24 August 1984, Volume 225, Number 4664 SCIENCE

The Magnetic Activity of Sunlike Stars

Arthur H. Vaughan

The roughly 11-year periodicity in the appearance of sunspots was first recognized about 140 years ago by the German amateur astronomer Heinrich Schwabe. This discovery met with little notice for nearly a decade until Alexander Humboldt, "next to Napoleon Bonaparte the most famous man in Europe" (*1*), drew attention to Schwabe's work and pointed tor. In the course of his studies from 1912 to 1925 (*3*), Hale showed that in successive sunspot cycles the sense of the polarity of the leading spots in the two hemispheres is interchanged, so that the solar cycle is actually a magnetic cycle with a period of about 22 years.

A great deal of knowledge about magnetic fields on the solar surface has been

Summary. Sunspots, flares, and the myriad time-varying "events" observable in the Sun—the only star whose surface we can examine in detail—are testimony that the Sun is a magnetically variable or active star. Its magnetic field, carried into interplanetary space by the solar wind, produces observable changes in Earth's magnetosphere and variations in the flux of galactic cosmic-ray particles incident upon Earth's upper atmosphere. Centuries of observation have enabled solar scientists to recognize that the Sun's magnetism exists and varies in a globally organized pattern that is somehow coupled to the Sun's rotation. Within the past decade O. C. Wilson demonstrated that analogs of solar activity exist and can be studied in many other dwarf stars. From the continuing study, knowledge of the precise rates of rotation of the stars under investigation is being gained for the first time. The results are expected to increase our understanding of the origin of solar activity and stellar activity in general.

out a corresponding cyclic trend in the amplitudes of small daily variations of the magnetic field at the surface of Earth (*2*). In 1908 the astronomer George Ellery Hale showed, from observations of the Zeeman splitting of lines in the Sun's spectrum, that sunspots are regions of intense magnetic field, several thousand times stronger than Earth's field. He found that sunspots usually appear in pairs of opposite magnetic polarity and that in the hemisphere above the solar equator the leading spots in the direction of solar rotation nearly always have one polarity, opposite to that of the leading spots in the hemisphere below the equa-

gained from decades of intensive observation of the Sun, the only star whose surface we can examine in detail. But, as we approach the end of the 20th century, the ultimate origin of the cycle remains an intriguing secret. There is reason to expect that future understanding will be guided by a study in which stellar analogs of solar activity have been kept under consistent observation for the past 18 years. As the study continues, important details are being added to what is known about the stars under observation (*4*).

A wide variety of phenomena on the Sun wax and wane in synchronism with the pattern of the cycle, including the excitation of the chromosphere (Fig. 1a)—a hot outer layer of the Sun's atmosphere first described and named for its "pinkish" color by the English astronomer Norman Lockyer in 1869. From spectroscopic evidence it has long been known that chromospheres are a feature of sunlike, or dwarf, stars less massive than about 1.2 solar masses, as well as of virtually all giants and supergiants of spectral type G0 and cooler. The chromospheres of these classes of stars cover a wide range of excitation. It was apparent even in the 1930's that detection of stellar analogs of the solar cycle would be of great interest and that a search might best be undertaken by looking for a spectroscopic signature of the chromospheric variations that conceivably would occur in the course of time in such stars (*5*). But an investigation of this kind became practical only with the development of a suitably precise photoelectric measuring technique whose calibration could be maintained over a period of many years.

Such a long-term study was initiated in mid-1966 at the Mount Wilson Observatory in California by O. C. Wilson. From 11 years of observation of 91 stars at monthly intervals he showed that variations in the chromospheric excitation of sunlike stars can be observed and systematically studied and that many such stars exhibit cyclic changes strongly resembling the activity cycle of the Sun (*6*). This discovery was of revolutionary importance in the field of astronomy concerned with explaining the solar cycle, a field in which progress had long been hindered by the fact that knowledge of the phenomenon was limited to the single example provided by the Sun. Moreover, the discovery occurred in an era of newly acquired ability to make very large-scale numerical computations, which had led to renewed interest on the part of theoreticians in modeling the complex processes underlying the

The author is a scientific staff member of the Applied Optics Division, Perkin-Elmer Corporation, 7421 Orangewood Avenue, Post Office Box 3115, Garden Grove, California 92641, and staff associate of the Mount Wilson and Las Campanas observatories, Carnegie Institution of Washington, Pasadena, California 91101.

solar cycle. The past decade has also seen remarkable advances in our knowledge and understanding of the atmospheric physics of sunlike stars and the Sun itself, brought about by observations in the ultraviolet and x-ray spectral regions made with spaceborne observatories.

Differential Rotation

No one would have sought to discover evidence for the existence of magnetic activity in stars if it were not for the example of the Sun, which must remain the source of all detailed knowledge of the phenomenon. From solar studies extending over centuries [for a recent general review, see (*7*)] it is evident that solar activity manifests a process that is organized on a grand scale.

Many of the most important features of the pattern had become evident before the end of the 19th century. Among the most striking features is the tendency of the sunspot zone to drift toward the equator in the course of each cycle and for the first spots belonging to a new cycle to appear at high solar latitudes even before the last spots of the previous cycle have dissipated. The trend is especially evident in an updated version of the "butterfly" diagram, first published by E. W. Maunder in 1922 (see Fig. 2b). From such a diagram it is apparent that successive cycles sometimes differ markedly from each other in intensity and duration. This is also evident from an examination of the mean annual number of sunspots over an interval of not quite four centuries (Figs. 1b and 2a).

By using sunspots as tracers, Galileo was able to show in 1610 that the Sun rotates with a period of about 25 days. Scheiner noted in 1630 that low-latitude spots indicate a more rapid rotation than high-latitude spots: in other words, the Sun does not rotate as a rigid body. This effect, now referred to as differential rotation, was thoroughly and systematically studied in the 19th century by Carrington (*8*).

Modern investigators use a variety of tracers as well as highly sensitive spectroscopic measurements of the Doppler effect to study the differential rotation of the Sun (*9*). The precise magnitude and latitude dependence of the differential rotation is found in general to depend upon the method of measurement, and this is partly because the differential rotation is a function not only of latitude but also of depth in the Sun's outer layers. Systematic deviations in the photospheric pattern of differential rotation occur in synchronism with the 22-year magnetic cycle (*10*). At a fixed latitude, the velocity in the direction of rotation of the Sun varies by an average of about 5 meters per second from the mean velocity in a period of about 11 years. At any given time, the velocity deviation is found to be a function of latitude, symmetrical in both hemispheres. With the passage of time a given zone of excess velocity, and the corresponding zone in the opposite hemisphere, drift toward the equator as traveling "waves." There are two cycles of the wave present in each hemisphere at all times, so that the time required for a wave to travel from pole to equator on the Sun is 22 years. The pattern of these waves is that of a torsional oscillation of wave number 2 per hemisphere. Other modes of torsional oscillation have also been reported. The waves are correlated with the butterfly pattern of emerging spots and magnetic flux on the solar surface: most of the activity emerges in the shear zone that lies just equatorward of a zone of accelerated rotation. Although the intensity of magnetic activity can differ strongly from one cycle to the next, no corresponding variations appear in the torsional oscillation; this result has led investigators to suspect that the torsional oscillation might have a fundamental causal role in the solar cycle. Cycle-related variations in the rotation measured from sunspots are also seen (*11*).

