SOLAR WIND VARIATIONS IN THE 60-100 YEAR PERIOD RANGE: A REVIEW

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ABSTRACT

The evidence for and against the reality of a solar wind variation in the period range of 60-100 year is re-examined. Six data sets are reviewed: sunspot numbers, geomagnetic variations, two auroral data sets and two ^{14}C data sets. These data are proxies for several different aspects of the solar wind and the presence or absence of 60-100 year cyclic behavior in a particular data set does not necessarily imply the presence or absence of this variation in other sets. We conclude that two different analyses of proxy data for a particular characteristic of the heliospheric solar wind yielded conflicting results. This conflict can be resolved only by future research. We also definitely confirm that proxy data for the solar wind in the ecliptic at 1 A.U. undergo a periodic variation with a period of approximately 87 years. The average amplitude and phase of this variation as seen in eleven cycles of proxy data are presented.

INTRODUCTION

The existence of a solar variation with a period in the range of 60 to 100 years has been the subject of controversy for many years. Data on the amplitudes of the sunspot cycle, auroral frequencies, ^{14}C, the weather, tree rings and the thickness of varves in Australian rocks (Williams, 1981) have been cited for or against the existence of a periodic variation in this time range. The suspected variation has been called, among other things, the Gleissberg variation, the Long Cycle, the 87 year cycle and the secular variation.

In this paper we take a much more restricted view of the proposed phenomenon. We note that many of the data sets used in the past refer to aspects of the solar wind rather than the sun itself and so we here confine our study to a review of data concerning variations of the solar wind with characteristic times in the 60-100 year range. Because the solar wind has been observed in situ for less than 2 eleven year solar cycles, we will have to rely on a data base that gives indirect information on the solar wind, that is, proxy data will be used. We will further restrict our study to proxy data for which the relationship between the observed quantities and the solar wind is understood at least in principle. For this reason no data involving solar weather relationships will be examined. In section 1 of this paper the 6 data sets used will be introduced briefly. We then discuss each set, its relation to other sets and the evidence it gives as to the reality of a long period variation in the solar wind. The results of the review are brought together in section 2 where it is concluded that there is conflicting evidence concerning a possible heliospheric-wide solar wind periodicity in the period range of interest but there is extremely good evidence for a long cycle of about 87 years in the solar wind in the vicinity of the earth. The amplitude and phase of the variation are displayed.

SECTION 1 - THE DATA

The six data sets to be used and the time periods they cover are shown schematically in figure 1. The sunspot number record starting in about 1700 provides proxy data for certain aspects of the sources of the solar wind since the beginning of the 18th century. The next three data sets, aa, Swedish auroras and medieval auroras, are proxy data for the solar wind in the vicinity of the earth since that wind drives the aurora and geomagnetic activity. The aa denotes the geomagnetic indices scaled by Mayaud (1973) from existing observatory records for the period since 1868. The Swedish auroral data set was constructed by Rubenson (1882) from reports from observers throughout Sweden and covers the period from 1721 to 1876. The data set denoted as "medieval aurora" are taken from the review by Siscoe (1980) who gives the number of auroras reported per decade in Europe and/or the Orient from 450 A.D to 1450 A.D. The bottom two data sets of ^{14}C are proxy data for the solar wind throughout the heliosphere since the ^{14}C abundance in the earth's atmosphere is indirectly determined by the cosmic ray intensity, which is in turn modulated by the heliospheric solar wind. The differences between the two ^{14}C data sets will be described when they are discussed in detail below.

In the remainder of this section the data sets in fig. 1 are reviewed, their reliability assessed and some comments made on intercalibration with other data sets. Each set is then examined separately to see what evidence it gives concerning the existence of a periodic solar wind variation in the 60-100 year period range. Each data set will be assigned to one of three categories,

1 - shows periodicity in the 60-100 year period range
2 - does not show periodicity
3 - is compatible with a periodicity but too short to be considered a member of category 1

There were no data sets that would belong to the 4th logical category, i.e. not compatible with a 60-100 year periodicity but too short to be considered a member of category 2. Before proceeding it is important to emphasize that since the data sets are proxy for three different aspects of the solar wind; the sources, the solar wind in the vicinity of the earth and the solar wind throughout the heliosphere, a periodicity in any one of these quantities does not necessarily imply a periodicity in the other two. The data sets will be discussed in the order shown in figure 1 except that the medieval auroras will be reviewed last.

