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Evidence in the Auroral Record for Secular Solar Variability

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The historical record of aurorae is continuous and usefully dense for at least the last 2000 years. Revival of interest in the secular variability in solar activity motivates a review of the auroral record. The existence of secular variations in the auroral occurrence frequency has been known since the early 1700's, including the existence of a significant attenuation of auroral activity during the Maunder Minimum. Investigation of secular variations prior to the Maunder Minimum is now possible based on six auroral catalogs that have been published within the last 20 years. The catalogs cover the time period from the fifth century B.C. to the seventeenth century A.D. and combine both oriental and European observations. Features corresponding to the previously recognized Medieval Minimum, Medieval Maximum, and the Spörer Minimum are clearly evident in both oriental and European records. The global synchronicity of anomalies in the auroral occurrence frequency is used to argue that they are caused by changes in the level or state of solar activity. The combined catalogs provide a sufficient number of events in the Middle Ages to resolve a quasi-80-year periodicity in the recorded auroral occurrence frequency. Also in the unusually rich intervals of the Middle Ages, clear quasi-10-year periodicities appear in the recorded occurrence frequency wave form. These are most reasonably interpreted as manifestations of the 11-year solar cycle and indicate that the solar cycle was then operative.

Early Recognition of Long-Term Auroral Variations

In 1716, for virtually the first time, the Royal Society and the Académie des Sciences carried articles on the aurora borealis in their journals. Both societies were then a half century old. However, merely 34 years later the *Philosophical Transactions* had recorded 200 observations of aurorae, and the *Mémoires de l'Académie* a similar number. The reason for the late and simultaneous debut was the return of the aurora to the latitudes of London and Paris, in or near which most of the societies' members lived.

The auroral events of the year 1716 most clearly announced that the prolonged solar and auroral calm that we now call the Maunder Minimum [*Eddy,* 1976*a*] had ended. But the onset of renewed auroral activity was noted already in the previous solar cycle. In 1707 an aurora was seen in Berlin and recorded in the journal of the Berlin Academy. Curiously, in New England, which is closer to the auroral zone than is London, Paris, or Berlin, the aurora returned suddenly in 1719. Contemporary accounts put the first recorded appearance of an aurora in Italy in the 1720's.

The return of aurorae to low latitudes ushered in the birth of post-Renaissance auroral studies and caused early investigators to look on variability itself over time periods from decades to centuries as a characteristic of the aurora. The three men who reported on the renewal of auroral activity to the societies of London, Paris, and Berlin searched historical records for examples with which to compare it. Contemporary literature and memory provided no ready examples, although later searches would uncover a number of weaker displays.

In England the reporter was the astronomer Edmund Halley, who referred to several sixteenth-century displays. The previous comparable display in England that he found occurred more than 140 years earlier, in 1574. In France it was the astronomer Maraldi, who cited the 1621 exhibition made famous by descriptions of it in the works of Pierre Gassendi. The reporter in Germany was the philosopher-mathematician Gottfried Wilhelm von Leibnitz, whose researches into the historical behavior of the aurora [*von Leibnitz,* 1710] led him to the *Saxon Chronicles,* in which he found earlier evidence for long-term variability in records from the tenth century.

To gather data on the puzzling temporal variations of aurorae, the cause of which was itself the subject of widely divergent speculation at that time, many investigators began to observe and record auroral events systematically. Others turned to historical sources to extend the data record into the past. There soon resulted a number of catalogs, listing contemporary and historical aurorae. By the time that Jean Jacques Dortous de Mairan published his landmark treatise on the aurora in 1733, he had accumulated a sufficient record to draw two important conclusions: the auroral occurrence frequency had increased suddenly in 1716 and had remained essentially constant since then, and there were a number of times in the past when auroral occurrences had resumed after a long absence [*de Mairan,* 1733]. He identified 22 such instances in the interval 500 A.D. to 1731 and referred to them as resumptions (reprises).

The aurora continued frequently to visit the populated latitudes of Europe, and doubt soon was expressed that such regular behavior could ever have been very different. In the second edition of his treatise, published in 1754, de Mairan vigorously defended the reality of significant temporal variations in the auroral occurrence frequency and, in particular, the reality of the auroral calm preceding 1716. Doubt on the subject vanished when the aurora again went into decline for a period of about 33 years, between 1792 and 1826, at a time when careful, routine observations of it were being made in Europe and America.

The subsequent resumption of the phenomenon in 1827 stimulated new attempts to discover empirically the law governing its long-term returns and departures. Christopher Hansteen in 1831 inferred a 95-year period in the returns of the aurora [*Hansteen,* 1831]. His result was based on an identification of 24 such returns in an auroral record extending back to 502 B.C. Denison Olmsted in an 1856 article concluded that its great returns occur at intervals of from 60 to 65 years and last from 20 to 25 years [*Olmsted,* 1856].

The articles by Joseph Lovering [*Lovering,* 1860, 1868] and

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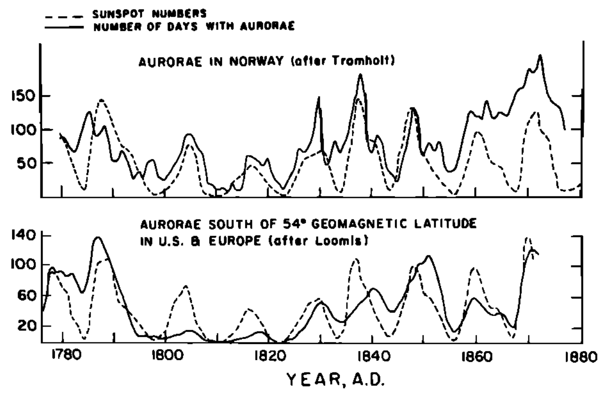

Fig. 1. (Top) The number of days per year on which aurorae were recorded in Norway. The figure was composed by *Harang* [1951] from data compiled by *Tromholt* [1902]. The panel relates to the region poleward of approximately 55° geomagnetic latitude. (Bottom) Similar data for events recorded in America and Europe equatorward of 54° geomagnetic latitude. The figure was composed by *Loomis* [1873].

the book by Hermann Fritz [*Fritz,* 1881] reviewed the subject thoroughly. Lovering demonstrated the close similarity between auroral variations recorded in Europe and in America. Fritz and Elias Loomis [*Loomis,* 1873] in the United States separately established that the variations in the frequency and intensity of the aurora conform closely to variations in solar spottedness. At this time the 11-year sunspot cycle recently had been recognized. Fritz advocated a 55.5-year period for the secular variation, a period that Rudolf Wolf had already inferred from his collection of sunspot data, composed of five of the 11-year sunspot cycles. The English astronomer John Herschel, commenting on the importance of the work of Wolf and Fritz, noted that the secular period of 55 years suits the auroral observations better than does the period of 65 years [*Herschel,* 1864]. Loomis favored a period of around 58 years.

In summary, prior to the twentieth century, long-term auroral variations were well established, and their investigation was an important subject under the general heading of auroral research. However, to the extent that the aim of the investigation was to determine the law of the variability it was not particularly successful. The 11-year variation was first discovered in the sunspot data, although it was then quickly found to be present in the auroral data also. The attempt to determine the period of the secular variation, which had yielded such a variety of results, was not long satisfied with the answer of 55.5 years. After further collection and examination of sunspot data, Wolf finally favored a secular period of 83 years, and a roughly 80-year period was subsequently assigned to the auroral data [*Schove,* 1955; *Gleissberg,* 1965; *Link,* 1968].

