Stellar Activity and Brightness Variations: A Glimpse at the Sun's History

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Radiometric measurements during the past decade from the Solar Maximum Mission and Nimbus 7 satellites have shown that the total solar irradiance varies in step with the sun's 11-year magnetic activity cycle. Stellar observations from the Lowell and Mount Wilson observatories now confirm and elaborate this discovery. These measurements show that older stars similar to the sun tend to become brighter as their magnetic activity level increases, just as the sun does during its 11-year activity cycle. Younger stars, however, tend to become fainter as their magnetic activity level increases. This contrasting behavior suggests that the balance between the competing phenomena that influence solar brightness variability has shifted during the sun's lifetime.

DOES THE SUN'S LUMINOUS OUTPUT VARY IN RESPONSE TO the appearance and disappearance of spots on its surface? Galileo, who is widely credited with the modern discovery of sunspots, may have asked this question. Certainly, his 17th-century contemporaries did (*1*). Experimentally, the question has proven difficult to answer (*2*). The most careful and determined ground-based measurements have demonstrated at best that any such fluctuations in solar brightness must be less than 1%. Significantly better precision may not be attainable from the ground, because it is hard to account accurately for sunlight absorbed and scattered by Earth's atmosphere. Measurements from spacecraft are, however, immune to this problem, and positive detections of irradiance variations associated with sunspots and other forms of solar magnetic activity have now been made by radiometers aboard the Solar Maximum Mission (SMM) and Nimbus 7 satellites (*3*).

Solar brightness variability involves a complex interplay between radiative flux deficits produced by sunspots, flux enhancements associated with active region faculae (*4*), and further contributions from bright magnetic network elements (*5*). On the time scale of days to weeks, dark sunspots and bright faculae cause solar irradiance fluctuations amounting to ~0.1%, with sunspots producing the most obvious effects (*6*). These variations arise both from the emergence and subsequent decay of sunspots and their associated faculae and from solar rotation, which carries these features into and out of view on the solar disk. The initial detection of this short-term variability by SMM and Nimbus 7 was quickly followed by the construction of competing irradiance models (7), which disagreed, in particular, about the importance of the facular contribution. Although it is now recognized that the facular excess roughly balances the sunspot deficit over the entire (several-month) lifetime of a solar active region (*8*), the relative prominence of the sunspot signature in the early SMM radiometry helped create a widespread (but mistaken) expectation that the sun would become brighter as its 11-year activity cycle waned and sunspots grew increasingly scarce (*9*). In fact, sustained measurements from both SMM and Nimbus 7 clearly showed that the sun became fainter by almost 0.1% between activity maximum (1980) and minimum (1986) and then started to recover as solar activity began its current rise (*10*). This behavior implies that solar brightness variability on the longer term time scale of the activity cycle is governed more by excess radiation from faculae and bright magnetic network features rather than by the sunspot deficit, which dominates the variability only on relatively short time scales (*11*).

With the existence of brightness variations connected to the sun's 11-year magnetic activity cycle now established, the study of relationships between solar phenomena and conditions in the terrestrial environment is attracting renewed attention. One example is the extended "Maunder Minimum" (*12*), which occurred from about 1640 to 1715 A.D., when magnetic activity was virtually absent from the sun and its radiative output was presumably reduced. The unusually cold weather experienced in northern Europe during the late 17th century was so extraordinary that the period is now known as the "Little Ice Age" (*13*). Was solar variability involved? Climate models suggest that a 0.2 to 0.5% reduction in solar irradiation during the Maunder Minimum could have produced a global cooling of about 0.4°C relative to the mean of that era, or about 0.9°C relative to the modern mean (*14*). Undoubtedly, our appreciation of the sun's role in climatic episodes such as the Little Ice Age will improve together with our understanding of solar variability. Unfortunately, a complete and confident characterization of solar variability and its relation to solar magnetic activity will require decades of additional solar observations covering many future activity cycles. For a more timely perspective on the sun's variability, we therefore look to the stars, especially those similar to the sun. Furthermore, the behavior of stars younger or older than the sun offers unparalleled insight into the likely past history and future course of solar activity and variability.

