STELLAR ACTIVITY: ASTROPHYSICS RELEVANT TO GLOBAL CHANGE

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ABSTRACT

FRESIP will obtain a great deal of data on stellar activity and flares on F, G and K dwarfs. Rotation periods, flare distributions and possibly stellar cycles will emerge. This apparently curiousity-driven research actually has implications for our understanding of global climate change. Significant climate change during the seventeenth-century Maunder Minimum is thought to be related to a change in the solar condition. Recently acquired data from the Greenland Ice-core Project suggest that far greater climate changes on decade time scales may have occurred during the previous interglacial. It is possible that a yet more drastic change in state of the Sun was responsible. We have no relevant solar data, but can begin to explore this possibility by observing an ensemble of solar-like stars.

1. SOLAR VARIABILITY AND GLOBAL CHANGE

While the variability of the Sun on time scales ranging from seconds (flares) to weeks (active regions) to years (sunspot cycle) has been known and recognized for decades, it has only been in the past 20 years or so that we have learned that this is only one of at least two, and perhaps more, states that the Sun may be in. We now know that from about 1640–1715 AD the Sun was in a significantly different state known as the Maunder Minimum, and that this state was associated with a major climate change called the "Little Ice Age." During these decades, winters in Europe (and presumably elsewhere) were significantly more severe than at present: ice was a problem on the Thames, Baltic seaports were frozen over for several weeks longer than before, glaciers in the Alps grew in size, etc. (see Noyes 1982).

The "Little Ice Age" clearly had significant consequences. However at this time we still do not know what the actual global temperature change amounted to in comparison to that of today. Estimates range from a mere 0.4 C to as much as 1.5 C (see Noyes 1982, Baliunas and Jastrow 1990 and references therein). The corresponding change in the solar constant may have been as little as 0.22 percent or as much as 0.75 percent.

Moreover a variation in the local irradiance is not the only factor at work in climate change. Numerous secondary influences are also liable to be important. For example, the height of the troposphere is known to be sensitive to seasonal changes in solar flux due to the earth's orbital eccentricity. Changes in atmospheric circulation are thus likely to result from changes in the solar irradiation. In this way, rainfall and snowfall patterns, for example, could vary with a change in the solar constant.

Radiocarbon records suggest that over the past few thousand years the Sun may have spent perhaps one-third of its time in a Maunder Minimum-like state.