A feature of solar activity described in 1894 by Maunder but not generally appreciated until relatively recently (*12*) is the fact that the activity fell to a very low level in the latter part of the 17th century. This 60-year interval of low activity, now called the "Maunder minimum," has been found to coincide with the most recent of several known past epochs for which an above-average content of the radioactive isotope ^{14}C relative to the stable isotope ^{12}C is found in ancient tree rings of known age. Carbon-14 is one of several isotopes produced by galactic cosmic-ray particles entering Earth's atmosphere. It is known that there is a negative correlation between the flux of cosmic rays impinging upon the atmosphere and solar activity. This is attributed to the bending of the trajectories of these electrically charged particles by the magnetic fields carried into interplanetary space by the solar wind, although other factors affecting the cosmic-ray fluxes are also known. Carbon dioxide containing ^{14}C resides in the atmosphere and oceans for at least a decade before being incorporated in sediment, polar ice, and living plants, so that variations on a time scale as short as the solar cycle are erased. But variations on time scales of a century or longer are apparent in the radiocarbon record in ancient wood of the last 8000 years (*13*). This record suggests that, at the current stage of its

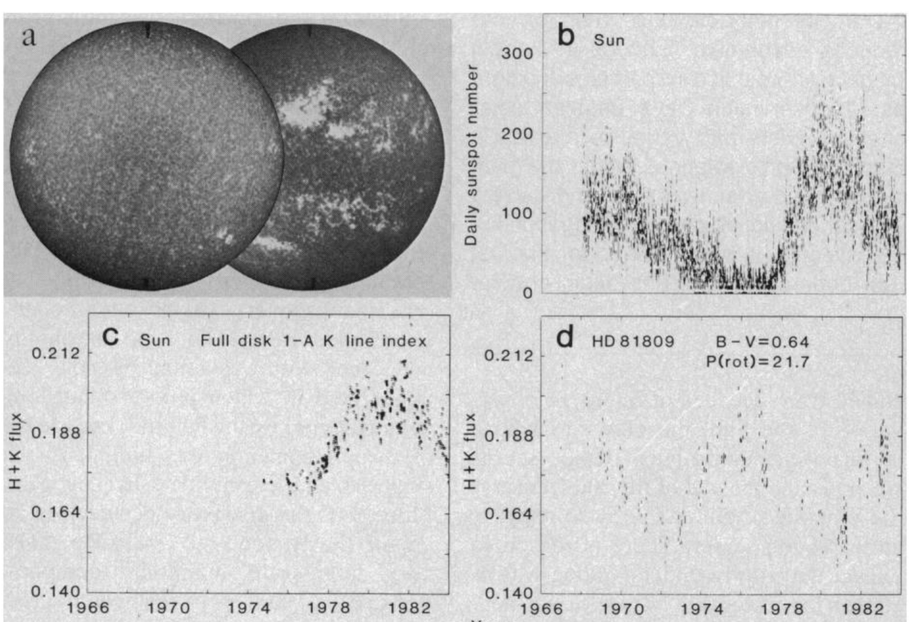

Fig. 1. (a) Chromospheric active regions on the solar surface photographed at the wavelength of the calcium K line near minimum in January 1976 (left) and in April 1979 (right) near the last maximum of solar activity. The bright patches are known to be associated with regions of enhanced magnetic flux on the solar surface. (b) Daily values of the international sunspot index from 1968 to 1983. (c) An index of full-disk calcium K line emission measured at Kitt Peak National Observatory with a solar K line photometer (*22*) in the same period, converted to the Mount Wilson scale. (d) Measurements of an analogous index of H + K line emission for the star HD 81809 (see text). This record exhibits variations similar to those of the Sun over a corresponding time interval. The Sun's activity cycle observed in this way would be clearly discernible at stellar distances.

evolution, the Sun may have spent as much as 30 to 40 percent of the last 1000 years in a "Maunder minimum" state of low activity (*14*).

About 20 years ago it was discovered from precise Doppler measurements that small areas of the solar surface rise and fall at a rate of a few hundred meters per second in a period of about 5 minutes. About 10 years later it was recognized that these 5-minute oscillations are associated with global motions in the Sun, analogous to the seismic waves that propagate along the surface of Earth and through its interior (*15*). Just as geologists make use of seismic waves to derive information about Earth's crust and core, solar scientists are beginning to use highly sensitive Doppler measurements to probe the inner structure, composition, and dynamics of the Sun. From recent studies has come evidence that the core of the Sun may be rotating several times faster than the surface (*16*). This would have obvious importance, not only for theories of solar magnetic activity but for theories of differential rotation and angular momentum loss in stars and perhaps for the understanding of the low flux of neutrinos produced by nuclear reactions in the solar core.

The most generally accepted explanation for the existence and large-scale behavior of the magnetic field of the Sun depends upon the fact that the sun rotates, and the fact that vertical circulation of convective eddies takes place in an outer shell that extends from the photosphere—the apparent surface—down to a depth that is an appreciable fraction (about a quarter to a third) of the Sun's radius. The thermonuclear fusion of hydrogen into helium that supplies the Sun's radiant energy is confined to a core whose radius is also about a quarter of the solar radius. This energy diffuses radiatively from the core outward to the base of the outer shell, where high opacity begins to force the onset of convection as the dominant mechanism of energy transport to the surface. The convection, in combination with the rotation of the Sun, gives rise to a pattern of circulation in which the fluid at different latitudes and depths in the convective shell is forced to rotate at appreciably different rates.

The fluid of which the Sun is composed is a good conductor of electric current. A magnetic field embedded in such a fluid behaves as if it is "frozen" into the fluid, moving with it and becoming deformed, twisted, and amplified, feeding on the energy of motion of the fluid. Investigators have made extensive studies of the generation of magnetic fields by such "dynamo" processes (*17, 18*). A number of models have been considered in attempts to understand the Sun as a magnetic oscillator. Although a great deal of new insight into the processes at work is emerging, thus far no model has succeeded in accounting for all the known features of the solar magnetic cycle. It is evident that a successful model will depend intimately upon physical conditions and processes that are hidden in the solar interior, and it is reasonable to expect that understanding the solar cycle will bring fundamental advances in knowledge about these processes in stars, and vice versa.

Strong Emission Lines

The convective outer shell is believed to be necessary for the existence of the hot chromosphere of the Sun and for the corona and the solar wind; the stars in which chromospheres are found are those in which outer convection zones are expected. The structure of these extremities of the solar atmosphere is modified by the magnetic field, producing a variety of transitory effects that can be observed and studied in detail at the wavelengths of the emission lines of abundant metallic ions and hydrogen when the white light of the underlying photosphere is filtered out.