In addition to increasing the suggested period for the secular variation to roughly 80 years, twentieth-century research led to suggestions of variations characterized by longer periods, namely 200 years [*Schove,* 1955] and 400 years [*Link,* 1968]. Attributing to these variations the property of periodicity is, however, less warranted than in the case of the 80-year cycle. The number of events in the pre-eighteenth-century auroral record has continued to grow as the result of historical searches in the twentieth century with additions from eastern and western sources. At the present time the longest-term variations emerge as a clear signal simply by plotting the recorded auroral frequency as a function of time. There are now enough events in the aurorally rich intervals to see distinct 11-year cycles.

To appreciate the extent to which auroral variations reflect solar variations, it is useful to begin with a few post–Maunder Minimum examples, for which solar and auroral records can be compared directly.

THE POST–MAUNDER MINIMUM RECORD

Two independent attempts to demonstrate systematically the correspondence between aurora and sunspot variations are shown in Figure 1. The top panel displays auroral data from the Scandinavian sector north of 55° geographic latitude. Isopleths of auroral occurrence frequency (so-called isochasms) drawn on a globe of the earth form approximate circles centered roughly on the geomagnetic poles. Auroral data are therefore often expressed in terms of latitudes referenced to the geomagnetic poles, so-called geomagnetic latitudes. In the Scandinavian sector, 55° geographic latitude is also approximately 55° geomagnetic latitude.

The data from which the auroral curve in the lower panel was drawn were compiled by Loomis from events recorded in both Europe and America. To exclude high-latitude data, he correctly chose a line of constant auroral occurrence frequency connecting both continents as a northern boundary to the observations. He picked the isochasm passing through the northern border of Massachusetts, which is approximately the 54° geomagnetic parallel. The two panels in the figure therefore nicely complement each other, giving separately the temporal behavior of the occurrence frequency of high-latitude and mid-latitude aurorae.

One sees in both panels the unmistakable tendency of the auroral curves to conform to the 11-year and secular variations in the sunspot number curves. (The two sunspot number curves are slightly different because the top panel was constructed about 70 years after the bottom one and sunspot numbers continued to be refined in the interim.) The auroral curve in the lower panel reveals the 11-year cycle more distinctly. Also, the minimum in the secular variation centered around 1810 is more pronounced in it than in either the high-latitude auroral curve or the sunspot number curve. One notices that in the low-latitude auroral curve the amplitude of the secular variation in general exceeds that of the 11-year cycle.

The fact that the low-latitude auroral curve is smoother and its variations more distinct than the high-latitude curve might reflect an actual change in the behavior of the aurora as a function of latitude. More probably, it reflects the fact that a larger geographical area contributed to the low-latitude curve, and so it is less subject to aberrations resulting, for example, from year-to-year differences in regional cloudiness. Sensitivity of the number of aurorae recorded to regional influences probably also accounts for the fact that the auroral frequency curve presented by *Angot* [1897, p. 97], based on entries in the auroral catalog of *Fritz* [1873] from central Europe south of 55° latitude, reproduces the sunspot variations over the interval covered in Figure 1 less well than either curve shown there and even more poorly over the preceding portion of the eighteenth century. It should be noted, however, that Fritz was able to identify the 11-year maxima and minima in the auroral record over the entire interval on the basis of anecdotal material in the auroral accounts themselves. Such accounts include information on the brightness and animation of displays, which also undergo the 11-year oscillation.

Regional influences are clearly illustrated in Figure 2, which covers the interval from the end of that in Figure 1 up

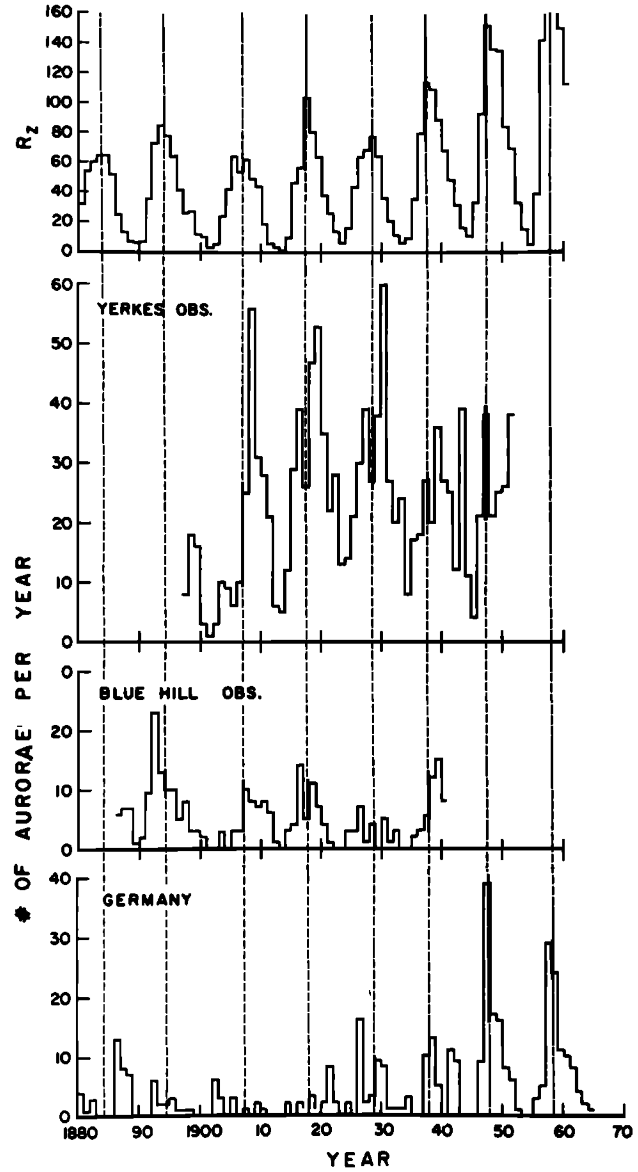

Fig. 2. Yearly average Wolf sunspot number (top panel) and the number of days per year on which aurorae were recorded at Yerkes Observatory [*Meinel et al.*, 1954], at Blue Hill Observatory [*Stetson and Brooks*, 1942], and in Germany [*Schröder*, 1972].

to 1965. The two observatory data panels show results obtained from systematic, routine observations from single locations. The observatories are very nearly on the same geomagnetic latitude. The much larger number of aurorae recorded at Yerkes Observatory is probably a consequence of the fact that the view northward from that site is uncontaminated by city lights, whereas Blue Hill Observatory is a few miles south of Boston. An eclectic catalog of unspecified sources of aurorae in Germany was used to construct the bottom data panel. It probably approximates more closely the usual type of catalog of past aurorae compiled from many sources.

Given only a single auroral data panel, one would see a suggestion of an 11-year cycle but be left in doubt about its permanence and stability. This is true even for the Yerkes Observatory record, which is certainly the best of the three, but the evidence for the first cycle and the last two cycles would not convince a critic who doubted the reality of a claimed persistent cycle. All three data records are needed to see that the cycle is in fact continuous.

In summary, both the 11-year cycle and the secular variation are detectable in time plots of auroral occurrence frequency. The occurrence frequency of aurorae seen south of 54° geomagnetic latitude appears to be more sensitive to the secular variation than the sunspot number itself. The solar-related time variations can be seen in data records from favorably located sites and countries, such as Yerkes Observatory and Norway, but more generally, regional influences will degrade the signal. The signal tends to improve with the size of the region contributing to it. Also, it is apparent from Figure 2 that a signal cannot be perceived over an interval in a record if the average auroral occurrence frequency in that interval falls below a certain number.