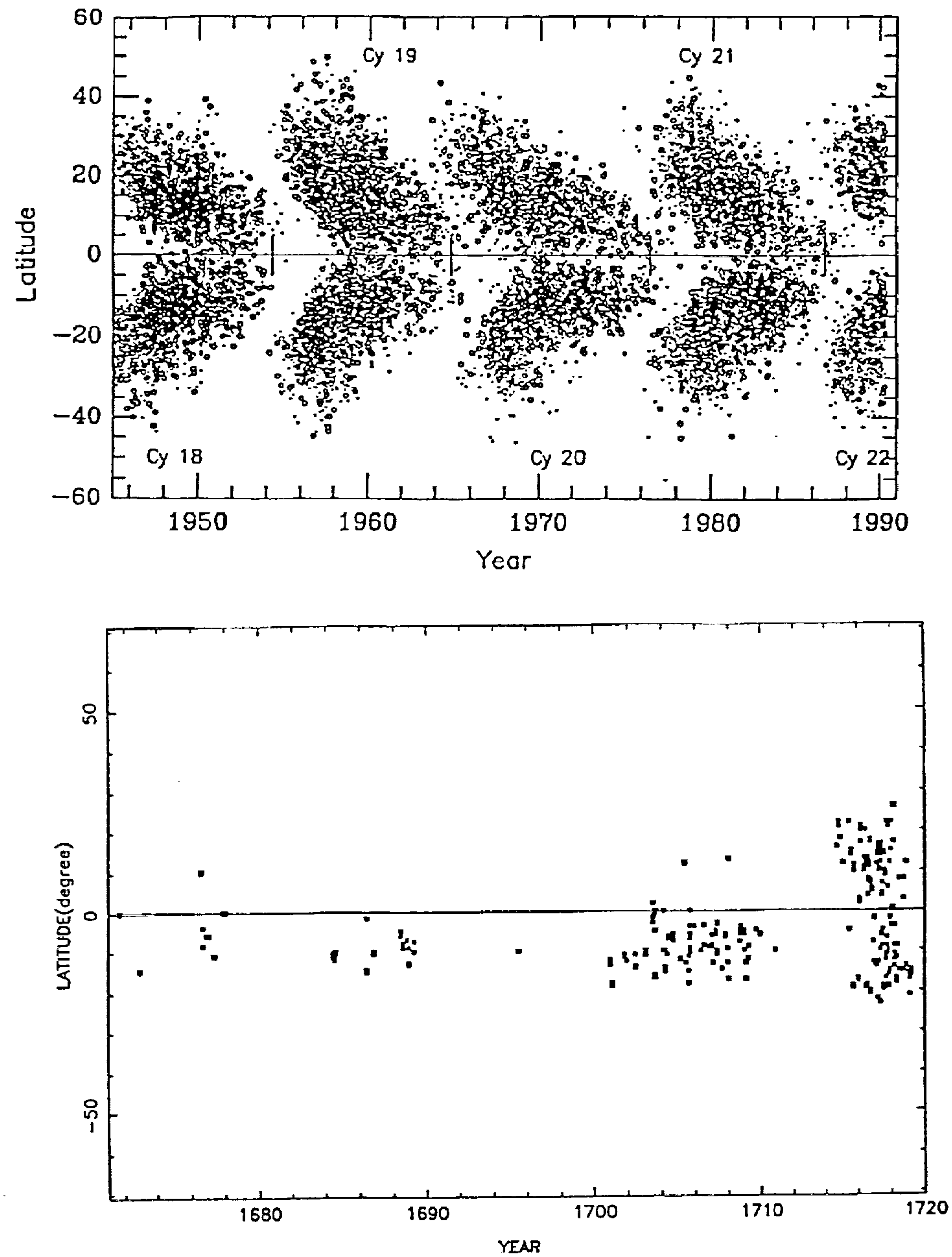


Figure 1. (top) Butterfly diagram of sunspots from the modern era showing parts of the five current solar cycles. (bottom) The same diagram during the Maunder Minimum inferred from observations at the Observatoire de Paris from 1660 to 1719. (from Ribes and Nesme-Ribes 1993)

As significant as the Little Ice Age may have been during relatively recent times, that change in climate phase pales in comparison to recent evidence from the Greenland Ice-core Project (GRIP 1993, White 1993). Civilization has arisen in the 10000 years that the earth has now been basking in an interglacial period. How stable is our interglacial climate? The new GRIP data suggest up to 10 C changes in temperature on a time scale of perhaps

5–20 years (!) from time to time during the last interglacial (Eemian) period some 115000 to 135000 years ago. Such a fluctuation today would have catastrophic consequences on societies, economies and eco-system. Unfortunately there is no solar data whatsoever to correlate with this huge climate perturbation. It is certainly suggestive that an even more dramatic change in the Sun than the Maunder Minimum may have occurred.

We are extemely limited in our ability to study the Sun on long time scales. However with FRESIP we can examine many other stars like the Sun and in effect study the sun in time by observing the distribution of activity states of solar-like stars.

Figure 1 (from Ribes and Nesme-Ribes 1993) is a butterfly diagram of the solar cycle reconstructed from 8000 daily observations made at the Observatoire de Paris from 1660 to 1719, i.e. during most of the Maunder Minimum, in comparison to the past fifty years. Sunspots were quite rare.

How do other stars come into play? The Mt. Wilson multi-year monitoring of Calcium H and K line indices of solar-like stars (see Baliunas and Vaughan 1985 and references therein) has resulted in an apparent correlation between low Ca index and lack of stellar cyclic variation, as in the case of the Sun during the Maunder Minimum. Moreover it appears that solar-like stars exhibit a somewhat bimodal distribution in the Ca index suggestive of two activity states analogous to the Maunder-minimum Sun and the "normal" Sun (Baliunas and Jastrow 1993).

We may thus be able to understand the states of the Sun in time (which may well be more than two) by studying the present distribution of spottedness of an ensemble of solar-like stars. On a multiyear time scale we may even be able to catch a star in transition from one phase to another.

Such a study of stellar activity is clearly more than simply curiousity driven research. Our ability to understand our own global environment may depend on how well we learn to interpret apparently subtle changes and differences in other stars.