Although most of the strong emission lines produced by the chromosphere and corona are located in the ultraviolet part of the spectrum that is absorbed by Earth's atmosphere and is observable only from space, the Fraunhofer H and K lines of ionized calcium are important exceptions. They carry about 15 percent of the energy radiated into space by the chromosphere of the Sun. Light at and near the wavelengths of these lines, at 3968.470 and 3933.664 Å in the near-ultraviolet, is strongly absorbed in the photosphere, so that bright chromospheric features above the photosphere stand out in sharp contrast (see Fig. 1, a and c). Their brightness is highly correlated point by point with the magnetic flux present in the underlying photosphere, and thus calcium H and K line core emission can be used to infer the existence and character of magnetic activity at stellar distances.

The method of observation introduced by Wilson consists of measuring, with a photoelectric spectrometer, the light flux in two spectral bands 1 Å wide centered at the H and K lines, relative to the flux in a second pair of bands about 20 Å wide located on either side. From these measurements one computes a relative HK flux index by dividing the sum of the fluxes at H and K by the sum of the fluxes in the reference bands. Since the

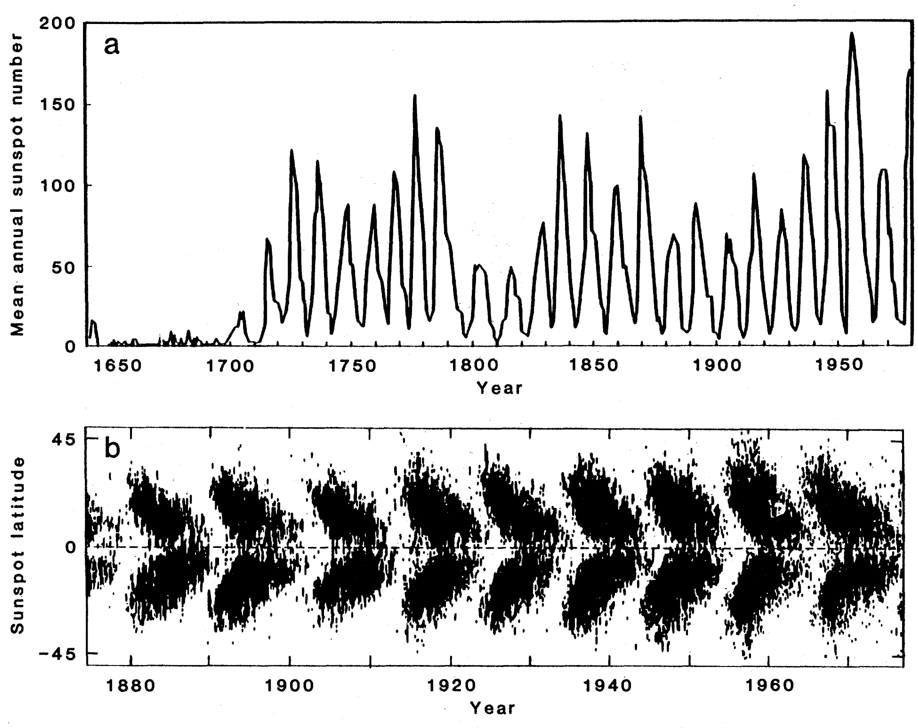

Fig. 2. (a) Mean annual number of sunspots from the early 17th century to 1980. Pronounced differences from one cycle to the next are evident both in intensity and in the timing of maxima. The 60-year period of low activity extending to about 1710 is the Maunder minimum. (b) "Butterfly" diagram in which the latitudes of emerging sunspot groups are plotted monthly; such a plot illustrates the tendency of the sunspot zone to migrate equatorward during each cycle. The first spots from a new cycle usually appear at higher latitudes before the last spots of the previous cycle have dissipated. [From (*7*), courtesy of the Science Research Council of Great Britain]

fluxes in the numerator and denominator of this ratio are measured simultaneously by photon counters, the ratio is insensitive to fluctuations in the light caused by telescope guiding errors and air turbulence.

For the first 11 years, the measurements were made at the 100-inch Hooker reflector at Mount Wilson with a scanning spectrometer that had been developed in the late 1950's and early 1960's. After mid-1977, the measurements were made at the Mount Wilson 60-inch telescope with a specialized "HK photometer" devised by Vaughan *et al.* (*19*). The new instrument closely reproduces Wilson's original photometric system for the H and K lines but is simpler to calibrate and use than the apparatus it replaced. Its operation is indicated in Fig. 3.

The stars included in the first 11 years of the survey range in surface temperature from about 3000 to 7000 K, the latter being about 1000 K hotter than the Sun. All of them lie, with the Sun, in the lower main sequence of the Hertzsprung-Russell diagram in which the luminosity of stars is plotted against their surface temperature or color index (*20*), a function of stellar mass.

The relative HK flux scale of a star measured by the HK photometer depends not only upon the strength of the star's chromospheric emission but also upon the strength of its photospheric emission at the nearby wavelengths of the reference bands of the photometer. Thus, the relative HK flux is larger for a cool star than it would be for a hotter star with the same amount of chromospheric emission. To eliminate this effect, investigators often choose to express a star's HK flux as a fraction of its total energy output by applying a color correction (*21*). The resulting absolute HK flux indeed is denoted R_{HK}.

Examples of long-term stellar chromospheric HK flux records are shown in Fig. 4, in which R_{HK} is plotted on a logarithmic scale as a function of time, over an interval extending from 1966 to 20 September 1983.

To control the calibration of observations, some 14 stars having very weak and presumably nearly constant chromospheric emission were included from the beginning of the survey to serve as standards. The flux records of two standard stars (HD 207978 and HD 29645) are shown in Fig. 4, a and b. For these stars the seasonal scatter in R_{HK} is at a minimal level of about 2 percent and the seasonal average values of R_{HK} have remained constant to within about 1 percent, which must be regarded as the effective limit of stability of the measuring apparatus. Some of the standards exhibit seasonal scatter that is larger than in these examples, an indication that such scatter, even in the standards, is partly real and not the result of measuring errors.

The stars whose HK flux records are illustrated in Fig. 4 exhibit a wide variety of forms of behavior, from sunlike activity cycles to pronounced variations that are markedly different from the solar cycle as we know it. This variety in itself was a remarkable finding of Wilson's original study. The resemblance of some of these records to the solar cycle is made clear if one compares them to observations of solar K-line emission recorded daily since 1975 by Livingston (*22*) at the Kitt Peak National Observatory in Arizona by means of a solar K-line photometer (see Fig. 1c). The Kitt Peak index differs in scale by a factor of 2 from that used for stars at Mount Wilson; when this is taken into account, the solar record is seen to resemble that of the star HD 81809 (Figs. 1d and 4c), whose color index and rate of rotation are also close to the solar values. It is clear that the solar cycle itself would be discernible at stellar distances, were the Sun observed in its H and K lines.