THE MAUNDER MINIMUM IN THE AURORAL RECORD

The imprint left by the Maunder Minimum in the auroral record has been described many times since the original articles appeared announcing the resumption of auroral activity in 1707 and 1716. The primary subject of the tenth *Eclaircissement* added by de Mairan to the second edition of his *Traité* is the documentation of the preceding auroral calm. Fritz repeats and augments this material in the fifth chapter of his book on the aurora. The two articles by Lovering mentioned above provide fully corroborative testimony from the annals of colonial America. The British and European data again were re-collected and supplemented in an article in the October 1886 issue of *The Edinburgh Review.* The auroral evidence for the Maunder Minimum had been well reviewed in these and other works prior to *Maunder*'s [1894] article. Nevertheless, his article provoked in the following issue a fresh, but brief, recounting of the concomitant auroral data by *Clerke* [1894]. In the present decade the vigorous revival of Maunder's claim led by Eddy has once more surfaced auroral information pertaining to that time period [*Eddy,* 1976*a*]. Also, the early colonial auroral record has again been resurveyed and discussed [*Mendillo and Keady,* 1976; *Eather,* 1980].

Except for the articles by Eddy the evidence advanced is anecdotal in form. The argument proceeds by comparing statements about auroral frequency, brilliance, and animation made by observers before, during, and after the interval in question. To complete the argument, the competence, veracity, and interest of the observers are established. To this reviewer the reality of the claimed interval of auroral calm has been effectively proven in this way, and the important next step is to quantify its duration and amplitude for comparison with other 'anomalous' intervals, such as the one centered around 1810. Space limitations prohibit recalling here all of the collected anecdotal material. A few examples are in order, however, to illustrate the main points that have been made.

The infrequency and feebleness of the general run of aurorae from the mid-1600's to 1716 is explicitly documented. That the abrupt onset of low-latitude aurorae forced Halley, von Leibnitz, and Maraldi to search historical records for examples for comparison has already been mentioned. *Maraldi* [1716] begins his article, 'We have observed a rare and curious phenomenon, which appeared in the month of April in this year 1716.' The German astronomer Gottfried Kirch, who also observed the 1707 event in Berlin, referred to it as an 'unusual manner of phenomenon' [*Kirch,* 1710]. The event prompted him and his son, Christfried, to begin a catalog of the aurorae that they observed. Twenty-nine years later it contained 106 entries, or an average of nearly four per year [*de Mairan,* 1754]. It contains no entries between 1707 and 1716. Christfried Kirch was further inspired by the peculiar temporal behavior of the phenomenon to compile one of the earliest catalogs of historical aurorae.

From the observatory at Paris the astronomer Giovanni Domenico Cassini had already detected the gap in the rings of Saturn that bears his name and four of its satellites before he discovered the zodiacal light in 1683 [*Cassini,* 1666–1699]. From that year he watched regularly for faint, dispersed luminosity in the heavens to add to the known phenomenology of such occurrences. He records possible auroral glows only on several nights in the summer of 1687. In the language of modern auroral descriptions they took the form of a quiet, homogeneous arc, stretched along and a little above the northern horizon, varying on different nights from feeble to very white in intensity. He compared his observations with the account of the 1621 display seen by Gassendi in southern France and described by him as being active. Cassini concluded that active aurorae must be 'a rare meteor.' (In old usage the word 'meteor' was a generic term whose scope is roughly captured in the broadest meaning of the word 'meteorology.') Cassini continued his work at the observatory until 1712 but reported no additional auroral occurrences.

It is perhaps justified to note here for comparison the remark made by Gregory of Tours late in the sixth century concerning the frequency of aurorae observed in that region of France, south of Paris: 'Portents appeared. Rays of light were seen in the northern sky, although, indeed, this happens often' [*Gregory of Tours,* 1974]. Still further south and closer in time to the commencement of the Maunder Minimum, auroral frequency and brilliance in Italy were such that Mario Guiducci, in a discourse delivered to the Florentine Academy in 1619, could refer to them in introducing the subject of the aurora, 'And I know, Academicians, that many of you will have seen more than once the sky at nighttime illuminated in its northern parts in such a way that its brightness yields nothing to the brightest dawn and closely rivals the sun' [*Guiducci,* 1960]. Guiducci's statement (probably written by Galileo) appears unremarkable when compared with the post–Maunder Minimum situation in which at least 52 aurorae were observed in Italy in the 24 years after 1727 [*Lovering,* 1860]. In describing an aurora seen in Italy in 1737, *Zanotti* [1738] says: 'The Aurora Borealis, which was formerly a rare phenomenon, and almost unknown in our climate, is now become very frequent.'

Assertions of high auroral frequency stand in marked contrast to the statements of Cassini, Kirch, and Maraldi and to an introductory comment made by Halley in his article on the aurora of 1716 [*Halley,* 1716]. He referred there to the auroral phenomenon as 'a matter so uncommon, never before seen by my self.' Halley was at this time 60 years of age and possessed an astronomer's interest in night sky happenings, both meteorological and astronomical. He declared that of 'all the several sorts of meteors I remember to have hitherto heard or read of, this was the only one I had not as yet seen, and of which I began to despair.'

Halley's remark raises the question of the preparedness of the observers of that time to recognize and record in scientific terms an aurora if one should occur. It is notorious that people often fail to see or respond to that for which they are unprepared. However, the general scientific education in post-Renaissance Europe and Britain, and in colonial America included actually more information on auroral phenomena than does such an education today. The reason is that the subject of meteorology was then an integral part of a scientific education, and in a tradition beginning with Aristotle, treatments of meteorology invariably discussed igneous or fiery meteors, in which the many species of aurorae were enumerated. For example, the second book of Gassendi's *Physicks* [*Gassendi,* 1658], a standard textbook during the last half of the seventeenth century, was devoted to meteors generally, and the seventh chapter to the aurora borealis exclusively.

The most popular book on meteorology in the English language in the seventeenth century was written by William Fulke, Doctor of Divinity (who was unfortunately referred to by Halley merely as W.F.D.D. and so has since gone unnamed in auroral literature). The full title of his book [*Fulke,* 1571] is so long that this excuse for not quoting it here uses fewer words by more than half than are in the title itself. It is sometimes referred to by the first three words in the title, '*A Goodly Gallerye.*' It was first printed in 1571 with subsequent editions in 1634, 1639, 1640, 1654 (the edition referred to by Halley), 1655, and 1670. It has thus gone through more editions than probably any other book in English on meteorology up to the present time. After an introductory section discussing causes the book begins with a description of 10 different species of aurorae, among them, in modern terminology, homogeneous bands, rays, corona, pulsating patches, flaming aurora, and fragmentary arcs.

Students at Harvard College in the seventeenth century also studied Gassendi and, in addition, Charles Morton's *Compendium Physicae,* which was compiled around 1680 [*Morton,* 1940]. Morton was educated at Oxford at the time of the formation of the Oxford Philosophical Society (1648–1649), the nucleus from which the Royal Society emerged in 1662. The contents of the *Compendium Physicae* therefore reflect a curriculum approved by the highest level of scientific authority at that time. When the book turns inevitably to the subject of meteorology, we see again the prominence of auroral phenomena in the chapter headings: Chapter 12, Of Fiery Meteors; Chapter 13, Of Comets; Chapter 14, Of Aery Meteors (i.e., winds, etc.); Chapter 15, Of Watery Meteors; and Chapter 16, Of Appearing Meteors (e.g., halos and rainbows). The chapter on fiery meteors includes descriptions of homogeneous bands and rayed arcs (modern terminology).

