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Wilson Bentley and the Northern Lights

As Wilson ("Snowflake") Bentley anticipated, a lifetime of auroral sightings could address a substantive scientific question. Analysis of his records reveals how Sun and Moon affect aurora viewing and offers aid to today's sky watchers.

By Gary Parker

On the first day of February, 1883, a young Jericho, Vermont, farmer witnessed a display of northern lights and was sufficiently inspired to record his observation. At age 17, Wilson Bentley (Fig. 1) thereby commenced a program of regular auroral observation that extended over his remaining forty-nine years and tallied 634 sightings of aurora. Bentley's original motivation for systematic auroral observation may have been his quest to understand the weather and sky conditions associated with the amazingly diverse forms of snowflakes whose photography he pioneered. Or perhaps simple wonderment and curiosity were his inspiration.

Figure 1: Wilson Alwyn Bentley (1865-1931), master of snowflake microphotography. Date unknown. Courtesy of Duncan C. Blanchard, The Snowflake Man: A Biography of Wilson A. Bentley *(McDonald & Woodward Publishing Company, 1998.)*

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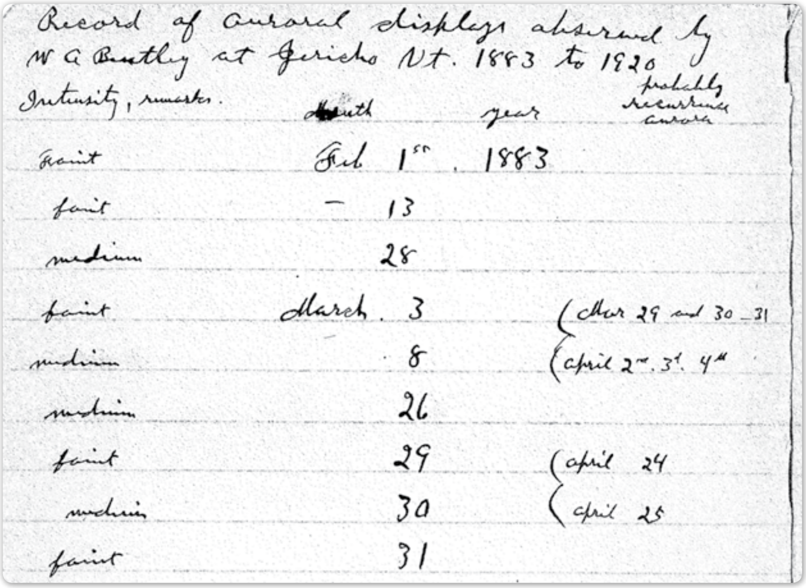
When in 1920, at age 55, he sent a compilation of his first 398 sightings to the editor of the prominent *Monthly Weather Review (MWR)*, he requested that his observations be "easily acces[s]ible to investigators of auroral phenomena," for whom they "may be of some real value."[1] As analysis will show, his intuition that a substantive scientific question could be addressed with such observations was sound. Further, the timing patterns within his compilation are a valuable asset to aurora watchers today.

Bentley's Auroral Records

In Bentley's communication to the *MWR*, a descriptor of brightness such as "faint," "medium," or "quite brilliant" accompanied almost every sighting date (Fig. 2). A few auroras have some additional commentary, such as "all over sky" and "colors red and green seen." During his last eleven years of observing, Bentley kept two notebooks that contain records for an additional 236 auroras.[2] In these notebooks, he allotted each day one line for weather data and drew "a circle with rays" (in Bentley's words) if an aurora occurred (Fig. 3). About 20 percent of these auroras inspired Bentley to write a comment to accompany the symbol.



Record of auroral displays observed by W A Bentley at Jericho Vt. 1883 to 1920

Intensity, remarks.	Month		year	probably recurrence aurora
faint	Feb	1st	. 1883	
faint	–	13		
medium		28		
faint	March.	3		Mar 29 and 30 – 31
medium		. 8		april 2nd. 3d. 4th
medium		26		
faint		29		april 24
medium		30		april 25
faint		31		

Figure 2: Bentley's first auroral sightings, from his correspondence to the Monthly Weather Review. *Courtesy of National Oceanographic and Atmospheric Administration Central Library.*

Figure 3: Bentley weather notebook entries for September 6 through 10, 1928. The rayed circles to the right of center record auroral sightings for September 7, 8, and 9, 1918. Courtesy of Buffalo Museum of Science and Jericho Historical Society.