At the time of publication of Wilson's survey in 1978 (*6*), the rotation rates of dwarf stars exhibiting cycles were unknown with the single exception of the Sun. The classical method of measuring stellar rotation depends upon the Doppler broadening of photospheric absorption lines in the stellar spectrum. The broadening is proportional to the line-of-sight component of surface velocity resulting from the rotation. In the Sun, whose equatorial speed of rotation is about 2 kilometers per second, the rotational broadening is so small as to be almost entirely masked by the intrinsic line widths produced by thermal and convective motions in the photosphere.

A feature of all the stars under obser-

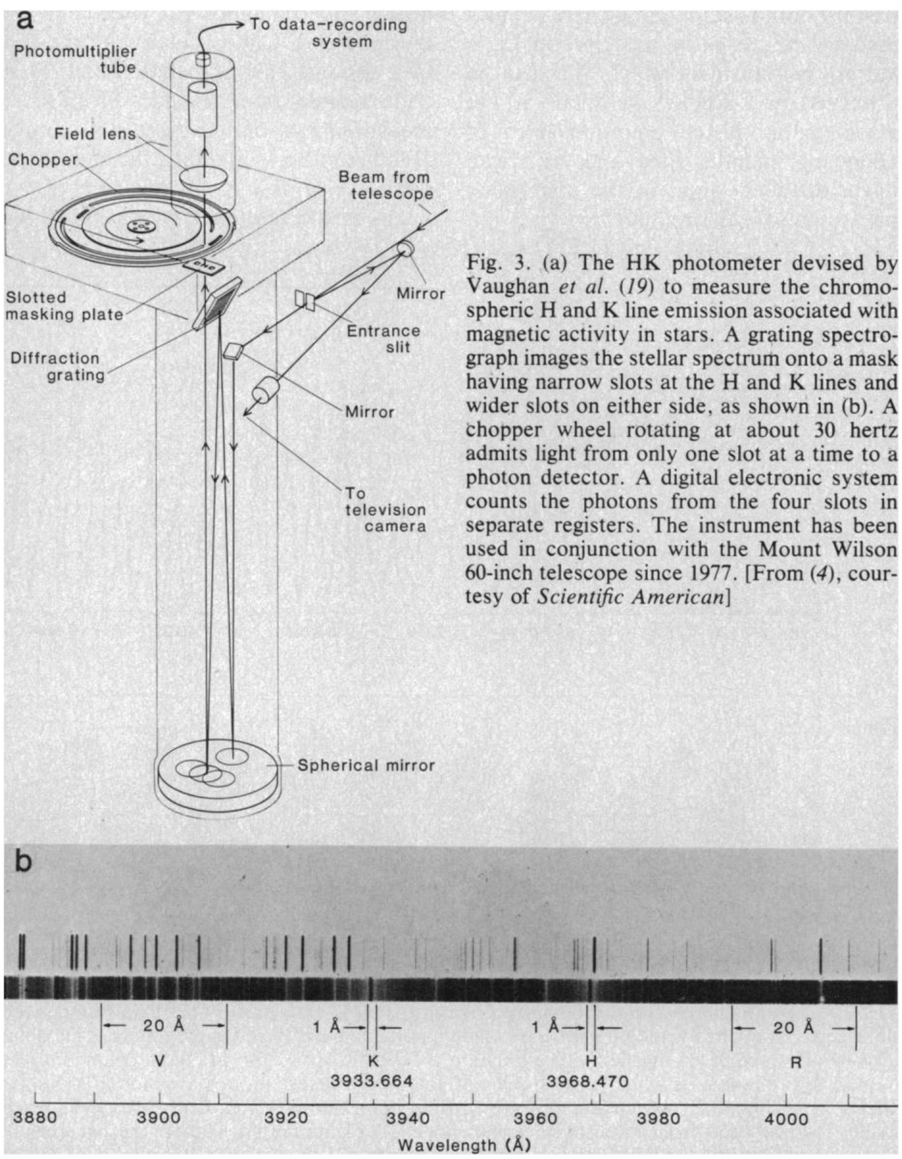

Fig. 3. (a) The HK photometer devised by Vaughan *et al.* (*19*) to measure the chromospheric H and K line emission associated with magnetic activity in stars. A grating spectrograph images the stellar spectrum onto a mask having narrow slots at the H and K lines and wider slots on either side, as shown in (b). A chopper wheel rotating at about 30 hertz admits light from only one slot at a time to a photon detector. A digital electronic system counts the photons from the four slots in separate registers. The instrument has been used in conjunction with the Mount Wilson 60-inch telescope since 1977. [From (*4*), courtesy of *Scientific American*]

vation, noted quite early in Wilson's survey and evident in Fig. 4, is the seasonal scatter in R_{HK}, small in the standards but many times larger than the errors of measurement in chromospherically active stars. Some part of this scatter must arise from sporadic events in the surface activity of a star. However, in the case of the Sun, occasionally a large "complex" of activity emerges and persists for several rotations. If this were to occur in a star, one would expect to see, superimposed upon any long-term variation that might be present, a periodic modulation of the HK flux index as the activity complex is carried into and out of view by rotation, the period of the modulation being equal to the star's period of rotation. Unresolved in observations at monthly intervals, the modulation would give rise to just such seasonal scatter as is observed.

To resolve the rotational modulation effect it would be necessary to make observations at intervals short as compared to the period of rotation, over a span of several weeks or months. Just such an intensive observing program was undertaken by a team of researchers working at Mount Wilson, beginning in July 1980 (*23*). This work demonstrated that in fact rotational modulation is the principal cause of the seasonal scatter in the long-term survey. Moreover, from these synoptic observations periods of rotation have thus far been determined, with a precision of a few percent, for 41 of the stars in the study. The observed periods range from 2.5 to 48 days (see Fig. 5).

From an early stage in the observation of rotational modulation in stars, a close connection was clearly apparent between a star's rate of rotation and the strength of its chromospheric emission in the H and K lines, in the sense that the faster the star's rotation, the larger the average value of its HK flux index; the relation between rotation and emission is also dependent upon stellar color index or temperature. Far-ultraviolet and x-ray emission in many of the same stars is also known to be correlated with rotation rate (*24*).