It is evident that the paucity of auroral reports during the Maunder Minimum does not reflect a lack of a familiar precedent. All of the early reports after the resumption of displays referred to Gassendi's account. Nor does it reflect a lack of available descriptive categories, although it is true that by the time of the resumption the available categories seemed old-fashioned and new ones were soon invented. Also, bear in mind that the Maunder Minimum occurred at a time of rapidly growing scientific curiosity about natural phenomena and at a time when the means had been established for simply publishing such a thing as an auroral observation. The flood of published auroral accounts following 1716 is a measure of the level to which general scientific interest and the accessibility of publication outlets had risen by the time of the resumption.

The evidence related above refers to latitudes below 55° and thus to the region that we have seen is particularly sensitive to the secular variation. To obtain a truer sounding of the depth of auroral minimum, data from latitudes closer to the auroral zone must be examined. Unfortunately, the informa-

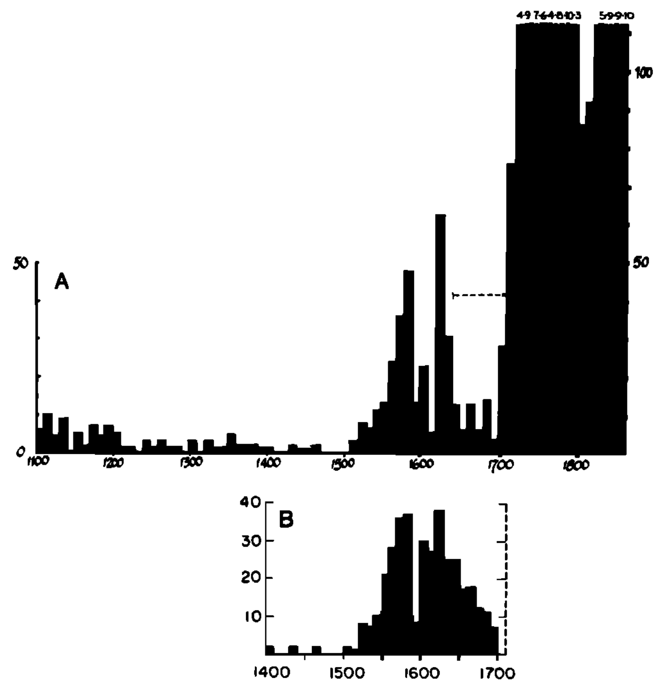

Fig. 3. (*a*) Data field composed by *Eddy* [1976*a*] from the auroral catalog of *Fritz* [1873] showing the number of days on which aurorae were recorded per decade in Europe south of the polar circle. The interval shown includes the Maunder Minimum, which appears as a gap in a curve that rises steeply from a low, pre-Renaissance to a high, post-Renaissance level. (*b*) Data field showing the number of aurorae per decade contained in the more recent compilation of *Link* [1964]. The attenuated auroral occurrence frequency during the Maunder Minimum is evident in this data set also.

tion thus far uncovered on seventeenth-century aurorae from these high latitudes is fairly scarce. However, de Mairan cites two important sources that point unequivocally to a diminished auroral presence in the northern regions prior to 1716. Anders Celsius, Swedish astronomer and inventer of the centigrade thermometer, was 15 years old at the time of the grand display of 1716. He began a catalog of aurorae observed in Sweden, which he extended back to 1706 and continued to 1732, at which time it contained 316 entries. He learned from old men living in Uppsala that the aurorae, which were frequent in Sweden after 1716, were novel to them. On the basis of his attempts to extend the auroral record backward he argued explicitly for the existence of a prolonged auroral calm in Sweden prior to 1716.

De Mairan's second source is a book by Johann Anderson on the natural history of Iceland published in 1746, in which the author states, 'It has always appeared extraordinary to me that the most ancient Icelanders, as they have assured me, should have been astonished themselves at the frequent appearance of the aurora in their island [that Anderson had witnessed for some time beginning in 1730], declaring that formerly they were much less common than today.' Other eighteenth-century authors (Torfaeus and Pontoppidan) are quoted by de Mairan and Fritz to show that brilliant displays were sufficiently rare in the latter half of the seventeenth century in Iceland and Norway as to cause general alarm and to be taken as prodigies.

Aurorae were not altogether absent during the Maunder Minimum either at low or at high latitudes. De Mairan himself lists 60 occurrences between 1645 and 1698 in the extended catalog included in the second edition of his treatise. There may even have been a high-latitude band of restricted latitudinal extent in which aurorae were fairly common. This interesting and important possibility comes to light in the account of the voyage of Captain Jean Wood to Norway and Novaya Zemlya in 1676 [*Wood*, 1705]. He states there that aurorae were frequently seen in Greenland and only occasionally in Iceland and Norway. In addition, Fritz quotes the author of a book on Greenland fisheries, who during the greatest depth of the auroral minimum as seen at mid-latitudes (see discussion below) wrote that 'The northern lights shine alone only for those who live in the region of the arctic circle.'

Eddy has largely led the effort to break away from reliance on purely anecdotal material and to quantify the Maunder Minimum as a temporal feature in physical solar-terrestrial parameters. With regard to the auroral data, which are our interest here, he has presented a plot of the number of reported northern hemisphere aurorae per decade south of 60° latitude listed in the catalog of *Fritz* [1873]. The plot, reproduced here as Figure 3*a*, shows the Maunder Minimum as a deep recession in a rapidly (on a scale of centuries) rising curve, whose general sweep traces the progress of printing and scientific enquiry from the Middle Ages to recent times. Other actual solar features lie half hidden in the curve prior to 1500, and we will return to these in the next section.

The catalog of Fritz has been criticized for containing a number of inaccurate entries. Two more recent and more accurate catalogs have been compiled by *Link* [1962, 1964]. The first covers the interval 626 B.C. to 1600 A.D., and the second continues to 1700 A.D. Reports per decade from 1400 to 1700 based on the Link catalogs are shown in Figure 3*b*. Although details in the two curves are different, the main features are the same. In particular, the auroral calm coincident with the Maunder Minimum is evident in both cases. The Link curve suggests that the minimum was deepest just prior to 1700. This agrees also with Fritz's expressed opinion on the variation of auroral activity through the seventeenth century [*Fritz*, 1881, p. 133], although it is not so apparent in the curve based on his catalog.

We will touch only briefly on the question of the continuation of the 11-year sunspot cycle through the Maunder Minimum. Both Maunder and Eddy point to the weak data base supporting the identification of maxima and minima corresponding to the 11-year cycle during this time. Such identifications had been made by Wolf on the basis of available sunspot data, by Fritz using auroral data, and again more recently by *Schove* [1955] on the basis of auroral data. Nevertheless, the point was correctly made that because of the small sample size the assignments of maxima and minima presumed the existence of the cycle, whereas the very existence of the cycle itself was an important question.

Subsequent to *Eddy*'s [1976*a*] article, Schove reexamined the data from the seventeenth century, using in part Link's catalog, and published [*Schove*, 1980] a revised list of 11-year maxima and minima, which again extends through the Maunder Minimum. *Link* [1978] also has prepared such a list giving the 11-year cycle maxima from 1610 to 1712 without a gap. His assignments are based on sudden changes in the frequency of reports recorded in his catalog (see also *Link* [1977]). In addition, *Vitinsky* [1978] and *Gleissberg* [1977] argue for the persistence of the 11-year cycle through the Maunder Minimum.