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The Magnetic Activity of Sun-Like Stars

The solar atmosphere is permeated and controlled by magnetic fields. The generation, configuration, evolution, and annihilation of these fields produce the phenomena collectively known as solar activity. The magnetic flux in solar active regions as well as the less conspicuous network is faithfully mapped by radiative emission from the solar chromosphere (*15*). Accordingly, chromospheric emission, especially that in the cores of the H (397 nm) and K (393 nm) resonance lines of ionized calcium (Ca II H & K), which are easily observed spectroscopically from the ground, provides a convenient and widely used diagnostic for solar and stellar magnetic activity.

Ordinary cool stars similar to the sun, that is, dwarf stars ranging from a few tenths up to about 120% of the sun's mass, always show chromospheric emission. By solar analogy, this emission is generally believed to reflect stellar magnetic activity. In 1966, using the Mount Wilson Observatory's 100-inch Hooker telescope, Wilson began a long-term study of 91 cool dwarf stars (*16*). Wilson discovered that the chromospheric Ca II H & K emission from most of the stars in his sample varied on the time scale of years, frequently in a regular fashion reminiscent of the 11-year solar activity cycle. In 1978, Wilson's study was transferred to the Mount Wilson 60-inch telescope, which has been dedicated entirely to the continuation and extension of his work (the "HK Project") (*17*).

These and related efforts have led to the realization that the average level of magnetic activity on a cool dwarf star is governed by its age, mass, and rotation rate (*18*). Young, rapidly rotating stars show strong activity that tends to vary irregularly rather than in a smooth cycle. In contrast, older, more slowly rotating stars, which as a class better resemble the present sun, have considerably lower average activity levels than do the exuberant stellar youngsters. The activity of these older stars, however, often varies in a smooth, cyclic fashion. The time scales of these stellar cycles range from a few years to a few decades. Among the older stars, those more massive than the sun tend to show low amplitude cycles, whereas those less massive than the sun almost always show an obvious cycle. Among stars of its age and mass, the sun currently has a relatively prominent activity cycle.

Starspots and Stellar Brightness Variability

The classic variable stars of astronomy, such as the eclipsing Algols, the pulsating Cepheids and Miras, and the eruptive novae, undergo brightness changes involving physical mechanisms that have nothing to do with magnetic activity and its associated spots, faculae, and chromospheric emission. However, the decades of effort aimed at accurately observing the brightness variability of such stars contributed directly to the development of the photometric techniques required to detect the more subtle brightness variations associated with stellar magnetic activity.

About 15 years ago, starspots were invoked to explain the photometric variations of a class of stars now known as the RS Canum Venaticorum (RS CVn) binaries (*10*). Their variability, which frequently amounts to 10% or more, is attributed to rotational modulation and to the growth and decay of enormous starspots (or starspot groups), by analogy with the sun. The variable components of the RS CVn systems are now believed to be evolved subgiant stars whose rapid rotation is enforced by tidal interaction with their nearby companions (*20*). Because of their extreme activity and the role played in its origin by tidal coupling, the RS CVn binaries probably do not represent particularly good solar analogs, and we do not consider them further.

More pertinent in the context of solar variability is another class of spotted stars, the BY Draconis (BY Dra) variables (*21*). These young, rapidly rotating, low-mass dwarf stars are characterized by unusually intense chromospheric emission as well as photometric brightness variations of several percent. Although many BY Dra variables are binary systems, others appear to be single stars (*22*). This discovery confirmed the suspicion that the strong magnetic activity of the BY Dra variables and the RS CVn binaries is actually a consequence of rapid stellar rotation rather than of the presence of a companion star, per se, and suggested that any cool dwarf star with sufficiently rapid rotation would show detectable brightness variations.