2. ACRIM SOLAR OBSERVATIONS

The Active Cavity Radiometer Irradiance Monitor (ACRIM) onboard the Solar Maximum Mission obtained absolutely calibrated solar bolometric flux measurements with 131 s sampling over most of a solar cycle (1980–1989) (see Hudson 1988, Willson 1994). Measurements with this instrument produced the first unequivocal detection of total (bolometric) solar irradiance variability. Figure 2 shows a dip in the irradiance coinciding with the passage of a sunspot group across the disk. This is not a unique event. Daily averages during 1980 show numerous dips associated with passage of spot groups as shown in Figure 3 (top).

Upon examining the light curves of Figures 2 and 3 more carefully one finds that there are enhancements of the flux as well as dips. In fact the enhancements often show up as "wings" on either side of sunspot deficits. Enhancements are due to increased emission from active region plage and faculae. In an idealized situation consisting of a single active region one would first measure an enhancement as plage and faculae surrounding spot groups rotate onto the visible hemisphere; as the spots appear the light curve would begin to dip, reaching a minimum as the active region/spot group transits the central meridian

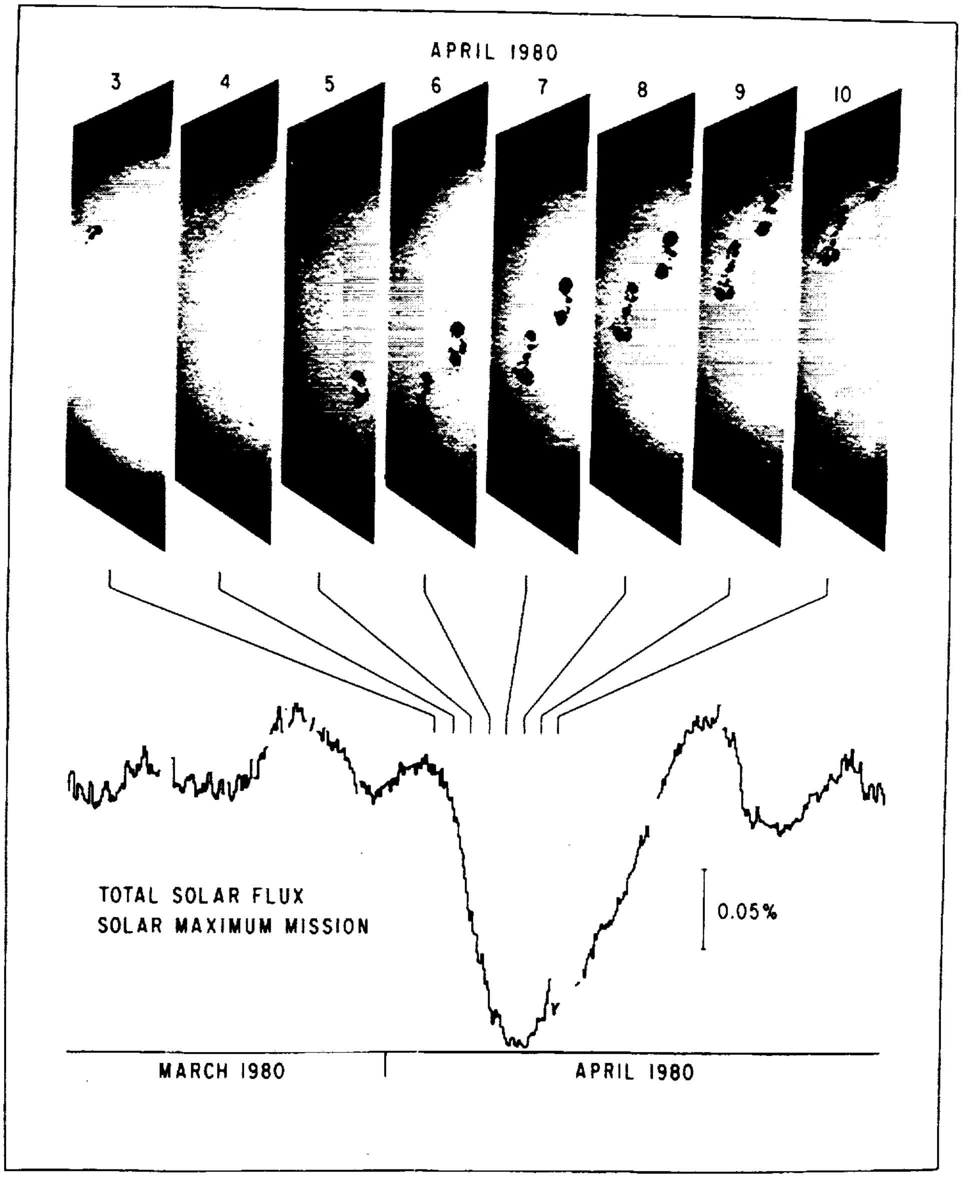


Figure 2. ACRIM observations showing a dip in the irradiance coinciding with the passage of a sunspot group across the disk. (from Noyes 1982, courtesy of H. Hudson)

with maximum projected area, and the process would reverse as the active region rotates off the visible hemisphere.

Overall, one finds that sunspot deficits appear with amplitudes of up to 0.15 percent and that emission increases up to 0.1 percent are attributable to plage and facular excesses resulting from the presence of active regions.

Models have been developed that can accurately (10–20 percent) relate the bolometric flux changes to areas covered by sunspot and plage/facular brightening. Figure 4 from Chapman et al. (1992) illustrates this. Ground-based photometric imaging can be used