Bentley may have chosen the symbol to represent a rising Sun accompanied by crepuscular rays. In Roman mythology, Aurora personifies dawn and at sunrise ushers light into the darkness. Early in the seventeenth century she lent her name to the northern lights. Symbolizing her with "a circle with rays" brings to mind both a rising Sun crowned with shafts of light and the rayed patterns frequently seen in northern lights. Most of Bentley's symbols are similar to that of September 9 in Fig. 3, a simple circle with rays on its upper half. But among the 236 symbols the number of rays varied widely, and Bentley sometimes inscribed the circles with lines and with shading (Fig. 4). The variability among symbols is striking and probably intentional.

Figure 4: A sampling of the diverse auroral symbols in Bentley's notebooks. Fig. 3 clarifies the origin of the horizontal lines, which are not part of the auroral symbol. Courtesy of Buffalo Museum of Science and Jericho Historical Society.

What is the significance of this diversity? Perhaps thinking of a clock, Bentley might have drawn the first symbol in Fig. 4 for an aurora that was visible between 10 p.m. and 2 a.m. For September 7 in Fig. 3, Bentley wrote "last all night" next to a circle surrounded by rays. Or perhaps thinking of a compass, he might have drawn the first symbol in Fig. 4 to represent a display that occupied the sky from northwest to northeast. Most of Bentley's auroral symbols have a preponderance of rays on the upper (north?) half of the circle, and north is the direction a Vermonter commonly views the aurora.

Bentley's patterns have approximate left-to-right symmetry. This symmetry discounts the clock hypothesis because it is unlikely that all the auroras would have had the same duration before and after midnight, or that a busy farmer would always stay up to find out. For eight auroras, he recorded observing times that conflict directly with the hypothetical clock. The compass hypothesis fails for the aurora that earned Bentley's most detailed description: He wrote of extensive activity to the south of the zenith, and yet he drew a symbol showing both rays and interior shading only on the top, or north, half of the symbol. Thus the symbol is not consistently either a clock or a compass.

A survey of the symbols favors a third hypothesis: Embellishments of the symbol function informally as a light meter. The brightest auroras, labeled "brilliant" by Bentley, correspond to the symbols most embellished by interior fill or widened circumference. The symbols with the most rays are mainly those for auroras that were either "brilliant" or "bright," Bentley's second level of brightness intensity. While Bentley's embellishments might simply be whimsical responses to memorable auroras, they might instead actually be a concise method of conveying information about brightness. If the written comments in the lost notebooks containing his first 398 auroras were as infrequent as those in the surviving notebooks, then it could be the symbol's pictorial detail that specified brightness for almost every aurora in his report to the *MWR*.

Over the set of 634 observations, Bentley's written descriptions are not generally extensive or systematic. The symbol itself may offer a rough measure of brightness. There was "real value" for auroral science, however, in the list of dates of occurrence.

BENTLEY'S INVESTIGATION IN CONTEXT

The half century prior to the start of Bentley's observing program was marked by an explosion of interest in the relationship between the Sun and the Earth that was triggered by a succession of surprising discoveries. The first of these, in 1843, was that the number of spots on the face of the Sun varied in a cycle,[3] now known to average about eleven years in length. A typical sunspot may persist for only days or weeks, but the number of spots on the face of the Sun at one time trends upward for four or five years followed by six or seven years of decline. Discovered on the basis of just two cycles' worth of sunspot observations, the pattern was soon sought and found in reliable sunspot records that extended back for over a century.[4]

Sunspot behavior would have been interesting only to astronomers had it not been for archival records of the strength and orientation of the Earth's magnetism. In the early seventeenth century measurements established that geomagnetism undergoes very slow but steady change. By the middle of the eighteenth century it was recognized that auroral displays often accompanied transient changes in magnetism. So when in 1852 the frequency of irregular magnetic disturbances was found to vary synchronously with the sunspot cycle,[5] scientists sought to understand the connections among three phenomena—auroras, geomagnetic disturbances, and solar activity.