Sunspot Numbers

The sunspot number is defined somewhat arbitrarily as the number of individual spots plus 10 times the number of spot groups (c.f. Gibson, 1973). Considering this definition it would be rather remarkable if the daily sunspot number had a very high correlation with any other physical quantity. The reliability of data on sunspots has been reviewed by Eddy (1976) during the course of his work establishing the reality of the Maunder minimum. Eddy concluded that sunpsot data have been very reliable for more than the last hundred years but that the reliability of the data declines for earlier periods. However, since perhaps the beginning of the 18th century the approximate amplitude and time of the eleven year solar cycle variation of the yearly averaged sunspot number is quite well established. Recently a great deal of work has been done on deducing sunspot numbers during the 17^{th} century Maunder minimum, but the relative amplitudes of the sunspot cycles described for that period can not be determined because of the rarity of spots and of systematic observations. For this reason the 17^{th} century sunspot data will be omitted from this study.

The relationship between the sunspot number and the parameters of the solar wind is not close and in general neither daily nor yearly average sunspot numbers can be used to predict velocities or magnetic fields of the solar wind near the earth (c.f. Gosling et al. 1977). However, the sunspot number does yield some information on the sources of the solar wind since the number of sudden commencements of geomagnetic storms arriving at earth each year is correlated to annual sunspot number with a correlation coefficient of 0.85, as shown by Mayaud (1975) using 100 years of data. Sudden commencements (i.e. sudden world wide increases in the horizontal intensity of the geomagnetic field observed at low and midlatitude magnetic observatories) are usually caused by solar wind shocks due to sudden ejections of high velocity solar wind, and so the number of sudden solar ejections is proportional to the sunspot number. In this sense the sunspot number gives information on the sources of one type of solar wind disturbance.

Fig. 2 (adapted from Eddy, 1976) gives the annual mean sunspot number from 1610 to 1975. The Maunder minimum is shown on the top panel. The second and third panels show the data used in this review; i. e. the data that give evidence concerning a 60-100 year variation in solar wind sources. The envelope of the 11 year sunspot cycle shows three relative minimums, circa 1755, circa 1810, and a broad minimum from 1880 to 1930. If we adopt a criterion that to be counted as a minimum cycle, the sunspot number can not exceed 70, then two minimum periods remain, one at the beginning of the 19^{th} century and the other at the end of the 19^{th} or the beginning of the 20^{th} century. These minimums are weak evidence in favor of a 60-100 year period in solar wind sources since they are compatible with such a period. From this view the appearance of the minimum to be expected in the early 18^{th} century would have been obscured by the general rise caused by the ending of the Maunder minimum. On the basis of this admittedly weak argument this data set is put in category 3; that is, it is compatible with a 60-100 year variation in properties of the sources of the solar wind but too short to be used as evidence for any such periodic behavior.

aa Indices

The second data set to be considered is the 100 years of aa indices produced by Mayaud in 1973 from the original magnetograms from Greenwich Observatory and the antipodal Australian stations. In contrast to the more familiar indices such as ΣKp or C_9, aa is a real physical quantity. The data set consists of half daily values of the range of geomagnetic disturbances measured in nanoteslas. It covers the period from 1868 to the present but can be considered a modern data set because, within the last 10 years, the actual traces of the magnetometer pens were used to produce it. This is in contrast to the case of, for example, sunspot data in which we have only the record of what the observer reports as having been seen and no hard copy record of the observations themselves that could be re-examined using modern methods.

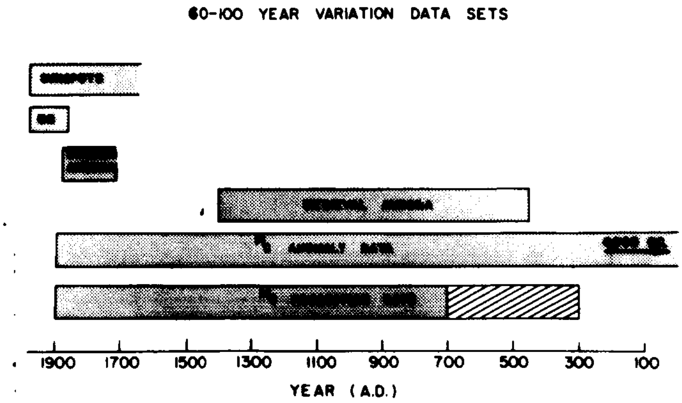

Fig. 1. Schematic of data sets discussed and the time period each covers. These data are proxies for three different aspects of the solar wind, as discussed in the text

