0 values were calculated from the data on proton fluence above different energies. The smooth curve represents the best fit log-normal distribution to the data.

hypothesis that R_0 and F values in individual events are correlated. The probability that R_0 and F are correlated was calculated to be less than 0·3 per cent.

Table 1. Statistical analysis of the characteristic rigidity R_0 (MV), in contemporary solar flare events.

Parameter	Solar cycle 19		Solar cycle 20		Solar cycles 19 + 20
	10-30 (MeV)	10-100 (MeV)	10-30 (MeV)	10-60 (MeV)	10-(60, 100) (MeV)
$\mu_n^\dagger$	1·81	1·89	1·76	1·8	1·85
$\sigma_n^\dagger$	0·14	0·14	0·18	0·16	0·15
$\bar{R}_0$	68	82	63	68	75
$^{\sigma}R_0$	22	26	28	25	27
$^{\sigma}\bar{R}_0$	3·7	4·5	4·7	4·2	3·2

† Mean and standard deviation for the best fit log R_0 distribution

The above results, consistent with, the earlier analyses, are extremely significant for the present analysis since they allow us to estimate the expected values for long-term averages if the solar cycles 19 and 20 are considered representative. In particular, we would like to stress here the importance of the third result, namely the statistically independent R_0 and F values in individual events. This has an important bearing on the physics of particle acceleration in flares. Both a harder spectrum (larger R_0 value) and a higher F value imply larger energy in the flare particles, but their statistical independence indicates that a highly variable mechanism is operative which controls the fraction of particles which leave the Sun. In order to accelerate particles efficiently to higher energies (events with larger R_0 values) more energy must initially be available. Implicit here is the assumption of equivalence between the observed solar flare spectra (at 1 AU) and the source spectra. This equivalence may not be exact due to the interplanetary propagation effects, resulting in some deviations in the observed spectra from the source spectra. However, in the case of *event-integrated* spectra, in the energy region of interest (10-100 MeV), both the observed spectra and the deduced source spectra show similar characteristics. Both of them can be represented either on exponential rigidity basis (dN=const $\times$ e^{-R/R_0} dR) or as power law in kinetic energy (dN=const$\times E^{-\gamma}$ dE). In the former representation the source spectrum has a slightly higher characteristic rigidity R_0, while in the kinetic energy representation it is characterized by a slightly lower value for the power law exponent γ, compared to the values of these parameters for the observed spectrum (Krimigis 1965; Wibberenz 1979 and references therein). Thus the assumed equivalence of the source and the observed spectra can be considered to be valid.

In view of the statistical independence of R_0 and F values in individual events, we can write down the following expression for the fluence in an *average flare event* above energy E (or rigidity R)

$$F(>R) = \int_0^\infty \int_0^\infty F(R, R_0, F')\, p(R_0)\, p(F')\, dR_0\, dF', \tag{2}$$

where $p(F')$ and $p(R_0)$ are respectively the probability (log-normal distribution) of obtaining a specified value of F' or R_0 in an event. The function $F(R, R_0, F')$ gives the fluence above rigidity R in an event of total fluence F' (> 137 MV), and characteristic rigidity R_0, and is given by

$$F(R, R_0, F') = F' (> 137 \text{ MV}) \exp\,[(137-R)/R_0] \tag{3}$$

Equation (2) can now be rewritten as

$$F(> R) = \bar{F}(> 137 \text{ MV}) \int_0^\infty \exp\,[(137 - R)/R_0]\; p(R_0)\, dR_0$$

where $\bar{F}$ (> 137 MV) is the time-averaged fluence per event above a kinetic energy of 10 MeV. Taking $\bar{F}$(> 137 MV) = 1·2 × 10^9 cm^{-2} based on contemporary data (Table 2), we obtain values of F(> R) and deduce the effective characteristic rigidity (R_0) values. These estimates, separately or together for the solar cycles 19 and 20, are in good agreement with the effective R_0 values deduced from F(> R) values obtained by directly summing up the fluences above different rigidities.

4.2 *J and R_0 Values in Contemporary and Ancient Solar flares*

The integral flux of protons above energy E as well as the R_0 values for solar cycles 19 and 20 along with the long term averages based on radio-nuclide studies of lunar samples are given in Table 3.