The first successful attempts to detect photometric brightness variability among ordinary, single, cool dwarf stars were undertaken about 10 years ago. In some cases, the targets were bright field stars, often selected from Wilson's survey (*23*). In others, members of nearby stellar clusters were observed (*24*). The most sustained of these latter efforts, now completing its ninth year at the Lowell Observatory, involves the Hyades, a young cluster about 10% of the age of the sun (*25, 26*). This study has shown that persistent brightness variability at the level of a few percent on the time scale of days to weeks is ubiquitous among cool dwarf Hyades stars. As is true for the sun, rotational modulation plus evolving stellar magnetic activity adequately explain the observed short-term photometric variations. Parallel photometric and chromospheric Ca II H & K emission observations of several Hyades stars from the Lowell and Mount Wilson observatories, respectively, show two characteristic patterns: (i) rotational modulation signals present in time series from the two observatories vary in antiphase, and (ii) abrupt, secular changes in photometric brightness are frequently accompanied by opposite (albeit more gradual) changes in chromospheric Ca II H & K emission. These patterns suggest that the stellar surface markings comprise dark continuum features spatially and temporally associated with bright emission features, a configuration strongly reminiscent of solar active regions with their dark sunspots and bright emission plages.

The Lowell Hyades observations also provided the first clear evidence of longer term, year-to-year brightness changes among young, solar-type stars. Like the short-term fluctuations, the longer term brightness variations amount to a few percent and are accom-

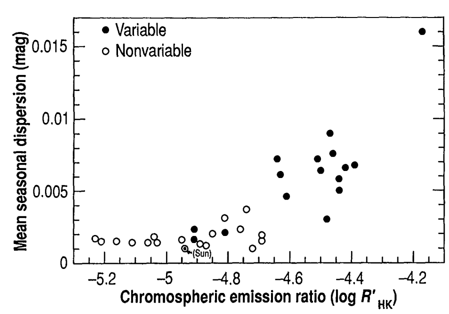


Fig. 1. Photometric variability on short (seasonal) time scales, compared with mean chromospheric activity. Photometric variability is plotted in logarithmic stellar magnitude units: 0.01 mag ≃ 1%, 0.001 mag ≃ 0.1%, and so forth. The chromospheric emission ratio, R'_{HK}, defined (*32*) as the chromospheric radiative emission in the cores of the H and K resonance lines of ionized calcium normalized by the stellar bolometric luminosity, measures the relative fraction of a star's total luminous output that is channeled through magnetic activity. Empirically, stars with strong chromospheric emission (and large values of R'_{HK}) show significant photometric variability (filled symbols) over seasonal time scales. The variability arises both from the axial rotation of a star whose surface contains spatially unresolved inhomogeneities (for example, starspots), and from the growth and decay of such features. The photometric variability inferred for the sun (not measured by us) is also indicated. All stars whose chromospheric activity is at least twice as great as the solar value show detectable brightness changes on short time scales. For stars weaker in chromospheric activity than the sun, seasonal photometric variability may be present but is masked by the experimental measurement limits.

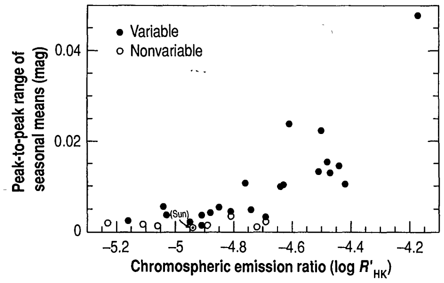


Fig. 2. Photometric variability over longer (year-to-year, the "activity cycle") time scales, compared with mean chromospheric activity, R'_{HK}. We have suppressed short-term variations by combining the individual measurements into annual means. The detectability threshold for year-to-year variation is therefore more sensitive than for intraseasonal variation. In contrast to the short-term variability shown in Fig. 1, more stars show significant longer term variations. In particular, year-to-year variability is clearly present among the older, less active stars similar to the sun. The long-term variability of the sun (not measured by us) has been indicated.

panied by changes in mean chromospheric activity. In sharp contrast to the sun, however, these young stars become brighter as their mean activity levels decrease, and inversely. This discovery raised several new questions: Does the relation between longer term photometric variability and chromospheric activity observed among Hyades stars characterize other young, active stars as well, or is it peculiar to the stars of the Hyades cluster? How do older, less active stars behave? Is the sun unusual among such stars?