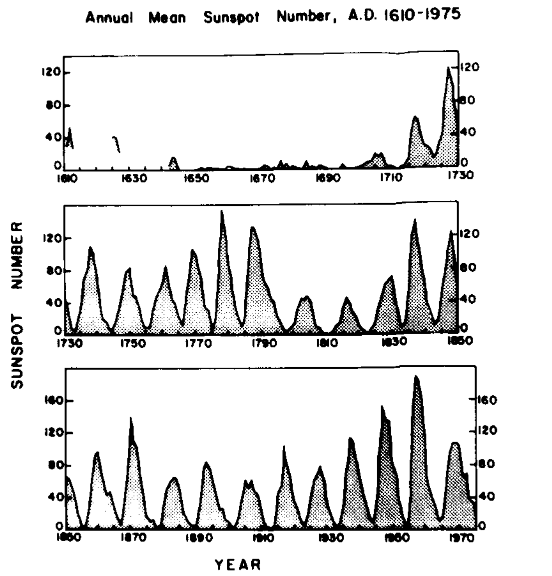

Fig. 2. The annual mean sunspot number, from Eddy,(1976). The low amplitude cycles near the beginning of the 19th and 20th centuries are weak evidence for a Long Cycle variation in one aspect of the sources of the solar wind.

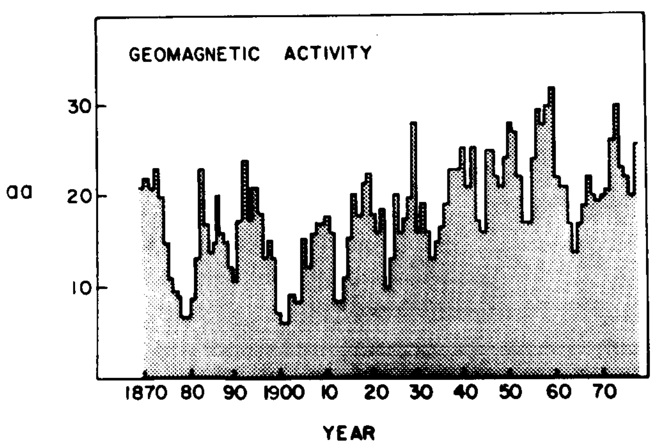

Fig. 3. The aa index of geomagnetic activity. These data are a proxy for the solar wind at 1 A.U. in the ecliptic plane (after Mayaud, 1973).

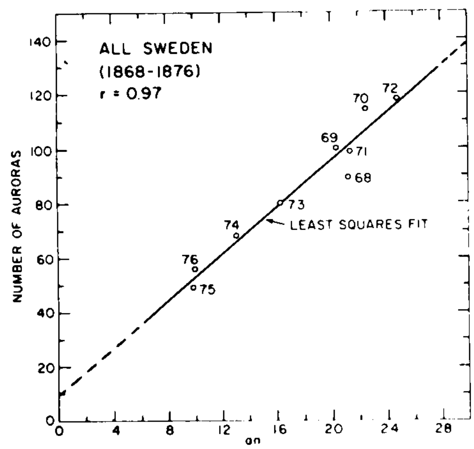

Fig. 4. A comparison of the aa index and the number of auroras reported each year in Sweden for the period when both data sets exist. (From Silverman and Feynman, 1980).

If we consider the magnetosphere as a solar wind detector and magnetic and/or auroral activity as read-out parameters, the aa indices, shown in fig. 3, form a data set that refers to the solar wind at 1 A.U. and in the ecliptic plane. The relationship between the sunspot data and the aa index has been the subject of several studies in the last few years (c.f. Legrand and Simon 1981, Feynman, 1982). In examining the relationship it should be kept in mind that both sunspot number and aa are accurate and reliable for the period since 1868 and the differences in their long term behavior must be caused by their being measures of two different phenomena. It is clear in figures 2 and 3 that geomagnetic activity remains strong during the declining phase of the 11 year sunspot cycle. In fact the level of aa during the declining sunspot number phase is so strongly related to the maximum sunspot number in the next cycle, about 6 years later, that aa has successfully been used to predict the value of the annual average sunspot number at the next maximum (Ohl 1976, Sargent, 1978). This strong relationship verifies that both the sunspot number and aa are reliable and have a physical meaning.