Table 2. Statistical analysis of fluence, $F_{>10\,\text{MeV}}$ (cm^{-2}), in contemporary solar flare events.

Parameter	Solar cycle 19 1954–1964	Solar cycle 20 1965–1975	Solar cycles 19 + 20 1954–1975
$\mu_n^\dagger$	8·8	8·1	8·4
$\sigma_n^\dagger$	0·6	0·75	0·75
$\bar{F}$	1·5 × 10^9	5·4 × 10^8	1·2 × 10^9
σ_F	3·7 × 10^9	2·3 × 10^9	5·0 × 10^9
$\sigma_{\bar{F}}$	3·7 × 10^8	1·7 × 10^8	2·5 × 10^8

† Mean and standard deviation for the best fit log F distribution.

Table 3. Integral flux (cm^{-2} s^{-1})* and the characteristic rigidity (MV)* in solar flares averaged over different time scales

Period	J(>10 MeV)	J(>30 MeV)	J(>60 MeV)	J(>100 MeV)	R_0(10−100)
(i) Contemporary					
Cycle 19 (1954–64)	143	41	12	3	82 (68)+
Cycle 20 (1965–75)	51	11	3	1	68 (63)+
Cycles 19 + 20 (1954–75)	114	28	8	2	75 (65)+
(ii) Long term average					
10^4 yr (^{14}C)[a]	200	72	26	9	100
3 × 10^5 yr (^{81}Kr)[b]	154†	52†	18	6	95
10^6 yr (^{26}Al)[c]	70 (125)§	25 (55)§	9 (24)§	3 (11)§	100 (125)§
5 × 10^6 yr (^{53}Mn)[c]	70	25	9	3	100
~ 10^8 yr (^3He)[d]	80	29†	10†	4†	100

*J (> 10 MeV) and R_0 for solar cycles 19, 20 and their composite has been obtained from the lognormal distribution fit to data compiled by Reedy (1977). The values of J(> E) were computed using the values of J(> 10 MeV) and R_0.
+The numbers within parentheses refer to R_0 values for the energy interval 10-30 MeV.
†Extrapolated values assuming exponential rigidity spectrum.
§The numbers within parentheses are from the revised data of Bhattacharya and Bhandari (1976); Bhandari (1981, personal communication).
[a]Boeckl (1972); [b]Yaniv, Marti and Reedy (1980); [c]Kohl *et al.* (1978); [d]Venkatesan *et al.* (1980)

The marked difference in the J values between cycles 19 and 20 can be easily understood since the average fluence for short durations can be drastically affected by the occurrence of one or two large events. This becomes evident from the raw data. In the solar cycle 19, about fifty per cent of the total fluence was due to 4 out of 32 events, whereas seventy per cent of the total fluence in cycle 20 was due to the 1972 August 4 event. The long term average fluxes are, however, expected to be free from such statistical uncertainty. This is easily seen from Fig. 3 where we have considered the effect of occurrence of an extra event with fluence exceeding F. Figure 3(a) gives the resulting time averaged $\bar{F}$ values per event due to the occurrence of this one event, as a function of F for different time periods $\langle T \rangle$ over which the averages are taken. Also shown in Fig 3(b) is the probability of occurrence per event of an event with fluence $\geqslant F$. These calculations are based on the lognormal distribution parameters for F, for contemporary flares (Table 2).

It becomes apparent that the short duration averages are prone to statistical uncertainties due to statistics of single event and therefore they may not have much significance. But the average flux estimates for long durations are free from such uncertainties. For example, due to the occurrence of a single event, the probabilities of the time averaged fluxes being doubled are about 10^{-7} and 10^{-14} for $\langle T \rangle = 10^4$ and 10^6 yr respectively. Consequently any measured variations in the long term averaged flux values for different durations should reflect real changes in the ancient solar flare intensity. For a critical assessment of the long term averaged flux values given in Table 3, reference is made to the recent work of Reedy (1980).