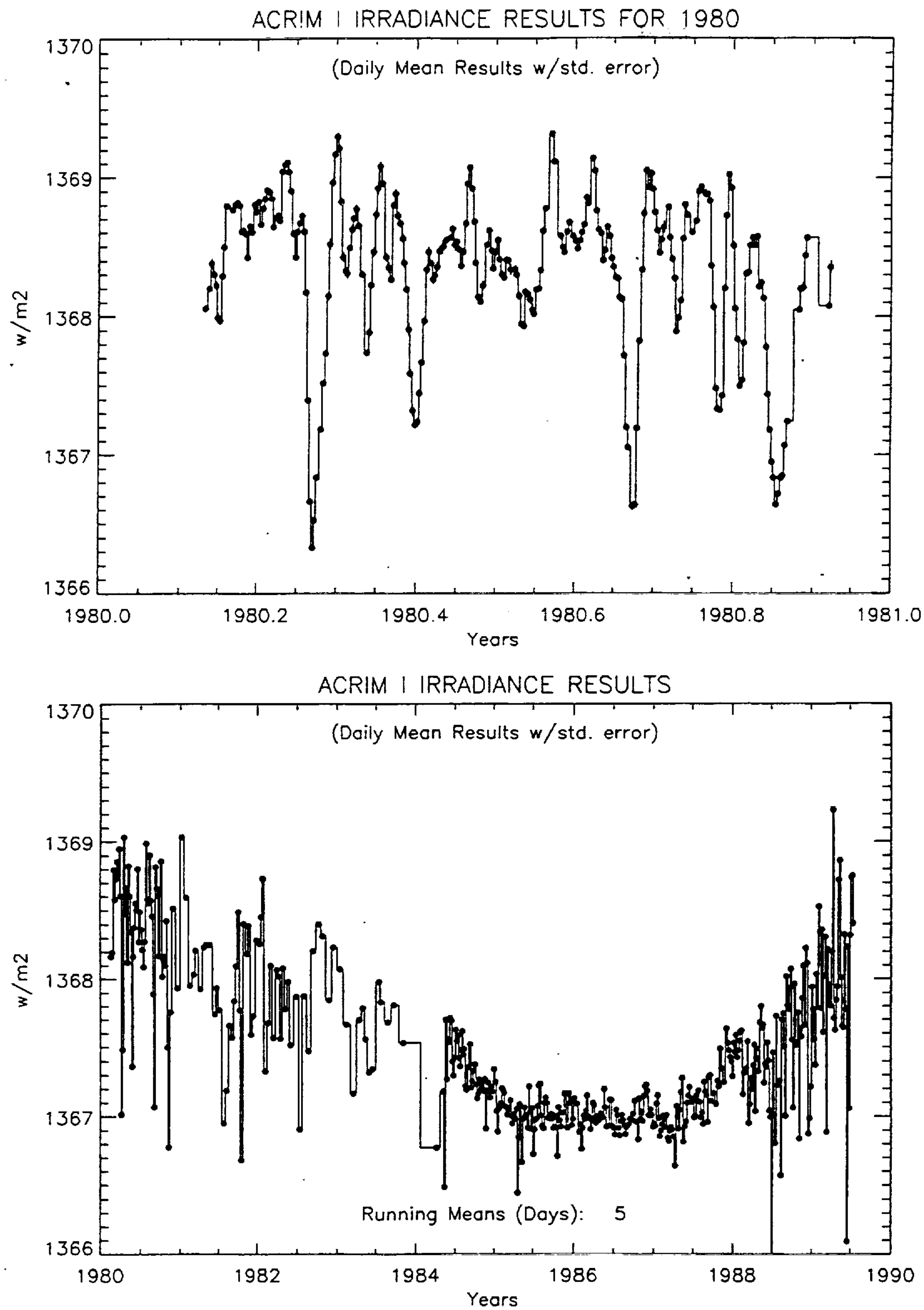


Figure 3. (top) ACRIM observations of daily mean solar bolometric irradiance during 1980. (bottom) The solar irradiance over the declining phase of cycle 21 from the time of launch of SMM (February 1980) through the maximum