Evidence for a long period variation in the solar wind at earth is seen in figure 3 in the general rise of aa at sunspot minimum between 1900 and 1954 (Feynman and Crooker, 1978, Feynman 1982). This rise is not present in the sunspot number at minimum but is present in the ^{14}C data (Stuiver and Quay, 1980). The annual average aa is related to some combination of average solar wind velocity and southward interplanetary magnetic field (c.f. Crooker et al. 1977) and the extrapolations of the empirical relations derived from in situ solar wind data imply a very low annual average velocity or southward interplanetary field near the turn of the century, minimizing about 1901 (Svalgaard, 1977, Feynman and Crooker 1978, Gringaus, 1981). A further analysis of aa was interpreted as showing a systematic intensification of variations associated with the 11 year cycle from 1900 to 1960 which was ascribed to a Gleissberg variation (Feynman, 1982). These studies of the aa index indicate the solar wind variations are consistent with a Long Cycle variation minimizing about 1900. This phase is of course consistent with the broad minimum seen in sunspot number cycle amplitude, but in the aa data the time of minimum can be more firmly determined. The aa data, then, are also placed in category 3.

Swedish Auroras

Swedish auroral observations from 1720 to 1882 were catalogued by the Director of the Central Meteorolgical Institute of Sweden, Robert Rubenson (1882). The data were collected from a variety of sources in all parts of Sweden. Rubenson's catalogue includes the geographical positions at which the observations were made. The yearly numbers of auroras seen in all Sweden and in the regions north and south of 61° 30" are available and have been restudied for their relavance to the long cycle variation (Silverman and Feynman, 1980, Feynman and Silverman 1980).

The Swedish auroral observations and the aa both refer to the solar wind in the vicinity of the earth but they are measurements of somewhat different phenomena. Both annual averages are available for the 9 years from 1868 to 1876 and the relationship between them shown in figure 4 (Silverman and Feynman, 1980) is remarkably close. Although the overlap of the two sets is small, they are so closely proportional to one another that the figure gives confidence in the accuracy of the Swedish auroral observations, as well as reaffirming the well known relation between the range of geomagnetic disturbances and the latitude at which auroras are seen.

The number of auroras reported for Sweden south of 61° 30" is shown in Fig. 5. There is an impressive minimum in the 2nd decade of the 19th century. There are six years from 1809 to 1814 during which fewer than three auroras were reported each year. The number of auroras did not recover until sometime after 1825. The existence of a world-wide minimum in solar-terrestrial relationships at this time is confirmed by observations made in the United States (Feynman and Silverman, 1980). This solar wind minimum of 1809-1814 took place about 90 years before the solar wind minimum of 1901 implied by the aa data. Merging these two data sets would result in a solar wind proxy data set going through two minimums, with a period of something like 90 years. Considering either the Swedish auroral data set or the merged aurora-aa set, these data are placed in category 3.

Carbon 14 Data Sets

The next two data sets to be discussed are derived from ^{14}C in tree rings (Lin et al. 1975; Stuiver and Quay, 1981). ^{14}C is indirectly produced by galactic cosmic rays which, in turn, are modulated by the interplanetary medium. Interaction with the solar wind throughout the heliosphere modifies the cosmic ray flux which arrives at the earth's atmosphere. Changes in the cosmic ray flux cause changes in neutron production rate. The production of ^{14}C depends on interactions of the neutrons with atmospheric nitrogen. The ^{14}C then mixes into the atmosphere and is incorporated into living organisms. When life processes stop, the ^{14}C in the organism is no longer exchanged with the atmospheric ^{14}C.