The Current Program

To address such questions and to explore more fully the technically difficult and largely unknown regime of stellar variability below amplitudes of 1%, a new photometric study of stars similar to the sun was initiated at the Lowell Observatory in 1984 (*27*). Twenty-nine stars in the new Lowell study were selected from Wilson's original chromospheric activity survey. Four more are from the extension of that survey, the Mount Wilson HK Project, bringing to 33 the total number of stars for which regular, parallel observations exist from the two observatories.

A variety of stars were included in the sample: young, active stars similar to Hyades stars; older, less active stars with observed cyclic chromospheric activity; and HK Project standard stars that show little, if any, variability in their chromospheric Ca II H & K emission. Although most of the 33 stars are dwarfs, the sample also includes one subdwarf and six stars that may be slightly evolved subgiants. Most of the stars were observed contemporaneously at the two observatories for 4 years, although three stars were observed for 3 years and one star for only 2 years. The annual observing season for any given star typically spanned 4 to 6 months. Ten to 20 nights of photometric observations and 30 to 90 nights of Ca II H & K emission measurements were obtained for each star during each annual observing season.

The nightly root-mean-square (rms) measurement dispersion of intermediate-band photoelectric photometry from the Lowell Observatory is about 0.3% (*28*). Therefore, if no additional instrumental or stellar effects are present, a time series comprising 10 to 20 nights should yield a seasonal average having a mean standard deviation of about 0.1%. The new Lowell program achieved these standards: empirically, we found that photometric observations of quiescent stars were characterized by a nightly rms dispersion of 0.2 to 0.3% and a seasonal mean standard deviation often approaching 0.1%. We interpreted measured dispersions that significantly exceeded these instrumental thresholds as evidence of stellar brightness variability. Control observations of several (presumably) nonvariable reference stars formed an integral part of the Lowell observing procedure, providing calibration benchmarks within the photometric database and linking it together. Each program star was compared to at least two reference stars, enabling us to use consistency checks as a second variability diagnostic (*25*). The presence of previously unknown variable stars among our reference stars posed a hazard to the interpretation of our observations.

The nightly precision of the Mount Wilson observations is typically about 1%, which implies a mean standard deviation of less than 0.2% for the seasonal averages. Because fluctuations in stellar chromospheric activity tend to be much stronger than these instrumental thresholds, the identification of significant stellar Ca II H & K emission variations was relatively easy and straightforward.

Short-Term (Seasonal) Stellar Variability

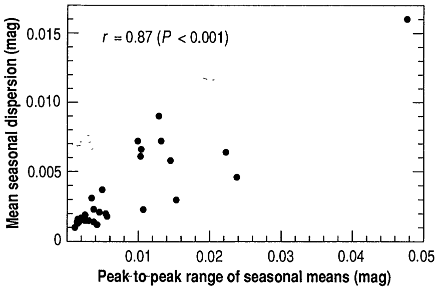
Sixteen of the 33 stars in the new sample exhibited statistically significant short-term (intraseasonal) photometric brightness variations during two or more years at levels ranging from several tenths of a percent to over 1% (Fig. 1) (*29*). Rotational modulation is certainly a major contributor to this variability. The onset of persistent, short-term variability occurred rather suddenly at a mean activity level about twice the solar value and was confined largely to the younger, more active stars in the sample. The infrequent detection of short-term variability among older, less active stars is probably a consequence of the experimental threshold imposed by the night-to-night measurement error rather than evidence that such stars lack intrinsic variability. The sun itself, if observed in this manner, would be judged quiescent on the seasonal time scale, because its intrinsic short-term brightness variability rarely, if ever, exceeds the nightly instrumental precision (about 0.2 to 0.3%) of the Lowell photometry.