Rossby Relation

The rotation-activity connection is regular enough to suggest that it might be represented by a simple empirical formula. Recently, Noyes and his colleagues (*25*) discovered a formulation that, in addition to adequately representing the observations, may have theoretical significance. Their formulation makes use of a fundamental parameter in hydromagnetic dynamo theory known as the Rossby number. The dimensionless number is the ratio between the rotational period of a star and the "convective turnover" time (t_c) required for a convective element to traverse the convection zone. The convective turnover time

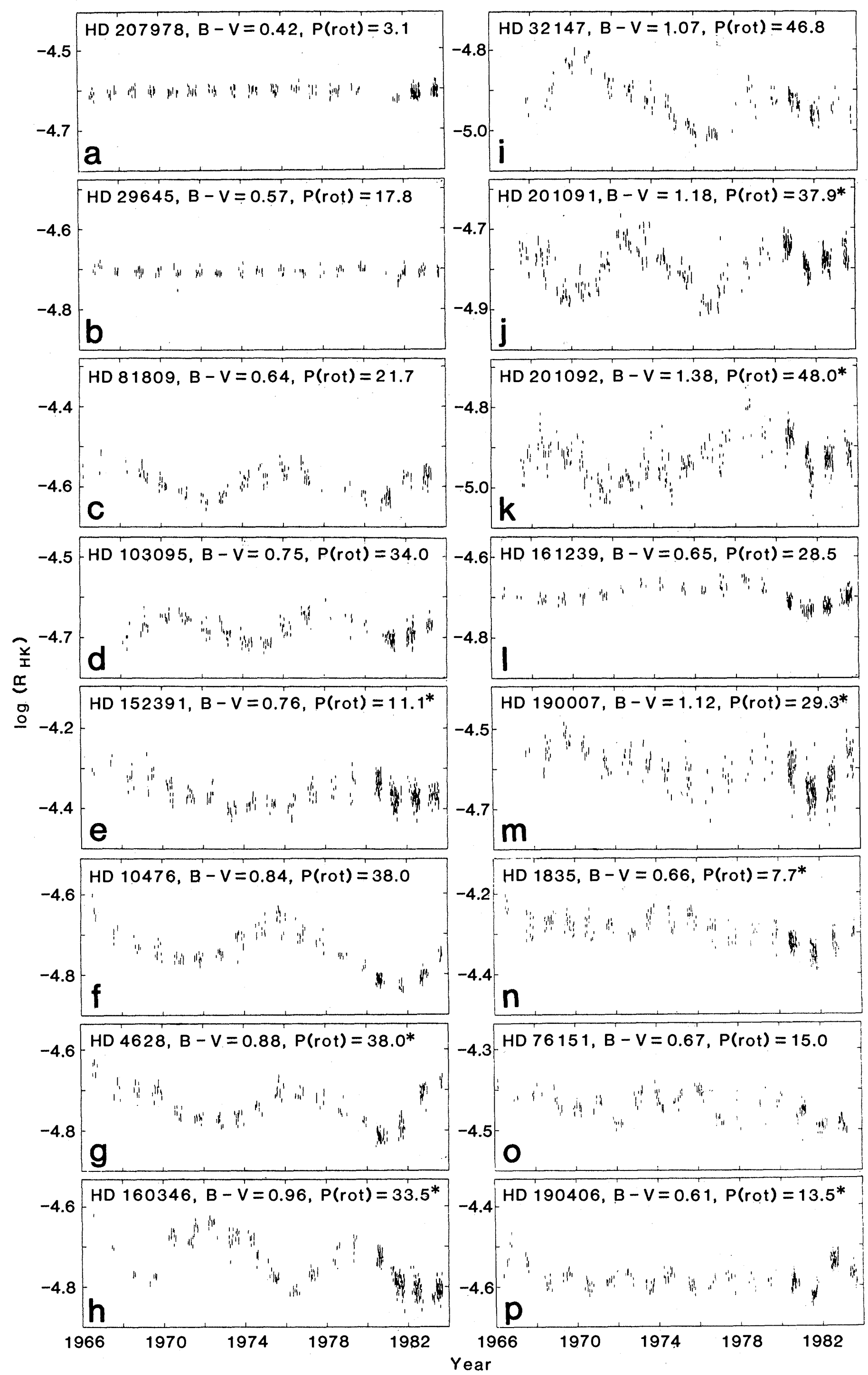

Fig. 4. Long-term HK flux records for 16 of the 91 stars that have been kept under consistent observation at Mount Wilson since 1966. The index R_{HK} (see text) is plotted on a logarithmic scale. A change of 0.1 in log R_{HK} represents a 26 percent change in R_{HK}. Stars are identified by their number in the Henry Draper catalog. The average of a night's observation for each star is plotted as a short vertical bar whose length is roughly equal to the accuracy of measurement. The measurements appear in seasonal groups separated by gaps of a few months of each year when a given star is out of range of nighttime observation. Prior to 1980, observations were limited to an average of about four nights per month. After June 1980, the frequency of observation was increased to a near nightly basis, resulting in the increase in density of points for the last four seasons. The legend for each star gives its B−V color index and its period of rotation [P(rot)] in days, either measured from its rotational modulation (with asterisk) or predicted from the Rossby relation (without asterisk) as described in the text.

depends upon the (not precisely known) depth of the convection zone; this depth in turn depends upon a parameter α describing the efficiency of the convective heat transport process in the convection zone of a star. Values for the turnover time in the Sun computed (*26*) from an approximate theory range from 4 to 16 days for values of α between 1 and 3. Rossby number is a measure of the importance of rotation-dependent Coriolis forces in producing helicity in the motion of rising convective eddies within the convection zone, which is usually regarded in dynamo theory as the location of the field generation process.

Noyes and his colleagues found that, when the chromospheric component of the mean HK fluxes of stars is plotted against their Rossby numbers in which the observed rotational periods are used, the points fall with fairly small scatter along a curve (Fig. 6a). This occurs, however, only if α is taken to be larger than unity (1.9 is perhaps close to the best value). Such a value for α is not in conflict with recent estimates, based upon theoretical calculations and upon helioseismology, for the depth of the convection zone in the Sun. That α should have the same value for all lower main sequence stars is an assumption remaining open to question, as the discoverers of the Rossby relation have emphasized.

Whatever the physical significance of the Rossby relation may prove to be, it can be a valid empirical tool with which to predict the period of rotation of a lower main sequence star from knowledge only of its color index or temperature and the average value of its H and K emission. For the stars used to derive the relation, the predicted periods are accurate to within about 20 percent (see Fig. 6b). By this method it is possible to supply predicted periods of rotation for all the stars under long-term observation and to examine the connection between rotation and their long-term behavior.

Trends in the Stellar Records

It is widely noted in the literature that stellar activity variations most strongly reminiscent of the solar cycle are mainly found only in stars with rotation periods in excess of about 20 days. Indeed, with one exception (HD 152391) (Figs. 4e and 5a), this is true of the 16 stars in the study that exhibit exceptionally well-defined and obvious cycles in their HK flux records.