In contrast to the case for $\bar{F}$, the much smaller spread in the case of R_0 values leads to a reasonably good estimate from data of short duration. The calculated change in the time averaged R_0 value due to the occurrence of an extra event of high rigidity even during a short period of 20 years is less than four per cent. Because of this, the effective R_0 value based on the contemporary data alone (1954-1975) is expected to be quite reliable.

Thus the time averaged R_0 values for different integrating periods (10-10^6 yr) would be expected to be similar within 5 per cent. The expected trend is reflected by

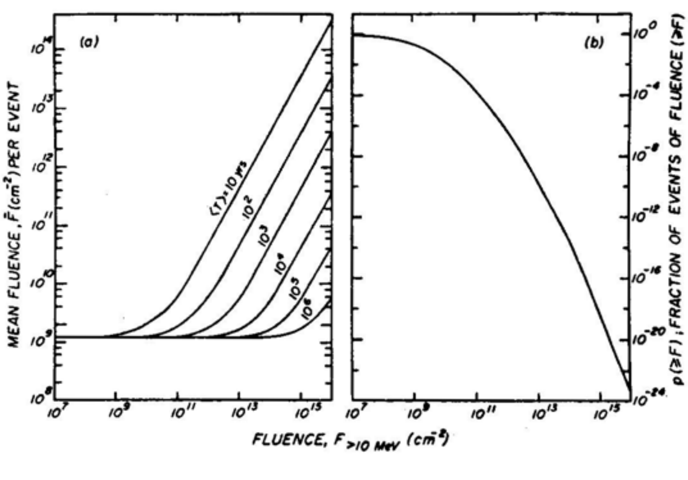

Figure 3. (a) The effective $\bar{F}$ values (mean fluence per event) due to the occurrence of an extra event of fluence $\geq F$, plotted against F for different time periods over which the averages are taken. (b) The theoretical values of ρ ($\geq F$), the fraction of events having fluence $\geq F$, are plotted as a function of F.

the fact that in spite of a significant difference in the average proton fluxes in solar cycle 19 and 20, the average R_0 is similar in both the cycles (Table 3).

Based on the above discussions and data in Table 3, we observe:

1. There exists a definite difference between the time averaged R_0 values for contemporary and ancient flares ($\langle T \rangle = 10^4$–10^6 yr). The ancient solar flares are characterised by a spectrum harder than that of the contemporary. As discussed above, this conclusion is free from sampling uncertainties.
2. The long term and recent time averaged J values differ by a factor of about 2 to 3. However, considering statistics of a single event, no meaningful conclusion can be drawn about possible differences between the contemporary and long term average J values.
3. Out of the different long term averaged flux values, those obtained from ^{14}C ($\langle T \rangle = 10^4$ yr) and ^{81}Kr ($\langle T \rangle = 3 \times 10^5$ yr) are distinctly higher. If this result is taken at its face value, it would imply a higher solar flare activity (by about a factor of two) in the past 10^4 or 10^5 years, compared to that in the earlier epoch of a few million years.

Considering the stability of the $\bar{J}$ value based on the long term averages, we consider a $\bar{J}$ value of ~ 100 cm^{-2} s^{-1} for $\langle T \rangle = 10^6$ yr to be a good representative of the average solar proton flux. This value can be appreciably affected only due to the occurrence of a large flare with fluence F exceeding 10^{16} cm^{-2}. It is also interesting to note here that the integrated fluence over 10^6 yr, with $\bar{J} = 100$ cm^{-2} s^{-1}, is 3×10^{15} cm^{-2}, which by itself rules out the occurrence of a single flare with fluence exceeding a few times 10^{15} cm^{-2}.