Strictly coincident measurements from the two observatories (one in Arizona, the other in California) were rare, in part because the sites tend to experience opposite weather patterns and in part because high-precision photoelectric stellar photometry requires excellent observing conditions, which occur only part of the time even at sites such as the Lowell or Mount Wilson observatories. No star was observed on more than 15 common dates per annual observing season, and the average was only seven. However, the available coincident observations clearly showed that short-term brightness fluctuations among the stars of the present program tend to be accompanied by inverse changes in chromospheric emission, just as they are for both the sun and Hyades stars. Thus, the sense of the relation between short-term brightness and chromospheric emission variations appears to be the same for all ordinary, cool, dwarf stars, including the sun. The observed behavior also suggests that active regions are a characteristic surface feature of all such stars.

Longer Term (Year-to-Year) Stellar Variability

Before examining the observations for evidence of longer term (year-to-year) variability, we suppressed short-term effects such as rotational modulation and active-region evolution by averaging the observations from each annual observing season. Applying objective criteria derived from formal statistical tests to these annual means, we found that 21 of the 29 stars observed for the full 4 years showed significant year-to-year photometric variability at levels ranging from a few tenths of a percent to over 4% (Fig. 2). Like the short-term variability, these longer term brightness fluctuations were more prevalent among the active stars of the sample. Unlike the seasonal variability, however, significant year-to-year variation was also detected among the less active stars. The variability of these less active stars rarely exceeded two or three times the solar level of about

Fig. 3. Short time scale photometric variability, compared with longer time scale variability. The correlation is highly significant (P is the probability of exceeding r with a random sample drawn from an uncorrelated parent population) and remains so even when the outlying point at the upper right is removed.



0.1%, which suggests that the amplitude of the year-to-year variability of the sun is fairly typical for such stars.

Short-term (seasonal) stellar variability, through rotational modulation, strongly reflects nonuniformities in the spatial distribution of stellar surface markings. In contrast, longer term (year-to-year) variability is mainly driven by real evolutionary changes in the number or contrast of these features, since averaging largely eliminates the rotational signal. Thus, even though the two variability measures are probably linked by a common underlying phenomenon, namely, stellar magnetic activity, one does not cause the other, nor are they functionally related. Therefore, in our examination of their relation we have treated them as random variables governed by a bivariate distribution. There is excellent correlation between the amplitudes of the observed short-term and longer term variability in the sample (Fig. 3), which suggests that stars tend to preserve irregularities in the distribution of their surface features even as the number of these features changes. This conclusion is reinforced by the fact that stellar rotational modulation signals tend to exhibit phase stability, even through episodes of active region evolution. The sun maintains such phase stability by creating successive active regions at relatively fixed "active longitudes" (*30*). Our observations imply that other stars may do the same.