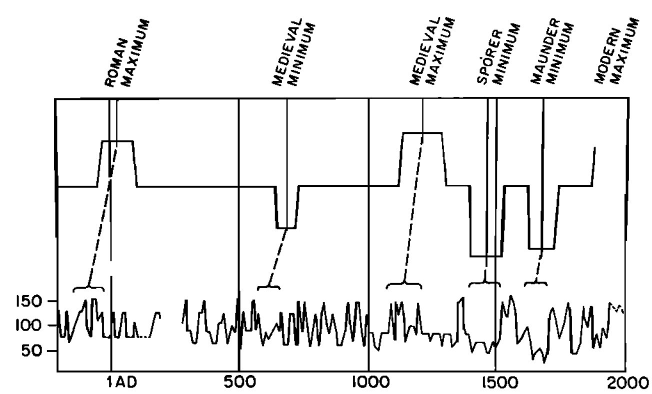

Fig. 4. Two quasi-quantitative profiles giving approximate simulations of the secular variation in the level of solar activity. The top profile was derived on the basis of ^{14}C anomalies in tree rings [*Eddy,* 1976*b*]. The bottom profile was derived from historical accounts of auroral and naked-eye sunspot observations [*Schove,* 1955]. Apparent correspondences between the main features are indicated.

THE PRE-MAUNDER MINIMUM RECORD

The northern lights, along with comets, meteor showers, bolides, and other heavenly and aerial wonders, are mentioned in extant histories, annals, and chronologies dating back to the time of imperial Rome. These draw upon even earlier sources, now lost, to extend the record of dated auroral displays in the western hemisphere to the fifth century B.C. The first catalogs devoted specifically to ancient aurorae were compiled shortly after the end of the Maunder Minimum, as was noted above. By the time that Fritz published his catalog in 1873, he could refer to at least eight prior catalogs that listed events predating the Maunder Minimum. Fritz's catalog contains over 400 possible pre-seventeenth-century auroral occurrences.

In his book on the aurora, published 8 years after the catalog, Fritz identified specific features in the secular variation. The sixth, tenth, twelfth, and sixteenth centuries he described as being aurorally rich and the seventh, eleventh, thirteenth, fifteenth, and seventeenth centuries as being aurorally deficient. As will be seen below, these designations are preserved with few changes in the most recent compilations. They are, however, now better resolved as temporal features and in terms of their relative amplitudes.

In the present century, Schove has made additions to the record of historical aurorae. He combined these and the previous listings with Chinese records of aurorae and naked-eye sunspots to construct an impressionistic representation of the variation in the amplitude of the solar sunspot cycle from classical Greek and Roman to recent times [*Schove,* 1955]. To make the representation, he assigned to each 11-year solar cycle, the series of which had first to be identified, a number corresponding to the maximum annual mean sunspot number for the cycle. The assigned number was, of course, not absolutely calibrated. On the basis of the indicators of solar activity available for a given cycle the cycle was indexed on a nine-point scale, from extremely weak to extremely strong. To this nine-point index there was a corresponding fixed scale of nine annual mean sunspot numbers, extending from 45 or less to 160 or greater. The procedure, though subjective, was nevertheless an initial step toward quantifying the historical data base. It thus allowed one to display graphically the kinds of variations underlying the conclusions on the secular variation that many investigators had made since the time of de Mairan. In comparison to the results based on pure number counts of aurorae described below, Schove's procedure had at least in principle the advantage of incorporating information on the degree of animation of the displays and on their geographical extent for the purpose of determining the general level of solar activity. However, for the advantage to have been realized fully the algorithm for converting the total amount of available information quantitatively into a suitable index would have had to have been specified.

The profile of solar activity thus derived by Schove is shown in Figure 4, together with the solar activity profile inferred by *Eddy* [1976*a, b*] on the basis of ^{14}C anomalies in tree rings. We see in the profile by Schove many of the features identified by Fritz. Prolonged minima are evident in the seventh, fifteenth, and seventeenth centuries, and there are prolonged maxima in the twelfth and sixteenth centuries. The other features noted by Fritz are not as clearly defined. The profile also shows an isolated maximum in the fourteenth century, which appears again as a distinct and interesting feature in more recent compilations described below.

The ^{14}C profile has coarser resolution than the auroral curve. As a 'low-pass' filter it has the advantage of being sensitive mainly to the more enduring excursions of solar activity. Five such excursions are indicated. It is not difficult to find correspondences between the two profiles, as noted specifically in the figure. They are most evident in the more recent features. There is a decided tendency, especially in the earlier events, for a feature in the auroral profile to be older than its ^{14}C counterpart. This might indicate that the times of the excursions were not sufficiently compensated for the temporal sluggishness of the natural process by which variations in solar activity become encoded in the ^{14}C record [*Eddy,* 1976*b*]. In any event, the comparison suggests that the auroral record, particularly in its most recent, high-resolution form, could be of use in determining the proper dates to assign to specific ^{14}C features.

In the last two decades, seven new catalogs of historical au-

TABLE 1. Recently Compiled Catalogs of Ancient Aurorae

Catalog Compiler	Date of Publication	Areal Coverage	Temporal Coverage	Number of Entries
Link	1962	Europe	626 B.C. to 1600 A.D.	385
Link	1964	Europe	1600–1700 A.D.	209
Stothers	1979*a*	Greece and Italy	480 B.C. to 333 A.D.	67
Newton	1972	Europe	450–1263 A.D.	65
Dall'Olmo	1979	Europe	450–1461 A.D.	61
Keimatsu	1976	China, Korea, and Japan	687 B.C. to 1600 A.D.	260*
Matsushita	1956	Japan	620–1909 A.D.	18*

*Listed as probable to certain in the assessment of the compiler.

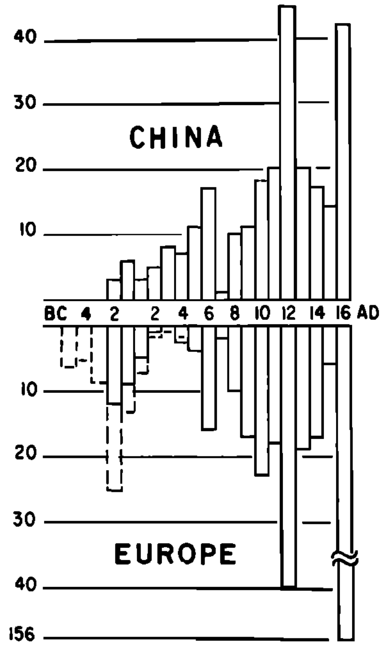

Fig. 5. The number of days per century on which aurorae were recorded in the orient and in Europe (figure modified from *Keimatsu* [1976]). Oriental aurorae are from the catalog of *Keimatsu* [1976], and European aurorae are from the catalogs of *Link* [1962] (solid line) and *Stothers* [1979*a*] (dashed line).

rorae have appeared (see Table 1). The two by *Link* [1962, 1964], as mentioned earlier, cover the intervals 626 B.C. to 1600 A.D. and 1600–1700 A.D. The first contains 385 entries, and the second 209. *Newton* [1972] lists 65 displays from the interval 450–1263 A.D. *Dall'Olmo* [1979] furnishes an additional 61 occurrences between 450 and 1466 A.D. Sixty-seven aurorae recorded in times of classical Greece and Rome, from 480 B.C. to 333 A.D., are given in a catalog compiled by *Stothers* [1979*a*]. These catalogs record western or near-eastern aurorae. Eastern aurorae are listed in a seven-part catalog by *Keimatsu* [1976] covering the period 687 B.C. to 1600 A.D. and containing a total of 578 auroral entries. Of these, only 258 are assigned by the author a reliability rating of 'probable,' 'very probable,' or 'certain.' The entries in the *Matsushita* [1956] catalog of aurorae seen in Japan are incorporated into the Keimatsu catalog up to 1600 A.D. The Matsushita catalog, however, extends to 1909 A.D. and includes events within the Maunder Minimum.