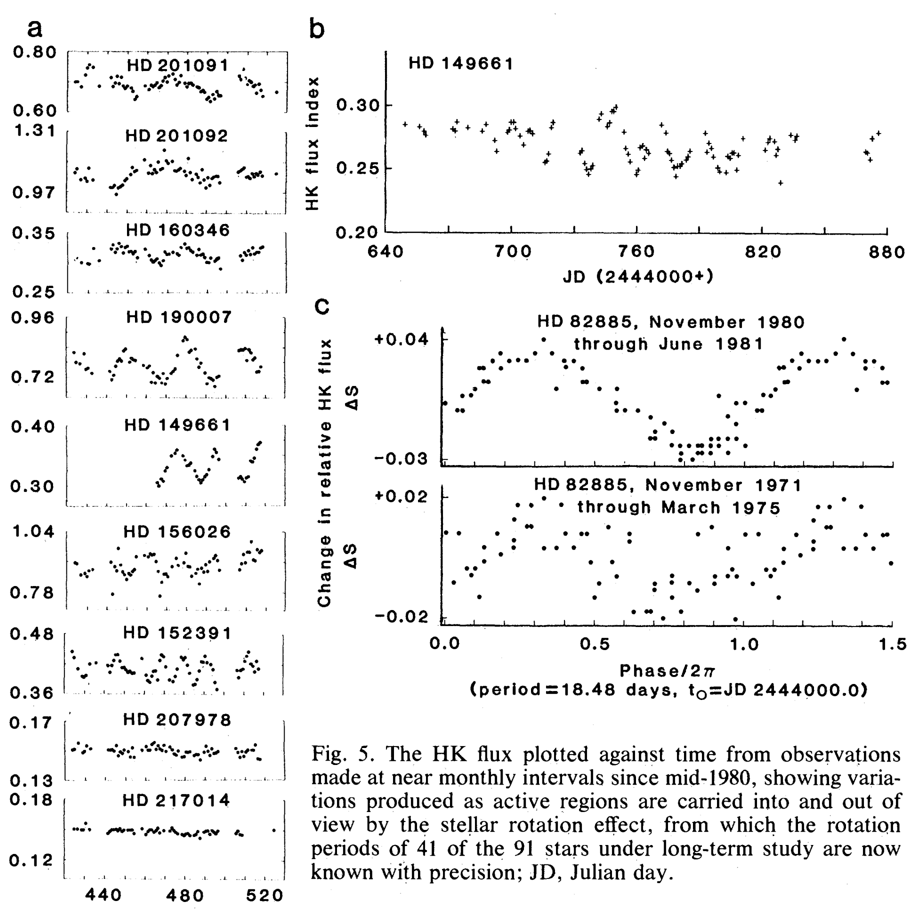

Fig. 5. The HK flux plotted against time from observations made at near monthly intervals since mid-1980, showing variations produced as active regions are carried into and out of view by the stellar rotation effect, from which the rotation periods of 41 of the 91 stars under long-term study are now known with precision; JD, Julian day.

Several characteristics familiar in the solar cycle can be noted in the stellar records. The scatter associated with rotational modulation usually becomes greatest near the maximum of the cycle. Successive maxima often differ appreciably in amplitude; this is especially notable in HD 160346 (Fig. 4h). Successive minima may also differ. In many cases, as in the Sun, the cycle rises to a maximum more rapidly than it declines after the maximum; HD 32147 (Fig. 4i) provides an extreme example of this, but for HD 201092 (Fig. 4k) the reverse is true. The intervals between successive maxima in stars range from about 7 to 12.5 years (or longer), with an average close to 10 years. For the Sun the long-term average is near 11 years, but the average is closer to 10 years in this century. The time between individual maxima has ranged from 8 to 14 years. The cause of this dispersion in the Sun is not known. Since the Sun must be regarded as a typical star, it is reasonable to suppose that the dispersion in stars arises at least in part from the same cause.

From the limited evidence now available one can say that whether a clear cycle exists seems to depend upon the rate of rotation of a star. Once the cycle becomes established, however, there is no obvious correlation between its time scale and the rotation period of the star or its color index or mass (*27*). Investigators are hopeful that systematic trends of some sort may yet be uncovered in studies that are in progress. Such trends, or their absence, could be of crucial importance in testing the divergent predictions of competing theoretical models of the cycle.

There are some 37 stars in the study whose observed or expected periods of rotation exceed about 18 to 20 days, including the 15 slow rotators already noted as showing pronounced sunlike cycles. Of the remaining 22 slow rotators, nine or ten can be described as probably cyclic but having ambiguous time scales. For example, HD 161239 (Fig. 4l) could have a cycle of about 12 years, but a component of variation on a time scale of about 4 years is also present. More than one time scale appears in HD 190007 (Fig. 4m) and perhaps also in other examples shown in Fig. 4. The activity of HD 156026 (Fig. 5a) increased more or less steadily from 1968 until 1980 but began to decline slightly in 1981: it could be an example of a cyclic star with a very long period. If we give the ambiguous cases the benefit of the doubt, it is possible that altogether 25 of the slowly rotating dwarfs in the study are cyclic. Even the remaining 12 slow rotators show some hint of long-term variation that could be significant but whose amplitude is much smaller than that of the solar cycle in the last two centuries. It is entirely conceivable that these dozen or so stars with weak activity (one-third of the sample of slow rotators that "might" be cyclic) are in a Maunder minimum state, in which the Sun may have spent a comparable fraction of its time in past epochs. If this is the case, then sooner or later such a star will regenerate its cycle or a star that now exhibits cycles will cease to vary. Half a millennium might elapse before any one star—or the Sun—undergoes another such change. But it is statistically likely that the waiting time for such an event will be reduced in proportion to the number of slowly rotating stars under scrutiny.

Even among stars that rotate rapidly one finds variations that could be construed as possibly sunlike or periodic, apart from the example of HD 152391 (Fig. 4e) already mentioned. HD 1835 (Fig. 4n) has twice declined slowly in activity for several years and then recovered in the span of one or two seasons. Similar "sawtooth" behavior is evident in HD 25998 and to some extent in HD 18256. HD 20630 remained at a high level for the first 6 years of the Wilson survey and then began to vary on roughly a 4-year time scale. Thus researchers suspect that the dichotomy between stars with and without cycles is perhaps not completely sharp.

It is among the more rapidly rotating stars that one encounters behavior quite unlike that exhibited by the Sun. HD 76151 (Fig. 4o) and HD 190406 (Fig. 4p) show prominent variations on time scales as short as 2 or 3 years and occasional systematic changes within a single season. Although common characteristics can be found in the HK flux records of such stars, these characteristics seem to emerge, like biological traits, in differing combinations from one individual star to another or even from one interval of time to another in the same star. With few exceptions, one can say that the more rapidly a star rotates, the more chaotic its chromospheric variations are likely to appear. Are distinct time scales or "modes" shorter than the "fundamental" sunlike cycle present in these stars? Given the sparseness of the data collected thus far, it is not yet possible to say.

A surprising fact uncovered by the study of rotational modulation was that in many stars the modulation continues unchanged in phase for very long times, far longer than the typical lifetimes of even the largest activity complexes on the Sun. An extreme example is perhaps HD 82885 (Fig. 5c), found (*28*) to show rotational modulation with remarkable stability in amplitude and phase over an 8-month interval in 1980–1981, with a period of between 18.0 and 18.6 days. Analysis of Wilson's survey subsequently showed (*29*) that, if the period is assumed actually to be 18.49 ± 0.05 days, the variations observed in 1980–1981 are almost exactly in phase with the unresolved variations of about the same amplitude in the survey data for this star throughout the decade from 1971 to 1981. It is difficult to understand how the precise location of a surface feature on a differentially rotating star could be thus "remembered" unless it is in some way associated with long-lived magnetic field patterns deep inside the star. Studies have shown that, even in the Sun, there is some tendency for active regions to occur preferentially at certain longitudes over intervals of several years (*30*). From geomagnetic studies it was inferred in 1975 that large-scale irregularities in the Sun's general dipolar magnetic field had persisted for as long as five sunspot cycles or 47 years (*31*).