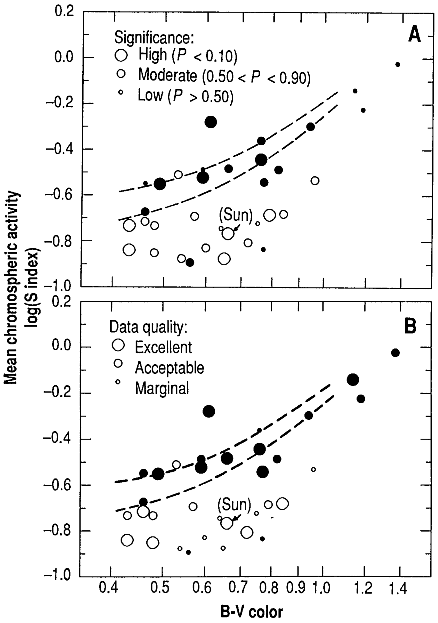


Fig. 4. The correlation between year-to-year photometric brightness fluctuations and changes in chromospheric activity level, plotted on axes that show the relation between two fundamental stellar observables, one measuring mean chromospheric activity (the Mount Wilson S index), the other measuring stellar surface temperature (the photometric B-V color index). The B-V color index increases with decreasing stellar mass and temperature for dwarf stars: thus, cooler, less massive stars are located toward the right side of the diagram. Chromospheric activity increases with larger values for the S index for a given (B-V) color. The S index also has a B-V color dependence, which accounts for much of its overall upward trend toward the right in this diagram (the emission ratio $R'_{\rm HK}$ of Figs. 1 and 2 is derived from the S index, in part by correcting for this color dependence). The two dashed lines enclose the region occupied by stars of the Hyades cluster and therefore indicate the run of mean activity for a sample of young stars with a common age but various colors (*33*). In both (A) and (B), open symbols represent positive correlations (that is, sun-like behavior) and filled symbols indicate anticorrelations. The symbols in (**A**) also encode by their size the formal significance of the correlation between year-to-year chromospheric activity changes and photometric brightness fluctuations. The symbols in (**B**) encode the quality of the underlying photometric data: the three sizes represent a subjective, but consistent, evaluation. The sample is strongly segregated: the young, active stars typically show an anticorrelation, and the older, less active stars (and the sun, which is also represented) show a positive correlation between year-to-year photometric brightness variations and chromospheric activity changes.

Because stellar activity cycles tend to be roughly comparable in length to the 11-year solar cycle, an observational record spanning 4 years is just too short to cover an entire cycle for many stars. Meaningful information about the longer term behavior of stellar activity, however, can be derived from time series substantially shorter than an entire activity cycle, provided the analysis is based on high-quality observations, or a numerous sample, or both. Although the precision of the present stellar observations does not match that of the solar radiometry from SMM and Nimbus 7, the size of the stellar sample provides some compensation for this. Therefore, initial examination of the Lowell and Mount Wilson observations for stellar brightness variations related to cyclic behavior in chromospheric activity is warranted.

Analysis of the annual mean measurements from the two observatories revealed that continuum brightness variations accompany changes in stellar chromospheric activity on the time scale of years. Furthermore, the sense of the relation appears to depend on mean stellar activity (Fig. 4). The younger, more active stars in the sample showed the pattern that characterizes Hyades stars: their brightness varied inversely with chromospheric activity changes on the year-to-year time scale. On the other hand, older, less active stars tended to show solar-like behavior: their brightness varied directly with changes in chromospheric activity.

The segregation of the two groups is striking. There are several stars in each group for which excellent observations were obtained, and no such star showed discrepant behavior. In fact, only three stars in the entire sample are obviously discrepant, and the photometric observations for two of these three have weak significance because of contamination from variable reference stars. The correlation between annual mean activity and annual mean brightness for several stars in each group was highly significant. For such stars, the sense of the relation between activity and brightness is obvious from simple inspection of the underlying mean values and their formal uncertainties (Fig. 5).

The Evolution of Stellar Magnetic Activity and Brightness Changes

The available evidence suggests that the activity of all ordinary, cool dwarf stars can be interpreted in terms of familiar solar phenomena, namely, magnetic active regions containing both dark and bright features, which are distributed nonuniformly over the stellar surface. On young stars, these features are more numerous, or larger, or have higher contrast than on older stars such as the sun, because the activity signatures observed on young stars are stronger and vary with greater amplitudes. The dark spots must also be more prominent relative to bright continuum features on young stars, since the spots dominate the photometric brightness variability on all time scales for such stars, rather than on just the short-term time scale, as for the sun. The observed amplitudes of the photometric variations suggest that the fractional surface coverage of dark spots on young stars is at least ten times greater than it is for the sun. The surface coverage of bright features, however, is enhanced by a smaller factor, possibly no more than 3 (*31*). Young stars apparently prefer to arrange their larger amount of surface magnetic flux into

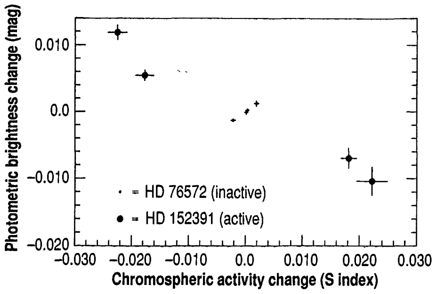


Fig. 5. Examples of the relation between year-to-year brightness variations and chromospheric emission changes over 4 years for a young, magnetically active star (HD 152391) and an older, less active star (HD 76572), comparable to the sun in magnetic activity. The contrasting behaviors of the two stars are clearly evident. The young star shows large-amplitude, anticorrelated variations in photometric brightness and chromospheric activity over the 4 years. The older star, on the other hand, shows much smaller, but positively correlated, year-to-year brightness and activity changes, just as the sun does during its activity cycle. The error bars (in both coordinates) represent the mean standard errors of the observations. In fact, much of the dispersion indicated by these bars arises from short-time-scale stellar variability rather than measurement error.

dark spots or spot groups rather than into bright faculae and magnetic network features.