It was concluded in the first part of this review that, in general, inferences drawn from auroral occurrence frequency data become more trustworthy as the areal extent of the data base is enlarged. The influence on the record of historical and climatic accidents diminishes as the geographical region contributing to the record increases. For this reason the comparison between eastern and western (recorded) auroral occurrence frequency presented by *Keimatsu* [1976] is especially interesting. The comparison is reproduced here in Figure 5, to which has been added Classical Age aurorae from the catalog of Stothers. Link's first catalog was used to obtain the data on the other European aurorae. Events rated probable or better in Keimatsu's catalog compose the China data field.

The figure shows a histogram of the number of aurorae recorded per century in Europe and in China from the second century B.C. to the sixteenth century A.D. The inclusion of the entries in Stother's catalog extends the European data field back to the fifth century B.C.

The histogram exhibits marked variations from century to century. The most likely candidates for the causes of these variations are changes in the level of solar activity, changes in social-political history, and changes in terrestrial magnetism or in climate. Even without reference to correlative data it is possible to make a reasonably strong case that at least the major isolated fluctuations in the histogram are the result of changes in the level of solar activity. The argument proceeds by the systematic elimination of the other possibilities.

As far as influences on the auroral record are concerned, the social-political histories of China and Europe throughout this period are essentially independent. It is true that both regions were approximately simultaneously affected by two episodes of invasions of nomads from the Asian steppes and Mongolia. However, the disruptions that they caused peaked in the fifth and thirteenth centuries, which do not coincide with notable features in the figure. We therefore conclude that the pronounced fluctuations occurring simultaneously in both regions, recognizable in Figure 5 as mirror-image anomalies in the histogram pattern, are not the result of changing conditions in social-political history.

A change in the strength or the direction of the geomagnetic dipole will alter the frequency of aurorae seen within a given geographical region. The dipole strength is known from archeomagnetic data to have performed a quasi-sinusoidal oscillation with a period of roughly 8000 years, which peaked in the fifth century A.D. at a value approximately 50% greater than that at present [*Cox,* 1969]. It is clear that the time scale for this variation is too long to account for four significant fluctuations, including both maxima and minima, over a time span of one millennium.

The change in auroral occurrence frequency at a given site caused by a migration of the geomagnetic pole can be profound. To illustrate this, imagine the pole with the presently existing pattern of auroral isochasms rigidly attached to it to move continually and uniformly along the geographic latitude circle that runs through its present position. As the pole successively passes through the meridian and the antimeridian of the given site, maxima and minima are successively recorded in the auroral occurrence frequency. The range of the auroral occurrence frequency produced in this way depends only on the geographic latitude of the site. For example, at 50° geographic latitude, roughly the latitude of London, Paris, Berlin, and the U.S.-Canadian border, the average number of auroral nights per year would range from less than one to approximately 50. At 40°, roughly the latitude of Washington, D. C., Madrid, Athens, and Peking, the number would range from less than one in 10 years to about eight per year. The range is nearly 2 orders of magnitude in each example. (The occurrence frequencies quoted here are based on the isochasms given by *Fritz* [1881].)

Polar migration could easily account for the magnitude of the marked changes in the number of aurorae recorded from century to century. Nevertheless, the in-phase synchronism of eastern and western fluctuations eliminates polar migration as the cause of these particular variations. Furthermore, studies of polar migration allow one to conclude that the time required to complete a full cycle exceeds the time between consecutive positive or negative anomalies in the auroral occurrence frequency histogram [*Keimatsu et al.,* 1968; *Barbetti,* 1977].

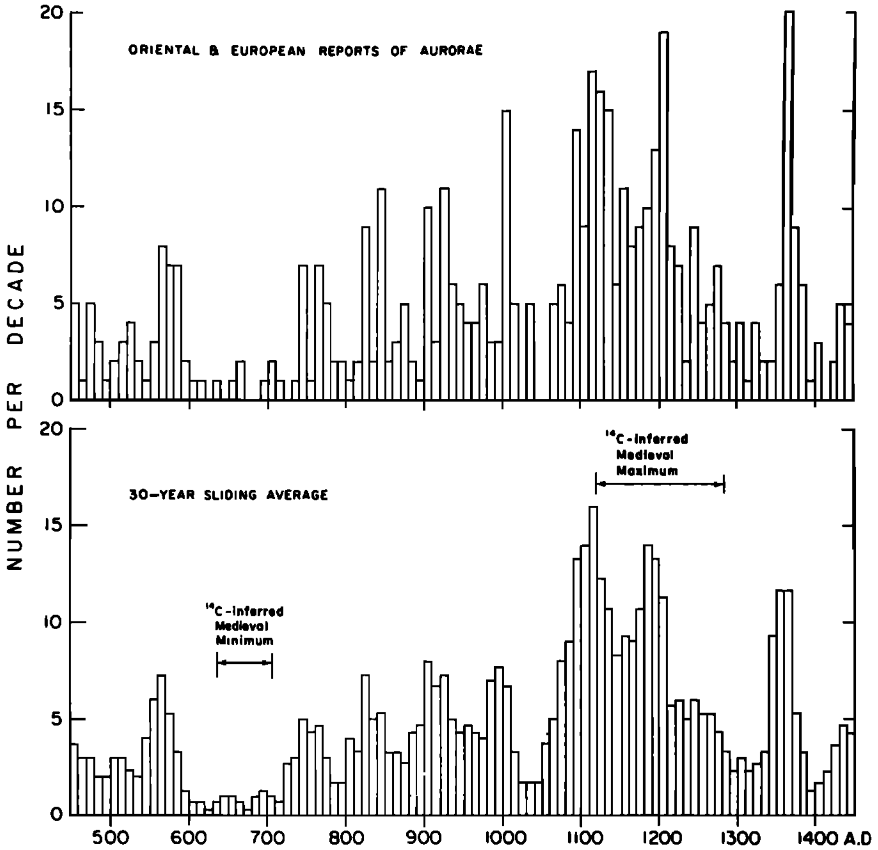

Fig. 6. The number of days on which aurorae were recorded per decade in the Middle Ages as compiled by *Link* [1962], *Newton* [1972], *Dall'Olmo* [1979], and *Keimatsu* [1976]. The bottom panel consists of three-decade sliding averages of the data given in the top panel.

Climatic variability is the remaining alternative to solar variability to explain the anomalies in the 'global' occurrence frequency of aurorae. Several kinds of evidence argue against this possibility. If the Maunder Minimum is considered to be representative of anomalous epochs, then the climate explanation is eliminated by the mass of data and testimonies that have established this as an epoch of greatly attenuated solar activity. Furthermore, although the Medieval Maximum in the auroral record coincides with a climatic optimum in Europe, it coincides with a period of climatic deterioration in China [*Chu,* 1973]. Yet a strong auroral maximum is indicated from both regions.

Consider next the specific features in the histogram in Figure 5. The mirror-image anomalies identify the sixth, twelfth, and sixteenth centuries as being relatively aurora rich and the seventh and fifteenth centuries as being relatively aurora poor. These agree in the main with the special periods called out by Fritz and Schove, but now, in effect, they are confirmed with an extended data set. Comparison with Eddy's ^{14}C solar activity profile leads one to associate the seventh-century depletion with the Medieval Minimum, the twelfth-century surplus with the Medieval Maximum, and the fifteenth-century decrease with the Spörer Minimum. Although there are no features indicated in the ^{14}C profile of Figure 4 corresponding to the relative auroral excesses in the sixth and sixteenth centuries, *Stuiver and Quay* [1980] report a ^{14}C tree ring study that reveals an increase in solar activity after 1530, with a maximum in the interval 1590–1620.