Although ^{14}C production rate is dependent on the heliospheric solar wind in a very complex way, studies of ^{14}C have been made for many years and methods of analysis are well advanced and sophisticated. The major changes in ^{14}C levels during the last few milleniums are caused by known changes in the earth's main field (Creer, 1981) but these can be accounted for. There is also a small residual variation of a few percent from the long-term trend. This residual is due to heliospheric cosmic ray modulation. The data set labeled ^{14}C anomoly data in fig. 1 consists of these residual variations and covers 8,000 years. The solar-terrestrial minimum around 1810 and major solar terrestrial events such as the Maunder and Sporer minimiums are clearly seen in the ^{14}C residual record (Stuiver and Quay, 1980). Lin et al., (1975) calculated the autocovariance function using this data set and their results are shown in fig. 6. There appears to be a 350 year variation but since that is out of the period range of interest here it will not be discussed further. There is also a general rise in the autocovariance at periods between 20 and 150 years. Superposed on this general rise is added power at about 80 years. Lin et al. (1975) interpret this in terms of a periodic variation in the range from 60 to 100 years. This data set then will be assigned to category 1 since it shows a periodicity.

Recently another analysis of ^{14}C data has been carried out by Stuiver and co-workers. Stuiver and Quay (1980) increased the temporal precision of the ^{14}C data by constructing counters which could measure the ^{14}C activity in tree rings with a precision of 1.5 to 2 parts per million. Then, instead of using

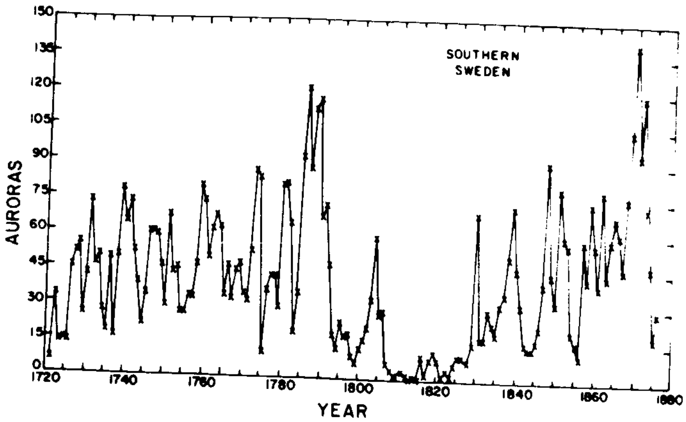

Fig. 5. The number of auroras reported each year in the region of Sweden south of 61° 31". Evidence for a solar-terrestrial minimum is seen is the small number of auroras reported between 1809 and 1825.

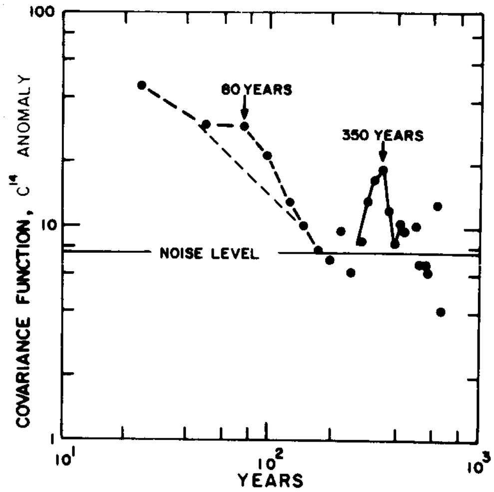

Fig.6. Autocovariance function for ^{14}C anomoly data (adapted from Lin et. al. 1975) showing increased covariance in the 60-100 year period range. ^{14}C data is proxy for the solar wind in the heliosphere.

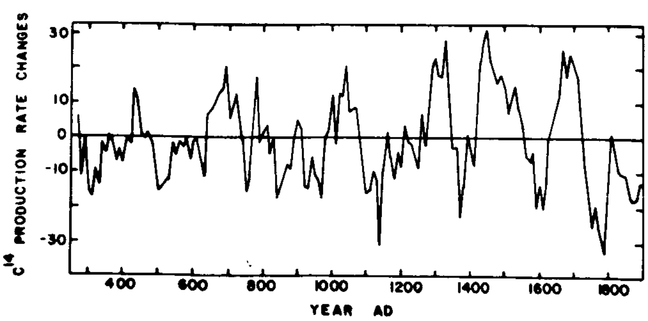

Fig. 7. The ^{14}C production data set from Stuiver and Quay, 1980 . As discussed in the text, this data set is derived using a model in which ^{14}C a 60 year residence time in the atmosphere.