Further evidence for the Sun's complicity in geomagnetic change was the 1847 discovery that irregular magnetic disturbances at low and middle latitudes were most frequent near the equinoxes,[6] implying that the orientation of the Earth with respect to the Sun played a role. That archival records of sunspots and of geomagnetism had underpinned these discoveries motivated extensive efforts to compile auroral observations. In 1868, Harvard Professor Joseph Lovering compiled records of "nearly 10,000 independent auroras" seen in North America and Europe over 1730-1864. With these, Lovering showed that the frequency of aurora followed the sunspot cycle and peaked at the equinoxes.[7] Through the end of the nineteenth century, Swedish, Danish, and Norwegian observers would add compilations with many thousands of additional auroral observations.[8]

In light of the plethora of auroras recorded at high latitudes, one must consider what a listing of the timings of 634 Vermont auroras could possibly add to the conversation. A list of occurrences lends itself to two types of correlative study. Bentley might have looked for patterns of simultaneous occurrence of auroras and changes in meteorological phenomena such as wind, cloudiness, or temperature. Prior to the development of reliable triangulation methods in the early twentieth century, some investigators claimed that auroras formed as close to the ground as did Bentley's beloved snowflakes. But there is no indication that Bentley pursued connecting auroras with meteorological properties.

A second type of correlative study appropriate to Bentley's data is the search for regular patterns of occurrence in time, and for such a study his record had "real value." There are three patterns of occurrence in time for which Bentley's data are well suited. A scientific paper published in 1983 showed that the sunspot cycle and the equinox effects are evident in Bentley's observations.[9] If Bentley had uncovered these two patterns in his data, he would have been confirming the 1868 discoveries of Lovering. But Bentley made no mention of having considered them. He did, however, recognize a third timing pattern in the occurrence of auroras. Strongly evident in Vermont auroras, this pattern offered promise for an important and original scientific contribution.

THE SCIENTIFIC OPPORTUNITY

In 1920, when compiling his first early sightings for the *MWR*, Bentley added a column to his table entitled “probably recurrence aurora” (Fig. 2). At some time between 1883 and 1920 he had noticed that auroras tend to be separated by about four weeks. In this rightmost column he listed the dates of later auroras that might be associated with the aurora whose date is in the central column. In his 1920 compilation, Bentley associated some 30 percent of the auroras with recurrence. The strength of this pattern was abundantly clear to him, but he did not pursue its explanation, hoping that others would uncover the “real value” of his compilation. The effort among scientists to understand this pattern continued into the middle of the twentieth century and, as with the other temporal patterns, it is connected—at least in part—to Earth’s relationship with the Sun.

Centuries before, Galileo established in 1612 that sunspots were on, rather than above, the surface of the Sun.[10] Individual sunspots remain stationary on the Sun, but they appear to move because of the Sun’s rotation. As we view the rotating Sun, the left (east) side approaches Earth while the right (west) side recedes. Long-lived sunspots take about two weeks to drift across the solar disk because of rotation. In 1858, English astronomer Richard Carrington noticed that the drift rate depends on a sunspot’s latitude and made a very careful determination of the average rotation period.[11] That interval of 27.3 days is now known as the Carrington rotation period.

By happenstance, the orbital period of the Moon measured by its placement with respect to the stars, the *sidereal* period of revolution, is also 27.3 days. The more familiar *synodic* period of the Moon, the interval from New Moon to New Moon, is 29.5 days. This snarl of similar numbers made for a lively century of correlation, conjecture, and confusion when scientists discovered and sought the causes of variable geophysical phenomena that have periods of about four weeks. In 1876 British researcher J. A. Broun reported a four-week pattern in the occurrence of geomagnetic disturbance.[12] 27.3 days and 29.5 days are both about four weeks, but the distinction proves crucial. Broun found a period of recurrence closer to 27.3 than to 29.5 days and so opined that the Sun was more important than the Moon as the cause of geomagnetic recurrence. A 1905 study gave stronger evidence for the dominant role of the Sun, but still hypothesized a minor role for the Moon.[13] Finally, in 1932 an extensive study of geomagnetic disturbance established the 27.3-day Carrington rotation period as *the* characteristic rhythm of recurrent geomagnetic disturbances.[14] The Moon has no role.