With regard to the suggested Roman Maximum we see in Figure 5 a repeat of the situation presented in Figure 4. If there is a corresponding maximum in the auroral data, it took place in the first or, more probably, the second century B.C. In this case, however, the data from China do not lend support to such a conclusion. Stothers also is careful to point out that one cannot be certain whether the variations in the recorded auroral occurrence frequency in southern Europe for this period result from plausible historical causes or from natural causes.

The time periods covered by the seven recent auroral catalogs overlap maximally in the 1000-year interval between 450 and 1450 A.D., which is essentially the period designated as the Middle Ages. By combining the independent listings from all catalogs one can increase the temporal resolution of the auroral secular variation in this period. The top panel in Figure 6 achieves a factor of 10 increase in resolution over that in Figure 5. One sees a tendency for anomalies to cluster and for changes from decade to decade to be coherent. The general aspect of the figure suggests a spectral component to the secular variation lying between 10 and 100 years. The bottom panel of the figure shows 30-year resolution obtained by a sliding average of the number-per-decade values given in the top panel. Both the less-than-one-per-century and the greater-than-one-per-century components of the secular variation are well revealed. This resolution is perhaps an optimum for the given number of events in the interval.

The two medieval features in the ^{14}C solar activity profile are indicated in the bottom panel. The temporal shapes of the corresponding features in the auroral record are quite sharply defined. In view of the fact that changes in solar activity as recorded in the form of ^{14}C anomalies in tree rings are low-pass-

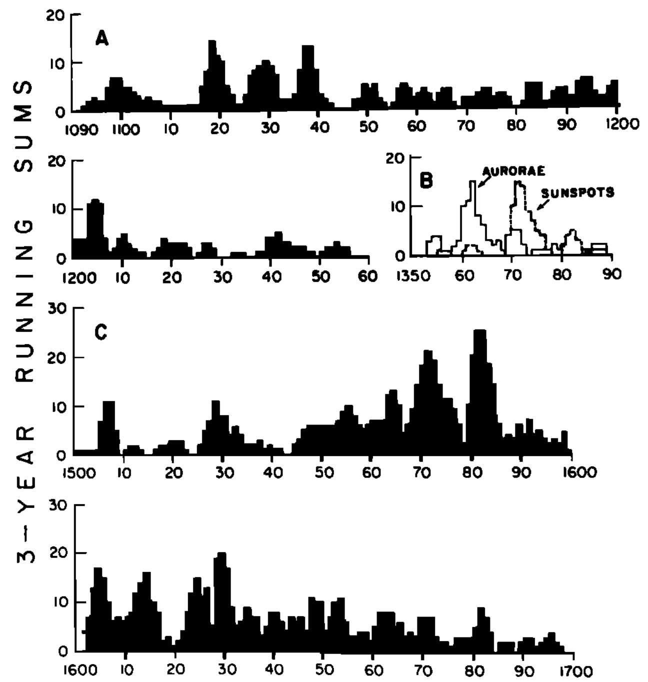

Fig. 7. (*a, b*) The number of days on which aurorae were recorded per 3 years, determined yearly, for the aurorally rich periods evident in Figure 6. (*c*) The interval from 1500 to 1700 A.D., compiled from the entries in the catalogs of *Link* [1962, 1964]. The sunspot data used to construct Figure 7*b* were taken from the catalog of *Clark and Stephenson* [1978].

filtered and delayed by the buffering action of the atmosphere, the auroral record probably locates the events more accurately in time. In the auroral record the Medieval Minimum extends from 590 to 720, and the Medieval Maximum from 1090 to 1210. Both of the aurorally anomalous intervals begin 30–40 years before the corresponding intervals designated by Eddy on the basis of the ^{14}C record. However, a more recent analysis of ^{14}C tree ring data finds a drastic increase in solar activity from 1070 to 1100, with the maximum extending from 1100 to 1150, declining thereafter to a minimum around 1280 [*Stuiver and Quay*, 1980]. With the exception of a second maximum near 1180 the auroral record conforms very closely to this determination.

The more rapid semiregular oscillations evident in the figure have an average cycle period of 87 years if one replaces the missing cycle in the Medieval Minimum and counts the suggestion of a cycle in the thirteenth century. *Link* [1968] identified virtually the same features on the basis of his catalog of western aurorae alone. He associated them with the quasi-80-year periodicity that had been described previously as operating back through the Middle Ages [*Schove*, 1955; *Gleissberg*, 1965].

In addition to the quasi-80-year oscillation, Link recognizes a quasi-400-year periodicity. He attributes the seventh-century Medieval Minimum, the deep, unnamed eleventh-century minimum, the fifteenth-century Spörer Minimum, and the twelfth-century Medieval Maximum to its control.

Finally, the largest feature in the top panel of the figure deserves special mention. Although the 1360 peak conforms to the expected maximum in the 80-year cycle, it differs from the other peaks in its amplitude and its isolation. It is a conspicuous anomaly also in the previous, graphically displayed summaries of secular auroral variations [*Schove*, 1955; *Link*, 1968]. Associated anomalies in correlative data add to its significance. The greatest cluster of pretelescopic, oriental sunspot observations bears a remarkable association with it, as is described below. Recent analysis of ^{14}C anomalies in tree rings from this age revealed a pronounced, well-defined decrease, corresponding to a solar activity maximum. The decrease reached a maximum in the decade of 1370 [*Stuiver and Quay*, 1980]. The combined auroral, sunspot, and ^{14}C aberrations certify the event as a genuine manifestation of a fluctuation in the level of solar activity. If one then accepts the assertion that this event is but an example of the general class of maxima that occur approximately every 80 years, this example perhaps differing from the others in magnitude but not in essence, it follows that the 80-year auroral cycle evident here is a manifestation of solar variability.

A higher temporal magnification is possible in the aurorally rich intervals, namely, the Medieval Maximum, the 1360–1370 event, and the interval between the Spörer and Maunder minimums. Figure 7 shows these at a resolution of 3 years.

The apex of the first 80-year cycle in the Medieval Maximum is resolved into three peaks spaced approximately 10 years apart. These are most reasonably interpreted as auroral expressions of the 11-year sunspot cycle. The crest at 1100 appears at the expected position if the series is continued backward in time, with one cycle missing. *Schove* [1955] locates the maxima in these cycles and the missing or weak cycle exactly as they appear here.

Although the peak at 1205, corresponding to the second 80-year cycle in the Medieval Maximum, resembles the earlier ones from the previous 80-year cycle in width and rise, it is isolated, which precludes identifying it with the 11-year cycle on the basis of an evident periodicity in the occurrence frequency.

The change in character from a signal with a clearly defined quasi-10-year cycle to an irregular signal raises the question whether the sunspot cycle was intermittent in this interval. We have simulated signals in which the probability of occurrence of an event is proportional to the absolute value or to the square of a sine wave with an 11-year period. The simulation was performed for situations in which the average number of events per cycle was 5, 10, 15, and 20. Wave forms composed of 3-year running sums were compiled, conforming to the procedure used to construct Figure 7.