As a solar-type star ages, its rotation slows, its overall level of activity gradually declines, and it tends to develop (or at least reveal) a smooth, regular activity cycle. The evolution of its brightness variability is probably more complicated, because the balance between the competing effects of dark spots and bright features, which initially favors the spots on all time scales, gradually shifts as the star ages to favor the bright features on the time scale of the stellar activity cycle. An overall decline in variability that simply reflects the evolutionary decay of stellar activity also occurs. At some point the spot deficit and the bright feature excess must pass through a temporary balance on the time scale of the activity cycle. A solar-mass star would reach this stage after about a billion years, that is, somewhat more than the age of the stars in the Hyades cluster. The mean activity of such a star, however, will still be high, relative to that of the present sun, and it should also show considerable short-term brightness variability arising from rotational modulation and active region evolution. For a star the age of the sun, the bright feature excess has become dominant on the time scale of the activity cycle, and year-to-year brightness variability has reappeared, albeit at a lesser amplitude than during the earlier, spot-dominated episode. Short-term variability continues to show a prominent spot signature. Older stars may conceivably also experience extended intervals, analogous to the solar Maunder Minimum, when activity, spots, and variability are all virtually absent.

If the sun itself has followed such an evolution, then the stars do, indeed, provide us with a unique glimpse at its history.

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2. For example, C. Abbott, *Smithsonian Misc. Collect.* **146** (no. 3) (1963). R. J. Angione [in *Variations of the Solar Constant*, S. Sofia, Ed. (NASA Conference Publication 2191, National Aeronautics and Space Administration, Washington, DC, 1980), p. 11–29] and R. C. Willson [*Space Sci. Rev.* **38**, 203 (1984)] have reviewed the history and technology of solar irradiance measurements.
3. Recent discussions of the SMM and Nimbus 7 radiometry may be found in papers by R. C. Willson and H. S. Hudson [*Nature* **332**, 810 (1988)] and C. L. Wolff and J. R. Hickey [*Science* **235**, 1631 (1987)], respectively. The Active Cavity Radiometer Irradiance Monitor (ACRIM) instrument aboard SMM was the first spacecraft experiment flown with the measurement of total solar irradiance as its primary goal. The earlier, but sparser and less precise, radiometry from the Earth Radiation Budget instrument aboard Nimbus 7 provided hints of solar irradiance variability [J. R. Hickey *et al.*, in *Variations of the Solar Constant*, S. Sofia, Ed. (NASA Conference Publication 2191, National Aeronautics and Space Administration, Washington, DC, 1980), pp. 59–72], but it was the initial SMM-ACRIM data [Willson *et al.* (*6*)] that decisively proved the existence of solar irradiance variations.
4. Active regions are temporary concentrations of magnetic flux on the solar surface. Young active regions often contain relatively cool, dark sunspots as their most prominent features. Sunspots have long been known to contain intense magnetic fields [G. E. Hale, *Astrophys. J.* **28**, 315 (1908)] and are dark because these fields interfere with convective energy transport immediately beneath the solar surface, or photosphere. Surrounding the sunspots are bright, but very small, features called faculae. The faculae are generally believed to mark where individual magnetic flux tubes penetrate the solar photosphere. These flux tubes are too small to inhibit convection, so they are not dark. Instead, they appear bright, because they increase the local emissivity by exposing hotter gas underlying the photosphere. Excess heating of the solar chromosphere above the facular areas creates emission plages, which are easily detected by their enhanced radiation in certain spectral lines. As an active region ages, its spots disappear and its faculae disperse, merge with the active network, and eventually also disappear.
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8. See Oster *et al.* (*7*); J. K. Lawrence, G. A. Chapman, A. D. Herzog, J. C. Shelton, *Astrophys. J.* **292**, 297 (1985); P. Foukal and J. Lean, *ibid.* **302**, 826 (1986).
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11. C. de Charentenay and S. Koutchmy [*C. R. Acad. Sci.* **301**, 151 (1985)] appear to have been the first to correctly predict and explain this behavior. Still others [for example, K. H. Schatten, in *Solar Irradiance Variations on Active Region Time Scales*, B. J. LaBonte *et al.*, Eds. (NASA Conference Publication 2310, National Aeronautics and Space Administration, Washington, DC, 1983), pp. 125–131] had predicted that the solar brightness would not respond at all to the activity cycle.
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Mental Models in Narrative Comprehension