The influence of the Sun's rotation on auroral occurrence was more difficult to establish and was a focus of research in the years Bentley was compiling aurora sightings. Despite making "elaborate allowance for . . . moonlight," an 1888 study of aurora timings failed to find a 27.3-day pattern.[15] An 1898 study did report the 27.3-day period but misconnected it with the sidereal month and also claimed that a second period was present.[16] A 1927 Norwegian study had more success by determining the relative strengths of auroras on each of five sequential days one month after a strong (or weak) aurora to see if strong followed strong while weak followed weak.[17] The strongest "echo" seemed to occur after an interval of about 27 or 28 days, clearly shorter than the ordinary 29.5-day lunar month. Solar rotation did seem to matter to aurora timings, but the challenge remained to tease a 27-day solar rotation period out of the auroral timings.

Adopting an innovative analysis technique, an important 1939 investigation of 5,224 auroras observed over Scotland during 1858-1938 made a reasonable claim to have detected the solar rotation period in auroral timings.[18] Unfortunately, the study made the indefensible inference that the recurrence was a true periodicity that had persisted over eighty years. This investigation stumbled because the Moon's strong and persistent influence on auroral timings obscures the shorter-term effects of solar rotation. Throughout Bentley's lifetime and beyond, the unresolved roles of Sun and Moon in auroral recurrence posed a substantive scientific question.

"Low" Latitude Auroras

Affecting every researcher's conceptualization of solar causation was the direct telescopic observation by Richard Carrington in 1859 of a spectacularly bright flaring of the Sun in the vicinity of a sunspot that was followed within a day by a geomagnetic storm and an aurora that extended to low Earth latitudes. Ensuing studies confirmed the capacity for solar outbursts to cause events at Earth, but not all flares produce them. Further, not all geomagnetic events are accompanied by auroras. Sun-induced disturbances at Earth were not all alike.

In 1954, astronomers at the Yerkes Observatory in Wisconsin published an important study of auroral occurrence patterns based on 1,267 sightings over the fifty-five years, 1897 to 1951.[19] Bentley recorded 634 auroras over forty-nine years. Cloudiness contributed to his lower sighting rate. Compared to Burlington, Vermont, the Yerkes location enjoys 15 percent fewer days of precipitation and 20 percent more sunny days. Additionally, professional astronomers at an active observatory would likely have been able to monitor the whole night more thoroughly than a farmer, for whom the next day's chores were always waiting.

The Yerkes and Bentley compilations are scientifically interesting because the details of auroral occurrence depend strongly on the observer's latitude. Auroras in the far north occur on most nights. Their timings respond to the sunspot cycle, equinoxes, and solar rotation in ways significantly different from those of auroras seen at the relatively low latitudes of Vermont and Wisconsin. The low latitudes of Jericho and Yerkes gave these compilations special value and made them a scientifically important supplement to tens of thousands of high-latitude sightings. Only the most energetic auroras reach low latitudes. Their recurrence is a property of the most powerful space disturbances.

After the Yerkes researchers confirmed the presence of sunspot cycle and equinox patterns in occurrence frequency, they tackled recurrence with an innovative approach for separating the lunar and solar contributions. They calculated the time separations between each aurora and any subsequent aurora not more than 400 days later. With great labor, they determined how often any interval from one day to 400 days separated auroras in their catalog.[20] The Yerkes analysis distinguished the roles of the Moon and Sun in recurrence and demonstrated that the solar effect fails to persist beyond one month.

WHAT BENTLEY'S DATA SAY

Bentley's forty-nine years of observations occurred within five sunspot cycles. With averages over the five sunspot cycles, Fig. 5 shows how sunspot number and auroral counts depend on position within a cycle. From a minimum number of sunspots at year 0, sunspot activity rises to a maximum after about five years. So, too, does the annual aurora count. But auroras linger at an elevated level for several years while the sunspot activity wanes. This lingering into the declining phase of the sunspot cycle also occurs for geomagnetic disturbances.

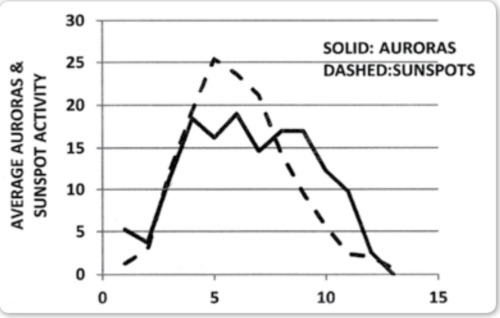


Figure 5: Aurora counts and sunspot activity averaged over five sunspot cycles. The Wolf (Zürich) sunspot number has been reduced by a factor of three to accommodate a common vertical scale. The author.