In the case where the occurrence probability function is proportional to the absolute value of a sine wave, more than an average of 20 events per cycle is required to perceive a distinct periodicity in the wave form. However, it is clear from Figures 1, 2, and 7 that the probability function is usually more sharply peaked than a sine wave. In the case of the sine-squared probability function a distinct periodic pattern emerges between 15 and 20 events per cycle on average. At an average of 10 events per cycle the simulated signal resembles very closely that seen in Figure 7 between 1150 and 1200 A.D. Reference to Figure 6 reveals that the recorded occurrence frequency was about 15 per cycle in the interval displaying the periodicity, but it was about 10 per cycle or less when no distinct peaks were recorded.

On the basis of the simulations a simple explanation for the apparent change from periodic to irregular character of the recorded auroral occurrence frequency is that there is a threshold in the average occurrence frequency that must be exceeded before the underlying periodicity in the signal can be perceived. The secular variation of solar activity including the

80-year cycle modulates the average number of aurorae that are recorded during the 11-year cycle. For the number of presently known aurorae recorded during the Middle Ages the secular modulation carries the average auroral occurrence frequency across the threshold during the most aurorally rich intervals.

That the threshold of detection of periodicity has evidently been crossed for significant periods during the Middle Ages should serve as an incentive and a justification to carry out further, systematic searches for historical auroral recordings. As an example, doubling the number of known aurorae recorded in the Middle Ages would possibly expose the complete wave form of the 11-year, 80-year, and longer-term variations for this 1000-year interval. It should be noted that *Stothers* [1979*b*] was able to infer the presence of the 11-year cycle of solar activity during the aurorally rich second century B.C. on the basis of his catalog of aurorae from classical antiquity.

Returning now to Figure 7*b*, we encounter a very curious association between the auroral record and the pretelescopic, oriental sunspot record, presented recently by *Clark and Stephenson* [1978]. It was noted earlier that the decade of 1360 possesses the largest number of recorded aurorae of all the decades in the Middle Ages. The Clark and Stephenson catalog contains 139 entries. These cover the interval 28 B.C. to 1604 A.D., giving an average of less than one per decade. While the sunspot catalog contains two entries in the aurorally rich 1360's, there are 23 entries in the following decade. The next largest number of entries per decade in the catalog is nine. The auroral and sunspot occurrence frequency profiles in Figure 7 each show the distinctive fast rise, slow decay shape characteristic of the 11-year solar activity cycle. However, the peaks in the two profiles are separated by one cycle. More important than the asynchronism in the two records is the direct evidence here for the operation of the 11-year solar cycle in yet another portion of the Middle Ages.

The bottom panel in Figure 7 covers the interval from the last two decades of the Spörer Minimum to nearly the end of the Maunder Minimum. It therefore includes the aurorally rich epoch separating the two minima. Essentially the same figure has been published by *Link* [1978], who presented it as evidence that the 11-year solar cycle operated prior to the Maunder Minimum. As in the top panel, one sees a tendency for the periodicity to become evident at times when the auroral occurrence frequency averaged over a solar cycle is high. The signal is indistinct at times when the average is low, as during the Maunder Minimum. However, the first three decades of the Maunder Minimum, the 1640's, 1650's, and 1660's, possess 25, 17, and 18 recorded events. The absence of a clear periodicity in this interval could reflect a change toward a less peaked wave shape, such as is typified by the absolute sine function.

SUMMARY AND PROSPECTUS

The secular variation in the level of auroral activity has been known since the early 1700's. Its main features have been progressively better resolved since then through a tradition of historical auroral research. The auroral record has now evolved to the point where the features that have been identified in the ^{14}C record stand as distinctive, highly resolved, major departures from an apparently stable, longer-term average. The principal deviations include the Medieval Minimum and Medieval Maximum and the Spörer and Maunder Minimums. The synchronicity of the anomalies in eastern and western records, as well as their correspondence to anomalies in the ^{14}C record, establishes that they are sympathetic responses to secular variations in the level or state of solar activity.

The solar cause of a briefer excursion around 1360 A.D. is similarly established. Its evident membership in a genus of like anomalies that recur on an average of 87 years in the Medieval auroral record implicates a solar cause for the entire genus and at the same time exposes a consonant periodicity in solar activity itself.

The temporal profile of the auroral occurrence frequency exhibits a quasi-10-year periodicity during aurorally rich intervals within the Middle Ages and the Renaissance. The pattern and the period of this signal conform to that produced in modern times by the 11-year solar activity cycle. The absence of a periodic signal at other times is most conservatively attributed to a lack of sufficient events in the record to make manifest such a signal.

The auroral record has proven itself to be a valuable data source for the investigation of the secular variation of solar activity. Significantly more information could be extracted from this source if further systematic historical research were to double approximately the number of events in the record prior to 1700. It is possible that a good representation of the last 2000 years of variations in solar activity at a resolution that includes the 11-year cycle could be achieved in this way.

More effort needs to be expended on converting the kind of information available in the auroral record to information about the level or condition of solar activity. Historical auroral information includes the secular variation of the auroral occurrence frequency that this review has emphasized and also the equatorward extent, the intensity and the degree of

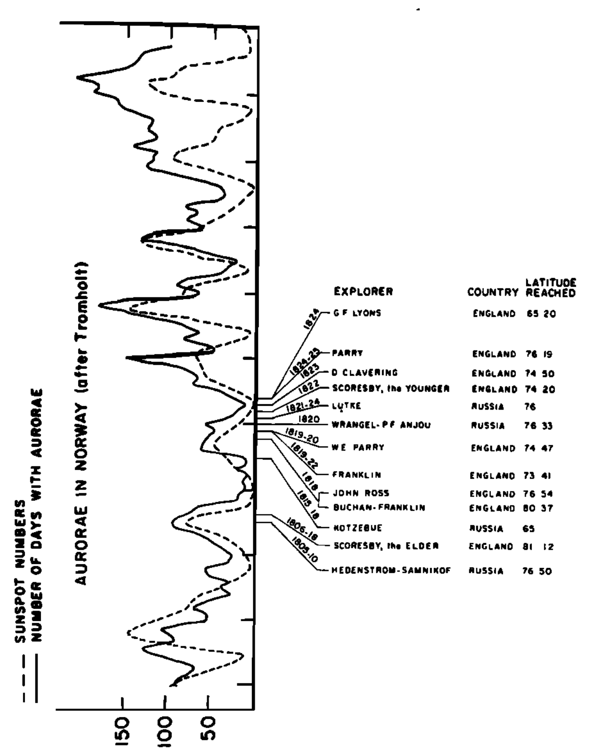

Fig. 8. Principal expeditions in search of northeast and northwest passages to China that sailed during the auroral calm of the early nineteenth century.

animation of displays, the categories of aurorae seen, and possibly in some time intervals the location and size of the auroral zones. From these types of data, the permissible inferences regarding the magnetosphere, the solar wind, and the sun must be determined.

Historical studies focused on times of specific anomalies of solar activity could be particularly valuable. The recent, post-Maunder Minimum auroral calm centered around 1810 can be used to illustrate the point. This event occurred at a time when systematic auroral catalogs were being made by individuals in Europe and America [e.g., *Dalton*, 1834; *Lovering*, 1860]. The event itself is well established as a solar activity anomaly by both the sunspot and the auroral record. In this interval, solar-terrestrial phenomenology departed remarkably from that with which we have direct acquaintance.

Polar exploration aimed at finding northeast and northwest passages to China was in full flower in the early nineteenth century. Figure 8 gives a list of the principal expeditions that sailed during the depth of the auroral calm. Expedition reports in many cases contain auroral accounts. A systematic study of all of the data available for this event could result in a description of auroral behavior and of the auroral zone sufficient to infer in fairly specific detail the corresponding condition of solar activity.

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