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Readers of stories construct mental models of the situation and characters described. They infer causal connections relating characters' actions to their goals. They also focus attention on characters' movements, thereby activating nearby parts of the mental model. This activation is revealed in readers' faster answering of questions about such parts, with less facilitation the greater their distance from the focus. Recently visited as well as imagined locations are also activated for several seconds. These patterns of temporary activation facilitate comprehension.

THIS ARTICLE IS A REVIEW OF RESEARCH ON HOW READERS or listeners construct mental models of the situation a writer or speaker is describing. This skill is the basis of language comprehension. Cognitive psychologists and education specialists focus on research in reading comprehension, because it involves many components of intelligence: recognition of words, decoding them into meanings, segmenting word sequences into grammatical constituents, combining meanings into statements, inferring connections among statements, holding in short-term memory earlier concepts while processing later discourse, inferring the writer's or speaker's intentions, schematization of the gist of a passage, and memory retrieval in answering questions about the passage. Thus, the study of comprehension has become for cognitive psychologists what the fruit fly became for geneticists, a means of investigating many issues (*1*). We describe studies of comprehension of elementary narratives or stories that have a simple structure. We do not distinguish studies based on reading from those based on listening, since the input modality is irrelevant to the points at issue.

Most researchers agree that understanding involves two major components (*2, 3*). First, readers translate the surface form of the text into underlying conceptual propositions. Second, they then use their world knowledge to identify referents (in some real or hypothetical world) of the text's concepts, linking expressions that refer to the same entity and drawing inferences to knit together the causal relations among the action sequences of the narrative. The reader thus constructs a mental representation of the situation and actions being described. This referential representation is sometimes called a mental model or situation model. Readers use their mental model to interpret and evaluate later statements in the text; they use incoming messages to update the elements of the model, including moving the characters from place to place and changing the state of the hypothetical story world. Readers tend to remember the mental model they constructed from a text, rather than the text itself (*2, 3*). The bare text is somewhat like a play script that the reader uses like a theater director to construct in imagination a full stage production. Throughout the story the narrator directs the reader's focus of attention to a changing array of topics, characters, and locations, thus making these elements temporarily more available for interpreting new information.

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Narrative Components

The internal representation of a narrative contains two major parts. First, an internal representation includes descriptions of the cast of characters, their occupations, relationships, and personal traits. These are important because they usually explain the characters' goals, plans, and actions as the plot develops. Second, the representation includes a mental map of the physical settings in which the actions occur. The settings provide enabling (or constraining) conditions for the actions.

Simple narratives usually center around a main character who has a complicated problem to solve, and the story describes his or her actions in overcoming obstacles to the solution. Readers assume that characters' actions can be explained by their goals and plans as played out within the constraints of the situation. By such explanations, readers build a network of causal connections among the events in the story—from some initiating events (for example, the rustlers steal cattle) through the various goals, subgoals, and actions of the main character (the sheriff chases them), overcoming obstacles (they shoot at him), arriving at some final resolution (he captures the rustlers and retrieves the cattle). Each goal is viewed as causing some actions that lead to outcomes.

Readers consider events on this main causal chain to be the most significant parts of a story. Trabasso and his associates (*4*) analyzed many simple narratives, asking whether each event (described in a story statement) was enabled or caused by earlier events, or enables