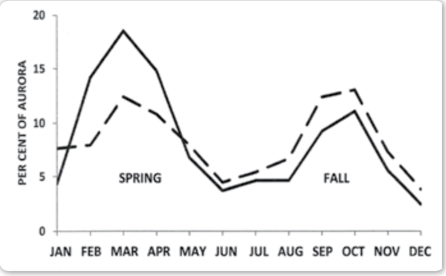


Figure 6: Distribution of Bentley's auroras over the months of the year. Solid line for 1883-1915, dashed line for 1916-1931. The author.

The distribution of Bentley's auroras through the year shows enhancements near the equinoxes in March/April and September/October (Fig. 6).[21] The enhancements are strong. Over 1883-1931 Bentley saw four times as many auroras in March as in June. Spring equinox outperformed fall equinox, an unexpected behavior. Examination of Bentley's data over shorter intervals reveals that the greater spring enhancement occurs only in the first half of his observations (1883-1915). Some 64 percent more auroras occurred in spring than in fall, a statistically significant difference.

Bentley identified one possible cause of this disparity when he remarked in his 1920 letter to the *MWR* that he had been experiencing "cloudiness, especially during fall and winter months." Another possibility was a change in lifestyle in 1918 or 1919. At age 53 or 54, Bentley "turned over most of the running of the farm to a neighbor."[22] The "dairy farm and sugar orchard were prime sources of income" for the Bentley farm,[23] and a reduction in farm chores such as sugaring may have lessened his nighttime hours outdoors in spring.

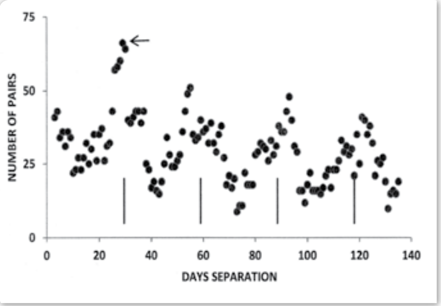


Figure 7: Count of pairs of auroras (vertical axis) in which the separation is between 3 and 135 days. This spectrum of separations is cyclic with maxima around multiples of the 29.5-day month, shown by vertical lines. The author.

Fig. 7 reveals how often a pair of auroras in Bentley's compilation has a given separation. For example, the highest dot in Fig. 7 (see arrow) occurs with a horizontal axis value of 29 and a vertical axis value of 66, meaning that a separation of 29 days occurred 66 times among Bentley's auroras. The distribution of the time intervals that separate auroras follows a sinuous pattern, with enhancements around integer multiples of the 29.5-day month (shown by vertical

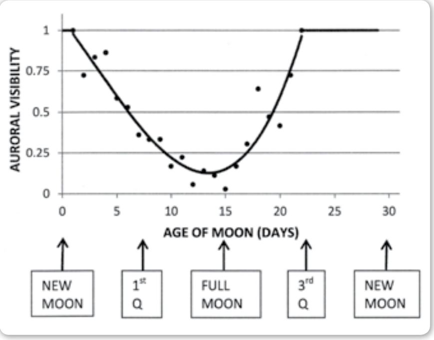


Figure 8: The effect of moonlight on Bentley's ability to see the aurora. The phase of the Moon is expressed as days after New Moon. The author.

lines). There is a strong tendency for auroras to be separated by the lunar month and multiples thereof. The final figures show why.

Fig. 8 shows the relative amounts the various days of the lunar month contributed to Bentley's compilation. By observing daily, he sampled the night sky at all phases of the Moon equally. Not all phases were friendly for seeing the aurora at his hour(s) of observation. The number of auroras that he observed at each phase measures his ability to see the aurora at his time of observation.[24] Moonlight hindered his ability to see the aurora. Fig. 8 shows that for an interval of ten days containing the Third Quarter and New Moon, Bentley experienced no difficulty from moonlight: His auroral visibility was 100 percent. But as the Moon waxes, sighting auroras becomes increasingly difficult. Near Full Moon Bentley saw only 10 or 20 percent of the auroras that would be visible in the absence of moonlight. His sightings tend to occur when the early hours of the night have the least moonlight.