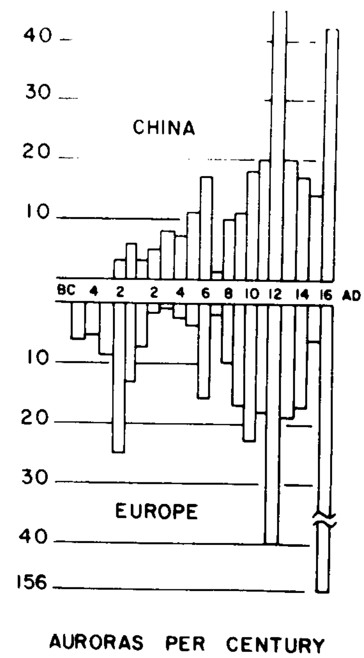

Fig. 8. A comparison of the number of auroras reported per century in Chinese and European records. (from Siscoe, 1980).

the ^{14}C anomoly data directly, they calculated the production rate of ^{14}C using a complex model in which the ^{14}C was stored in the earth's atmosphere before it interacted with the biosphere. The residence time of the ^{14}C in the atmosphere was an adjustable parameter. The ^{14}C production rates from 300 AD to 1900 AD were calculated using a 20 year and a 60 year atmospheric residence time and the results for the 60 year residence time is shown in fig. 7 (Stuiver and Quay, 1980). Maximums in about 1450, 1650 and 1810 correspond to the Sporer, Maunder and 19th century solar-terrestrial minimums. Stuiver and Quay compared the behavior of the ^{14}C production rates to the aa series and the sunspot numbers for the last 100 years and concluded that the ^{14}C production behaves more like the aa index than like the sunspot numbers. They found that the correlation coefficient between the ^{14}C production rate and the annual average aa was 0.67, which is quite high considering the aa is related to the solar wind at earth whereas ^{14}C probes the entire heliosphere.

Stuiver (1980) has carried out a power spectral analysis of the post 700 A.D. ^{14}C production rates shown in fig. 7. He does not find any increase of power in the 60 to 100 year frequency range so that this ^{14}C production data set must be placed in category 2, i.e. it does not shown any periodic behavior in the period range of interest here. Both the ^{14}C anomaly data and the ^{14}C production data will be discussed further in section 2.

Medieval Auroras.

The final data set to be discussed is derived from reports of auroras seen in Europe and the Orient from 450 A.D. to 1450 A.D. and will be referred to as medieval auroras. This data set was reviewed by Siscoe (1980) who, following Keimatsu (1976), investigated the accuracy of auroral report data by comparing the number of auroras per century reported from China and Europe separately as shown in fig. 8. Not only are the envelopes of the two frequency distributions almost the same but the actual number of reports from both areas are remarkably close. These results give confidence in the accuracy of the data. Siscoe (1980) also presented the thirty year running averages of the number of auroras seen per decade in the combined European-Oriental data set as shown in fig. 9. These data, like the Swedish auroras and aa are proxy for the solar wind at 1 A.U. in the ecliptic plane. The minimums circa 600-700 A.D., 1050 A. D., and 1350 A. D., are reflected in the ^{14}C data as is the maximimum from 1100 to 1200 (Stuiver & Quay, 1980).

As Siscoe points out and as has often been suggested before, (see review by Siscoe, 1980), this data set appears to show a periodic variation with a mean period of about 87 years. In order to test the validity of this observation in a more objective way the data will be analysed here by a modified superposed epoch method. The zero times of the epochs are chosen to make the average interval length 87 years. Since the data consist of the number of auroras per decade, it is not possible to use intervals of exactly 87 years each. Instead each interval consists of 9 decades of data but the zero time is adjusted so that the last decade of a few intervals is also used as the first decade of the next interval. A second modification must be made to the usual superposed epoch method because of the large amplitude of variations with characteristic times longer than 100 years, i.e. The Maunder and Sporer type minimums and the 12^{th} century medieval maximum. If a standard superposed epoch analysis were carried out the results would be dominated by these events. To prevent this, the number of auroras observed in each interval was normalized to one, and the fractional number of auroras in each bin calculated. The resulting data were arranged to perform the superposed epoch analysis shown in the upper panel of fig. 10. Each point represents the ratio of the number of auroras reported for a decade to the total number of auroras reported for the 90 year interval. The average of all the values is 0.11, shown by a bar in the figure. The data appear to be very systematically distributed about the average. For example almost all the points in the 3rd and 4th bins are above the average whereas almost all the points in the 2nd to last and last bins are below average. In order to test the validity of the method the analysis was repeated for several other choices of cycle length and the results for a 70 year cycle are shown in the lower panel of fig. 10. These results are typical of those for the other cycle periods tested. Here, although there is perhaps a hint of some systematic behavior within each of the bins, the distributions of points about the average of 0.14 does not appear to deviate significantly from chance.