In the chromospherically active star HD 149661 (Fig. 5, a and b) two frequencies of HK flux variation are sometimes simultaneously present, producing a "beat" in the modulation and a corresponding double peak in the autocorrelation. It is tempting to suppose that this effect might arise from a pair of active regions at different latitudes on the star in the presence of differential rotation (*29*). The two periods, 18 and 21 days, differ by 15 percent, which is comparable to the solar differential rotation between the equator and regions near the poles but larger than the solar differential rotation within the sunspot zones. The differential rotation in HD 149661 could well be larger than the Sun's. It is also conceivable that a star could have more than one spot zone (or active shear zone) in each hemisphere, although the butterfly diagram clearly shows that the Sun has only one. Ten stars have thus far been identified in the Mount Wilson survey that occasionally show such double periodicities (*32*).

About 5 years ago the HK photometer was used to survey (*33*) the HK emission fluxes in a large fraction (several hundred) of the dwarf stars in the northern celestial hemisphere within a distance of 25 parsecs (82 light-years) of the Sun. In this survey each star was observed only once or a few times, but the range of variation of an individual star is usually small enough that even a "snapshot" suffices reasonably well as an approximation of a star's average level of activity. To this solar neighborhood survey it is now possible to apply the Rossby relation in order to estimate from the known HK fluxes and colors the previously unknown periods of rotation of

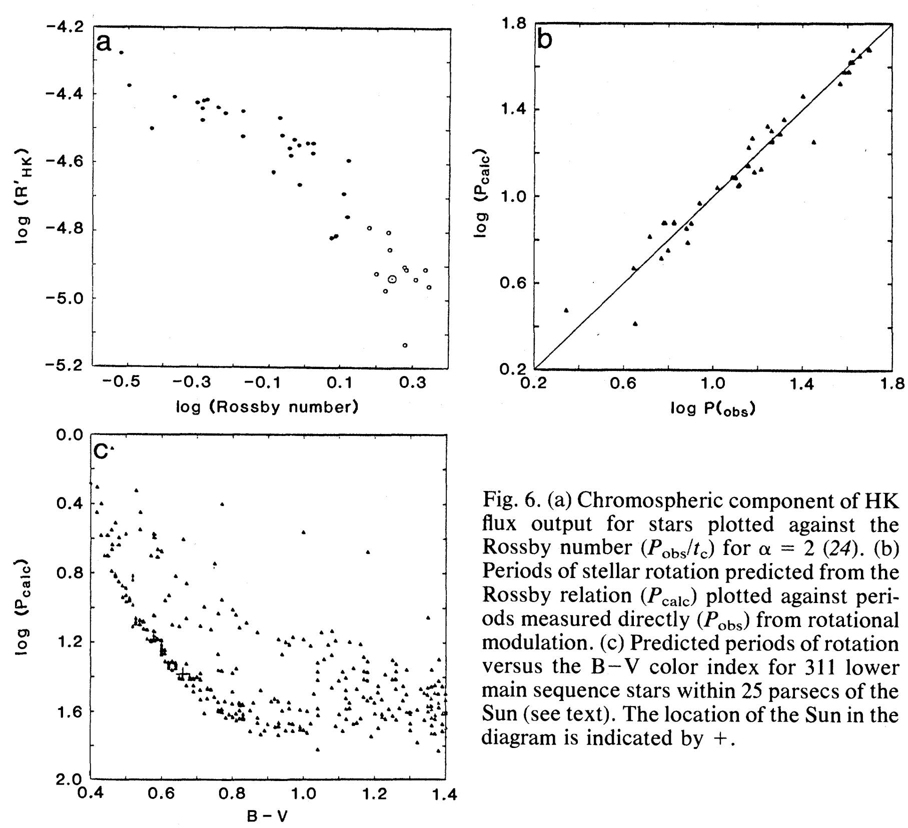

Fig. 6. (a) Chromospheric component of HK flux output for stars plotted against the Rossby number (P_{obs}/t_c) for α = 2 (*24*). (b) Periods of stellar rotation predicted from the Rossby relation (P_{calc}) plotted against periods measured directly (P_{obs}) from rotational modulation. (c) Predicted periods of rotation versus the B−V color index for 311 lower main sequence stars within 25 parsecs of the Sun (see text). The location of the Sun in the diagram is indicated by +.

these stars. The resulting periods are plotted, on a logarithmic scale (with periods increasing downward), against their B−V colors, in Fig. 6c. To minimize extrapolation beyond the range in which the Rossby relation is calibrated by observation, only stars with B−V less than 1.4 are plotted. Even so, the diagram should be regarded as tentative. Such a diagram is of interest for at least one reason, and possibly a second that can be mentioned only briefly.

It was established some years ago that both chromospheric activity and the rate of rotation of main-sequence stars decrease with advancing stellar age *(34)*, presumably as the result of torque exerted by the stellar wind. Thus, the early Sun would have been represented by a point at the top of the diagram in Fig. 6c. In the course of time this point would have moved almost vertically downward, reaching its present position after about 4.6 billion years. But its present position is very close to the rather sharp lower boundary of the distribution of points in the diagram, along with many other stars of about the same color, some of which must be even older than the Sun. This circumstance suggests that a star with B−V between about 0.45 and 0.9 slows in the course of time to some definite minimal rotation rate that is a function of its mass. Thereafter, either no significant further spindown occurs or else thereafter, unlike the Sun, the much older stars presumably included in the sample do not "obey" the Rossby relation. There is independent evidence from satellite measurements of the solar wind in interplanetary space that the angular momentum now being carried away from the Sun by particle flow and magnetic fields in the solar wind is not sufficient to account for significant further deceleration of the Sun's present rate of rotation *(35)*. Figure 6c may well provide a strong observational confirmation of this result and a demonstration that it is a universal phenomenon among dwarf stars, thus far unexplained by theory. Indeed, from Fig. 6c it can be inferred that this terminal rate varies as about the fourth power of stellar mass.

It is also of interest that in Fig. 6c the density of points, as far as can be determined from the limited number, decreases more or less smoothly upward, as would be expected if (as most investigations suggest) star formation has occurred in the Galaxy at an essentially uniform rate during the last few billion years, and if stellar spindown takes place smoothly as a function of time. The nonlinearity of the Rossby relation (in which the HK flux "saturates" at high rates of rotation) gives a plot of the HK flux against B−V an appearance rather different from that of Fig. 6c. Such a plot was discussed in *(33)*.