Among the auroras in the weather notebooks, Bentley recorded twenty-six clock times for dynamic changes in the displays. These ranged from 7:40 to 11 p.m. Bentley reported only two morning auroras and three auroras that lasted all night: He seldom reported sightings after midnight. Fig. 8 and the recorded clock times agree that Bentley's aurora watch occurred predominantly in the early hours of the night.

The undulating curve in Fig. 9 is a theoretical construct to aid in the interpretation of Fig. 7. This curve shows the separations that would be expected to occur *assuming* (1) that auroras occur independently of the phase of the Moon, (2) that the smooth curve in Fig. 8 describes the probability of seeing an aurora in the presence of moonlight, and (3) that all auroras occur in the most active half of the sunspot cycle. These simple assumptions predict a spectrum of separations (sinuous curve) very similar to that actually observed (dots in Fig. 9). Above this curve there are extra pairs with one- and two-day separations (see arrows on left) and with separations *near* one month (the location of the first vertical line). Excess pairs of auroras at one- and two-days' separation oc-

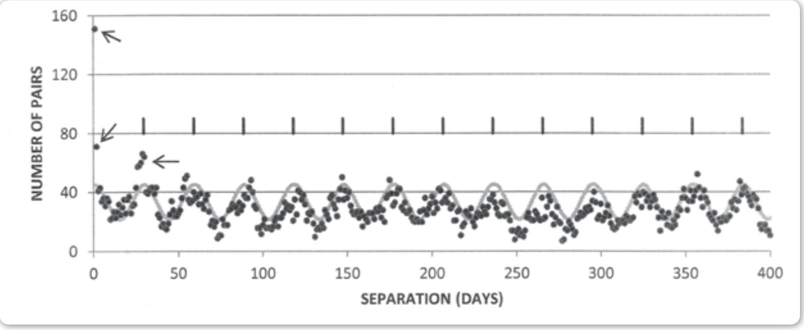


Figure 9: An expansion of Fig. 7 to include the pairs counts at separations of 1 and 2 days and a model-based prediction of the separation spectrum to be expected if the Moon were the sole cause of the recurrence of auroras. The author.

cur mostly because of the persistence of large Sun-induced disturbances in Earth's upper atmosphere. The dots well above the curve for separations in the range twenty-six to thirty days have pairs in excess of those produced by the Moon. This excess is centered to the left of the vertical line (see horizontal arrow) and results from solar rotation, not from the Moon.

According to Fig. 9, the Moon modulates the spectrum of separations of auroras by establishing a persistent rhythm in our ability to see auroras. A separation of one month occurs about twice as often as it would if auroras happened at random. The Moon and the Sun make comparable contributions to this enhancement. But at intervals of two or more months, auroral recurrence is due entirely to the Moon.

Conclusion

The 1954 Yerkes study confirmed the solar cycle and equinox variations in frequency for low-latitude auroras. By showing that some auroras recur at an interval slightly shorter than the lunar month, the study confirmed that solar rotation can affect the timings of auroras. It demonstrated that removing the influence of the Moon from the spectrum of separations of auroras is necessary to reveal the influence of the Sun. The Yerkes report became the definitive study of the timing patterns of auroras in the early days of modern space research.[25] It is interesting that all of the principal scientific conclusions reached in the Yerkes study could have emerged more than two decades earlier from a Jericho, Vermont, farmhouse had Wilson Bentley analyzed his auroral timings.

As Bentley anticipated, an extended compilation of auroral sightings made at a fixed location with a procedure standardized by a single observer had scientific value. His persistence in maintaining this long, daily watch significantly extends his scientific legacy beyond the phenomenal artistry of his snowflake imaging. Bentley recorded auroras until well into the last month of his life, but he never pursued the analysis and interpretation of his extensive compilation. In the spirit with which he generously shared his images of snowflakes, Bentley left a lifetime of auroral observations for future studies of the northern lights.

Epilogue: With Bentley as Guide

The timing patterns implicit in Bentley's compilation of auroras are a useful resource to sky watchers at midlatitude locations such as Vermont. Through these patterns, Bentley's forty-nine years of night sky watching give him voice to guide those who seek to view northern lights. What practical advice would Bentley offer the casual observer?

On average, Bentley saw one aurora every twenty-eight days. To improve on a 1 in 28 chance of sighting an aurora on a particular night, the observer needs to find a location from which the sky is as free of light pollution as possible. An overcast sky is an obvious nonstarter. The eye needs at least ten or fifteen minutes to adapt to the dark. With these preliminaries out of the way, an observer's chances can be much further improved with Bentley's guidance.