A number of solar cycle periodicities ranging between 20 to 250 yr (besides the 11 yr cycle) have been suggested from an analysis of sunspot numbers and ^{14}C tree ring data (Bonov 1972; Cohen and Lintz 1974; Eddy 1976; Wittmann 1978). The possibility of longer term periodicity cannot be ruled out since the above values were obtained from short duration data extending upto a few thousand years in the past. For the present purpose, we will assume that the prominent variations in the solar activity are restricted to cycles of durations $< 10^3$ yr, and thus any variation in $\bar{J}$ values for $\langle T \rangle$ exceeding 10^3 yr should result from the occurrence of a single or a few large flares. Thus, the higher values of $\bar{J}$ for $\langle T \rangle = 10^4$ and 10^5 yr, based on ^{14}C and ^{81}Kr data (Table 3) are suggestive of the occurrence of a few large flares with fluence $F(> 10$ MeV) of $\geqslant 10^{13}$ cm^{-2} during the last 10^4 yr and of $\geqslant 10^{14}$ cm^{-2} during the time interval between last 10^4 to 10^5 yr. Based on the ^{14}C tree ring data Lingenfelter and Hudson (1980) ruled out the possibility of the occurrence of such large flares during the ^{14}C mean lifetime scale (~ 10^4 yr). However, in view of the large attenuation of amplitude in tree rings compared to that in solar flare production, this conclusion must be checked carefully. An alternative explanation for the variations in the long term averaged $\bar{J}$ values will be to postulate a longer term solar activity cycle of period lying between 10^5–10^6 yr.

Since we are dealing with solar flare spectral parameters averaged over a large number of events, the effect of interplanetary propagation on the time averaged spectral parameters are expected to be similar both for the contemporary and for the ancient solar flares. Thus the differences in the time averaged spectral parameters for contemporary and ancient solar flares observed at 1 AU should represent differences in their source spectra as well. Therefore the higher value for the characteristic rigidity R_0 in ancient solar flares averaged over $\langle T \rangle \geqslant 10^4$ yr indicates the availability of larger amount of energy during particle acceleration compared to flares occurring in the last two solar cycles. It may be reiterated here that the variation in $\bar{J}$ between the contemporary and ancient flares lies within a factor of three. The prob lem before us is to deduce the average R_0 value during earlier epochs of high rigidity. This calculation can only be made if we have an *a priori* knowledge of the variations in $\bar{J}$ values during high and low rigidity period. We have, therefore, deduced working values of $\bar{R}_0$ during the active periods by assuming (i) equal duration of high and low activity period (quite consistent with the deduction of Eddy for the duration of Grand Maxima and Minima) and (ii) ratio of mean $\bar{J}$ (maxima)/$\bar{J}$ (minima) to be in the range 1 to 5. The values of $\bar{R}_0$ (Maxima epoch) thus obtained are in the range 130 to 300 MV.

We now wish to make some general remarks about the sources of variation of solar activity. We are basically dealing with a short enough time scale that whatever the process, it must be related to periodicities in the observed solar surface phenomena, such as variations in the sunspot numbers. Although there is no consensus yet on the solar flare models, it is clear that during periods of sustained solar minimum or maximum, the energy available for particle acceleration may be quite different, being larger during active periods such as the Eddy maxima. For recent discussions and review on storage and conversion of magnetic energy see Akasofu (1981); Schussler (1980); Brown and Smith (1980) and Mullan (1975).

It is generally believed that solar flares depend for their energy source on the toroidal magnetic field created inside the Sun by the action of the solar differential rotations on the poloidal field. The internal toroidal field is like a wound-up spring. Following Mullan and Kent (1979), one may imagine that the spring gets more and more tightly wound up as the cycle progresses and the effects may be appreciable for cycles of 100-250 yr periodicity. Evidence for subsurface storage of energy has recently been provided for the Sun by Glencross (1979). In order to see the validity of the hypothesis that higher energy may become available during the progression of a solar cycle, we have analysed the data for solar cycles 19 and 20 Indeed one does observe a fairly good positive correlation between R_0 in individual events with $F \geqslant 5 \times 10^8$ cm^{-2} and ΔT, the time elapsed since the beginning of the cycle. It may be noted that no such correlation could be found for the F values of the individual events.

The present work thus provides clear evidence for a long term variation in solar activity. The high value of the characteristic rigidity in ancient flares can be understood only if the past solar activity was higher than that observed in the last 25 years. This variation can be understood in terms of Eddy's hypothesis of periodic maxima and minima in solar activity. The changes in the mean flux values averaged over different durations in the past also indicate either the occurrence of one or a few large solar flares ($F \geqslant 10^{13}$ cm^{-2}) during the last 10^5 years or a long term solar activity cycle with periods lying between 10^5 to 10^6 yr.

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