Sensitive modern techniques of observation are beginning to offer researchers the possibility of detecting other effects of magnetic activity besides the enhancement of chromospheric emission lines. These effects include the broadening of magnetically sensitive photospheric absorption lines (compared with insensitive lines) by the Zeeman effect in magnetically active stars *(36)*, from which the strength of the field can be directly inferred. Precise photometry can reveal the subtle variation in stellar brightness—or rotational modulation—caused by the presence of "starspots" in the case of very active stars *(37)*. From high-dispersion spectrograms of detailed features on the solar surface it is known that the profiles of the H and K lines differ systematically from one kind of feature to another; from study of changes in the line profiles as a star rotates, inferences might be made about the kinds of features present on its surface and their distribution in latitude and longitude. These and other detailed and systematic studies remain tasks for the future. It is reasonable to expect that the extension of solar physics into the domain of stars will continue to be an exciting venture.

References and Notes

1. Quoted from the article by A. M. Clerke in *Encyclopedia Brittanica*, ed. 14 (1929), p. 887.
2. A. Humboldt, *Kosmos* **1** (1851).
3. G. E. Hale and S. B. Nicholson, *Astrophys. J.* **62**, 270 (1925); list of errata, *ibid.* **63**, 72 (1926).
4. O. C. Wilson, A. H. Vaughan, D. Mihalas, *Sci. Am.* **244**, 104 (February 1981).
5. O. C. Wilson, *Science* **151**, 1487 (1966); an early attempt to uncover chromospheric variations in stellar spectra photographically was reported by D. Popper [*Astrophys. J.* **123**, 377 (1956)].
6. O. C. Wilson, *Astrophys. J.* **226**, 379 (1978).
7. G. Newkirk and K. Frazier, *Phys. Today* **35**, 25 (April 1982).
8. R. C. Carrington, *Observations of Spots on the Sun* (Williams and Norgate, London, 1863).
9. R. F. Howard, *Rev. Geophys. Space Phys.* **16**, 721 (1978).
10. ——— and B. J. LaBonte, *Astrophys. J.* **239**, L33 (1980).
11. P. A. Gilman and R. F. Howard, *ibid.*, in press.
12. J. A. Eddy, *Sci. Am.* **236**, 80 (May 1977); *Science* **192**, 1189 (1976).
13. M. Stuiver and P. D. Quay, *Science* **207**, 11 (1980); *Solar Phys.* **74**, 479 (1981); H. E. Suess, *Radiocarbon* **22**, 200 (1980); M. Stuiver and P. M. Grootes, in *The Ancient Sun*, R. O. Pepin, J. A. Eddy, R. B. Merrill, Eds. (Pergamon, New York, 1980), pp. 165–173.
14. J. A. Eddy, personal communication; *Solar Phys.* **89**, 195 (1983).
15. R. B. Leighten, R. W. Noyes, G. Simon, *Astrophys. J.* **135**, 474 (1962); R. Ulrich, *ibid.* **162**, 993 (1970).
16. A. Claverie, G. R. Isaak, C. P. McCleod, H. B. van der Raay, *Nature (London)* **293**, 443 (1981).
17. M. Schüssler, in International Astronomical Union Symposium 102, *Solar and Stellar Magnetic Fields: Origins and Coronal Effects*, J. O. Stenflo, Ed. (Reidel, Dordrecht, 1983), p. 213.
18. E. N. Parker, *Sci. Am.* **249**, 44 (August 1983).
19. A. H. Vaughan, G. W. Preston, O. C. Wilson, *Publ. Astron. Soc. Pac.* **90**, 276 (1978).
20. A measurement of surface temperature used by astronomers is the ratio of a star's radiant energy output at two selected wavelengths or, on a logarithmic scale, the difference in magnitudes at these wavelengths. In the most commonly used system the logarithmic color index B−V refers to the "blue" minus "visual" or yellow spectral regions. This index increases as temperature decreases and is close to 0.66 for the Sun.
21. F. Middelkoop, *Astron. Astrophys.* **107**, 31 (1982).
22. W. C. Livingston, personal communication.
23. A. H. Vaughan *et al.*, *Astrophys. J.* **250**, 276 (1981); S. L. Baliunas *et al.*, *ibid.* **275**, 752 (1983).
24. R. Pallavicini, L. Golub, R. Rosner, G. Vaiana, in International Astronomical Union Symposium 102, *Solar and Stellar Magnetic Fields: Origins and Coronal Effects*, J. O. Stenflo, Ed. (Reidel, Dordrecht, 1983), p. 77.
25. R. W. Noyes, L. W. Hartmann, S. L. Baliunas, D. K. Duncan, A. H. Vaughan, *Astrophys. J.*, in press.
26. P. A. Gilman, in International Astronomical Union Colloquium 51, *Stellar Turbulence*, D. Gray and J. Linsky, Eds. (Springer, Berlin, 1980), p. 19.
27. A. H. Vaughan, in International Astronomical Union Symposium 102, *Solar and Stellar Magnetic Fields: Origins and Coronal Effects*, J. O. Stenflo, Ed. (Reidel, Dordrecht, 1983), p. 113.
28. J. Frazer and H. Lanning, personal communication.
29. R. W. Noyes, *Second Cambridge Conference on Cool Stars, Stellar Systems, and the Sun*, M. S. Giampapa and L. Golub, Eds. (SAO Special Report 392, Smithsonian Astrophysical Observatory, Cambridge, Mass., 1982), vol. 2, p. 41.
30. J. W. Dodson and E. R. Hedeman, *Solar Phys.* **42**, 121 (1975).
31. L. Svalgaard and J. M. Wilcox, *ibid.* **41**, 461 (1975).
32. S. L. Baliunas *et al.*, in preparation.
33. A. H. Vaughan and G. W. Preston, *Publ. Astron. Soc. Pac.* **92**, 385 (1980); L. Hartmann, D. Soderblom, R. W. Noyes, N. Burnham, A. H. Vaughan, *Astrophys. J.* **276**, 254 (1984).
34. O. C. Wilson, *Astrophys. J.* **138**, 832 (1963); R. P. Kraft, *ibid.* **150**, 551 (1967); A. Skumanich, *ibid.* **171**, 565 (1972).
35. V. Pizzo *et al.*, *ibid.* **271**, 335 (1983).
36. G. W. Marcy, *ibid.*, in press.
37. R. R. Raddick *et al.*, *Publ. Astron. Soc. Pac.* **94**, 934 (1982).

38. Construction of the HK photometer was funded by National Aeronautics and Space Administration grant NSG 07148. The work at Mount Wilson was supported by the Carnegie Institution of Washington, by grants AST 79-21070 and AST 81-21726 from the National Science Foundation, and by grant 2548-82 from the National Geographic Society. The work reviewed owes its rapid recent development to the ideas and cooperative labors of many workers. I thank S. L. Baliunas, D. K. Duncan, J. A. Eddy, R. F. Howard, M. M. Neugebauer, G. Newkirk, R. W. Noyes, and O. C. Wilson for informative discussions and suggestions during the preparation of this article and W. C. Livingston for providing solar K line data in advance of publication.