First, be alert tonight if there was an aurora yesterday. The day after an aurora is over six times more likely than a random day for seeing an aurora. The second day after an aurora is three times as promising as a day at random, so don't give up if the first night after an aurora is unrewarding.

Secondly, check the eleven-year sunspot cycle and seek auroras when the Sun is active, as may be determined easily from the internet. The four quietest years for sunspots are unlikely for auroras; the other years are much more promising. You need not hit the peak year of the sunspot cycle to have favorable odds. The months near the equinoxes—March, April, September, and October—are two or three times more likely to be productive than the summer and winter months. Too bad: It's so comfortable on warm summer nights, and the crisp air of frigid winter nights offers such clear skies.

Finally, the Moon is no friend to the seeker of aurora. But you simply *have to* look at all times of the month because if there is a visible aurora near the time of Full Moon, it is an aurora determined to be seen. An especially powerful space disturbance is producing an aurora that no one would dare miss. Bentley wrote that among his first 398 auroras, "the blood red one of Feb 13th 1892 impressed me most strongly."[26] Accompanied by a pair of major geomagnetic storms on the same day (itself an extremely infrequent occurrence), this display only one day away from a Full Moon was described on the front page of the next day's *New York Times* as "the most wonderful exhibition of the aurora, or northern lights, possibly ever seen from American soil."[27] Teaching by example, Wilson Bentley would have us looking up nightly for that next amazing display.[28]

NOTES

[1] W. A. Bentley, "Record of auroral displays observed by W. A. Bentley at Jericho, Vt., 1883-1920" and manuscript presentation letter to *Monthly Weather Review*, September 19, 1920. National Oceanographic and Atmospheric Administration Central Library, Silver Spring, Maryland, manuscript ID 38398100344310. Currently online at http://docs.lib.noaa.gov/noaa_documents/NOAA_historic_documents/WB/QC9717U52V41883.pdf. The letter is reprinted in Duncan C. Blanchard, *The Snowflake Man: A Biography of Wilson A. Bentley* (Blacksburg, Va.: McDonald & Woodward Publishing Company, 1998).

[2] Through the New York Heritage Digital Collections website, the Buffalo Museum of Science has made these notebooks available online at http://www.nyheritage.org/collections/bentley-snow-crystal-collection. This extensive collection of Bentley materials includes Field Notebooks, among which notebooks 8 and 9 contain Bentley's weather observations for 1921-1931.

[3] H. Schwabe, "Sonnenbeobachtungen im Jahre 1843," *Astronomische Nachrichten*, 21: 495 (1844), 233-236.

[4] R. Wolf, "Mitteilungen über die Sonnenflecken IX," *Astronomische Mitteilungen der Eidgenössischen Sternwarte Zürich*, 1(1850): 207-246.

[5] E. Sabine, "On Periodical Laws discoverable in the mean effects of the larger Magnetic Disturbances. No. II," *Philosophical Transactions of the Royal Society of London*, 142(1852): 103–124.

[6] J. A. Broun, "On the Variations of the Daily Mean Horizontal Force of the Earth's Magnetism Produced by the Sun's Rotation and the Moon's Synodical and Tropical Revolutions," *Philosophical Transactions of the Royal Society of London*, 166(1876): 399.

[7] J. Lovering, "On the Periodicity of the Aurora Borealis," *Memoirs of the American Academy of Arts and Sciences*, 10:1(1868), 9-358.

[8] R. Rubenson, "Catalogue des aurores boréales observées en Suède (I-II)," *Kungliga Svenska vetenskapsakademiens handlingar*, 15:5(1879) and 18:1(1882). S. Tromholt (J. Fr. Schroeter, ed.), *Catalog der in Norwegen bis Juni 1878 beobachteten Nordlichter* (Kristiania, 1902). Other compilations are noted by S. M. Silverman, "On the literature of the aurora in Nordic countries," in C. S. Deehr and J. A. Holtet, eds., *Exploration of the Polar Upper Atmosphere* (Dordrecht, Holland: D. Reidel, 1980), 443-448.