The top panel of fig. 10 then is interpreted as demonstrating 1000 years of an 87 year period in the frequency of auroras at midlatitudes. This implies a variation of the solar wind at 1 A. U. in the ecliptic with a period of about 87 years. The uncertainty in the period is about a year or two. The period can not be determined more precisely by the superposed epoch method because a change of a year or two in the interval length will not make a statistically significant difference in the data distributions.

The amplitude and phase of the variation can also be determined reasonably accurately. The points in fig. 11 give the averages of the data in each bin of the upper panel of fig. 10. The first and last points in the figure are the same and are the bin 9 average. The dashed line is a simple sine function that was chosen to approximately fit the data. The phase of the curve was also chosen to give the best fit. The horizontal line is the average of the entire data set as in fig. 10. The minimum phase is about two decades before the first bin so the statistical minimum corresponds to about 435 A. D. (before the fall of Rome). On the average in a cycle, 2 1/2 times as many auroras will be seen at midlatitudes for cycle maximum as for cycle minimum. Due to uncertainties in period length and phase we can not meaningfully extrapolate to the 19th and 20th centuries.

The medieval auroral data set is assigned to category 1.

TABLE 1

data set	proxy for solar wind at	number of cycles	category
sunspot number	sources	2	3
aa indices	earth	1	3
Swedish auroras	earth	1	3
^{14}C anomoly	heliosphere	~100	1
^{14}C production	heliosphere	~16	2
medieval auroras	earth	11	1

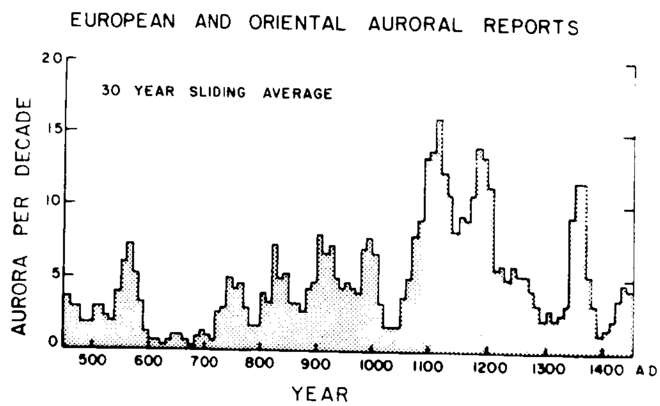

Fig. 9. A thirty year running average of the number of auroras reported per decade in the combined European-Chinese data set (from Siscoe, 1980).

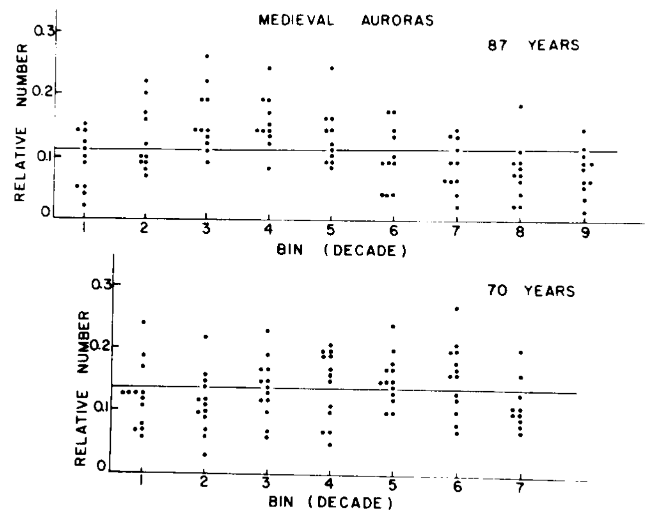

Fig. 10. Modified superposed epoch analysis of the data in fig. 9. The top panel shows the data using an average interval length of 87 years. The lower panel shows the results of using a 70 year interval length.