[9] S. M. Silverman and D. C. Blanchard, "Wilson Bentley's Auroral Observations," *Planetary and Space Science,* 31:10(1983), 1131-1135. Their Table 1 correctly lists 633 dates of auroras recorded by Bentley, who noted an additional sighting on February 23, 1931.

[10] Galileo Galilei, "Second Letter to Mark Welser on Sunspots" (August 1612). *Istoria e Dimostrazioni intorno alle Macchie Solari* (Roma: Giacomo Mascardi, 1613). In S. Drake, trans., *Discoveries and Opinions of Galileo* (Garden City, N.Y.: Anchor Books, 1957), 105-119. Herein Galileo attributes the apparent motion of sunspots to solar rotation and approximates the period of rotation as "about one lunar month."

[11] R. C. Carrington, *Observations of the Spots on the Sun from November 9, 1853, to March 24, 1861, Made at Redhill* (London: Royal Society, 1863).

[12] Broun, "Variations," 387-403.

[13] E. W. Maunder, "Magnetic Disturbances, 1882-1903, as Recorded at the Royal Observatory, Greenwich, and Their Association with Sun-spots," *Monthly Notices of the Royal Astronomical Society,* 65(1905): 2-34.

[14] J. Bartels, "Twenty-Seven Day Recurrences in Terrestrial-Magnetic and Solar Activity, 1923-1933," *Terrestrial Magnetism and Atmospheric Electricity,* 39:3(1934), 201–202a.

[15] C. Chree, "Aurora Polaris," *Encyclopedia Britannica*, 11th ed., 2(1910), 927-934.

[16] N. Ekholm and S. Arrhenius, "Den Einfluss des Mondes auf die Polarlichter und Gewitter," *Kungliga Svenska vetenskapsakademiens handlingar*, 31:2(1898).

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[17] H. U. Sverdrup, "Observations of the aurora, 1918-1925," in *Land Magnetic and Electric Observations, 1918-1926* (Washington, D.C.: Carnegie Institution Publication 175), 6:5(1927), 461-524.

[18] F. E. Dixon, "A 27.3-day period in the aurora borealis," *Terrestrial Magnetism and Atmospheric Electricity,* 44(1939): 335-339.

[19] A. B. Meinel, B. J. Negaard, and J. W. Chamberlain, "A Statistical Analysis of Low-Latitude Aurorae," *Journal of Geophysical Research*, 59:3(1954), 407-413.

[20] Application of this procedure to Bentley's observations produces Figures 7 and 9 below. G. D. Parker, "Timing Patterns in Event Lists: Recurrent Geomagnetic Storms," *Journal of Atmospheric and Solar-Terrestrial Phys*ics, 67(2005): 1403-1410, examined the statistical properties of this procedure and applied it to geomagnetic disturbances.

[21] In the calculations for Figures 5 and 6, four auroral dates from nearby Weather Bureau stations inserted into the record for an interval of several months in 1920 when Bentley did not observe. This procedure follows that of Silverman and Blanchard, "Bentley's Auroral Observations," 1132.

[22] Blanchard, *Snowflake Man*, 168.

[23] F. E. Hartwell, *Forty Years of the Weather Bureau: The Transition Years* (Bolton, Vermont: Long Trail Studios, 1958), 72.

[24] Smoothing these visibility data produces the solid lines for later analysis. Data points are shown at lunar phases where the visibility is significantly compromised by moonlight.

[25] Well-known to the first generation of post-Sputnik space scientists, two bibles of space science prominently cited the Yerkes study: J. A. Ratcliffe, ed., *Physics of the Upper Atmosphere* (New York: Academic Press, 1960), 287; J. W. Chamberlain, *Physics of the Aurora and Airglow* (New York: Academic Press, 1961), 113-114.

[26] W. A. Bentley, in Blanchard, *Snowflake Man*, 163-164.

[27] *New York Times*, "Brilliant Electric Sight," 14 February 1892, 1.

[28] Supported by long-term occurrence statistics, Bentley's advice may be categorized as space climatology. In contrast, space weather forecasting depends on physical models whose predictions of aurora relate to the behavior of causative phenomena. Operative since 2014 and currently online, the OVATION model of the Space Weather Prediction Center (SWPC) of the National Oceanic and Atmospheric Administration offers a 30-minute auroral forecast based on solar wind conditions at a spacecraft immediately upwind of Earth. SWPC is currently testing a 3-day auroral forecast protocol.