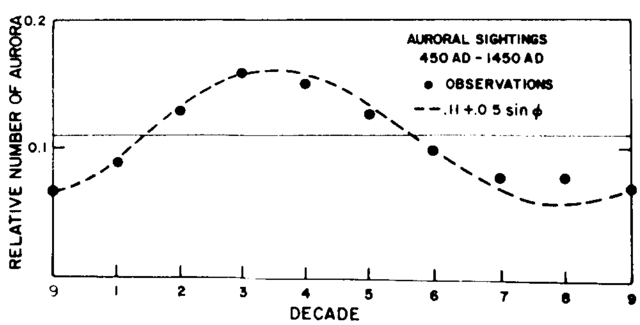

Fig. 11. The bin averages of the data in the top panel of figure 10. The sine curve is an approximate fit to the observations giving the amplitude and phase of the 87 year periodic variation. This figure demonstrates that there is a real variation in the solar wind at earth with a period and phase approximately as shown.

SECTION 2. THE CONCLUSIONS

The results of this review are gathered together in table 1. Since the data sets refer to three different aspects of the solar wind, a long period variation of one of these aspects does not require or imply a long period variation in either of the other aspects. Disagreements exist among the results only when two analyses of proxy data for the same aspect of the wind result in conflicting results. From table 1:

1). We have insufficient evidence to tell whether or not the annual sunspot number, and therefore the annual number of shocks in the solar wind, changes with the Long Cycle, but what data we have are compatable with such a change.

2). All of the proxy data for the solar wind at earth either show a definite long period variation or are compatible with such a variation. This finding is discussed further below.

3). A single type of proxy data for the solar wind in the heliosphere has been analyzed by two seperate groups and the results are conflicting, one being interpreted as showing a Long Cycle and the other as ruling a Long Cycle out.

The resolution between the two analyses of the ^{14}C data is not at all clear at this time. There are several possibilities. For example, the increase in the autocovariance function at about 80 years may not be statistically significant, or, conversely, it may be that the variation is very weak and 100 cycles of data are needed in order to be apparent in a power spectral analysis. It may also be possible that the long period variation was suppressed when the ^{14}C production data were derived from the ^{14}C residual anomoly data. The data set for which Stuiver (1980) ran the power spectral analysis used a 60 year atmospheric residence time in calculating the production rate from the residual anomolies. This may have significantly lowered the intensity of an already weak variation. Stuiver and Quay (1980) show both the production data with a 20 year residence time and with a 60 year residence time for the period around 1811-1813 when we know that solar terrestrial phenomena in general were weak. Although both data sets show a variation of the expected sign for that time, the signal is relatively suppressed for the 60 year residence time data set. However, all that can be said now is that two analyses of ^{14}C data disagree. Until that disagreement is resolved we can not come to any conclusion concerning the existence of a long period variation in the properties of the heliospheric solar wind that modulate atmospheric ^{14}C.

The situation is quite different for proxies of the solar wind at earth. Here there is no conflict of results. Swedish auroras and geomagnetic activity are easily consistent with a long period, and they agree with each other in phase, i. e. the minimums are about 87 years apart. The medieval auroras form a long enough data set so that the cycle is clearly seen in a modified superposed epoch analysis and the average amplitude during the 1,000 years from 450 A. D. to 1450 A. D. was such that more than twice the number of auroras were seen at maximums as at minimums.

Even if the controversy concerning the heliospheric solar wind were to be settled against the long cycle appearing in that data, it would not constitute any contradiction with the data on the solar wind at earth. It might imply that the solar wind had an 87 year cycle in some local property. As one example, the neutral sheet might rock relative to the ecliptic plane. However, the hypothesis of a local change is not required by the observations at this time.

It is concluded that we have definitely observed a long period variation in the solar wind at earth for at least 1,000 years and probably 1,500.

The existence of a Long Cycle expressed in auroral frequency would not necessarily be obvious to individual observers. Fig. 9 shows that the slower changes, such as those associated with the medieval maximum can be much larger than those of the 87 year type. Furthermore, the minimums and maximums are separated by forty years and few people are likely to keep records that long. Even when auroras are the subject of much interest and speculation, changes on that time scale are likely to be discounted. For example, space sciences graduate students of the 1970's may well have taken their professor's descriptions of the magnificent auroras of 1935-1959 with a grain of salt.

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