phase of cycle 22 (July 1989) until the reentry of the satellite (December 1989). (from Willson 1994)

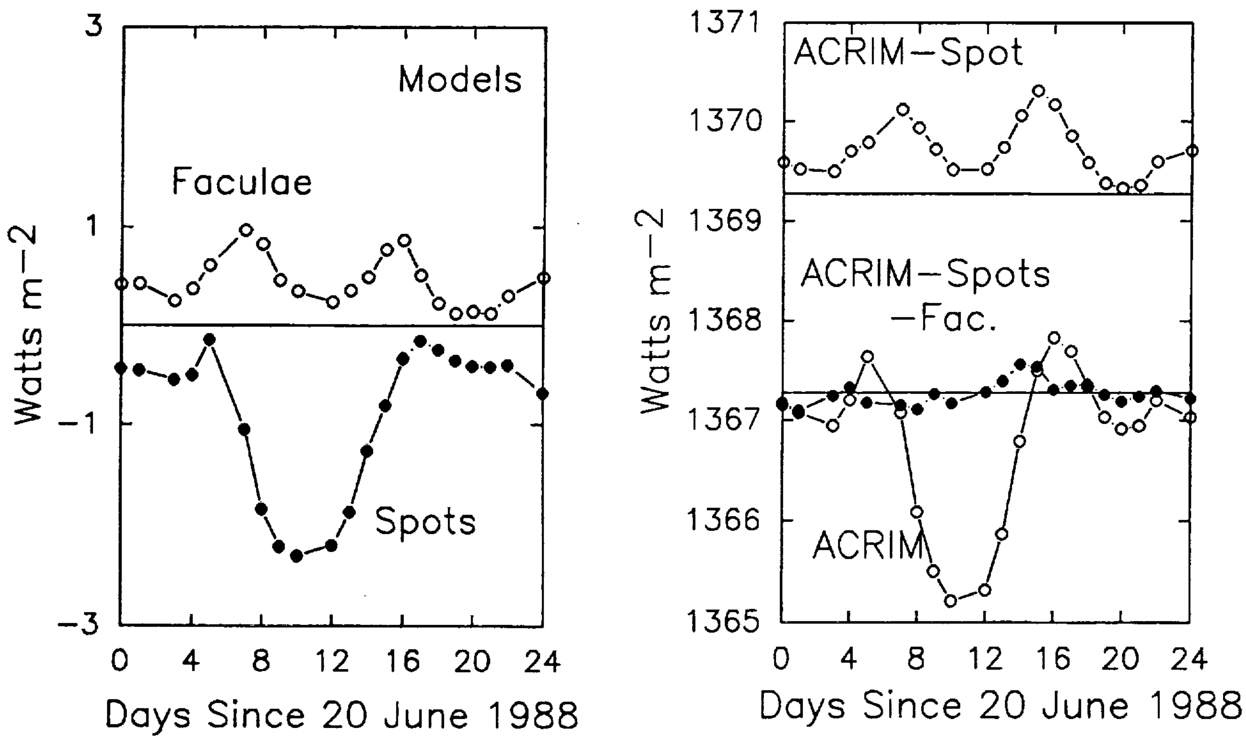


Figure 4. (left) Modeled facular excess and sunspot deficit calculated from ground-based two-color photometric images of the Sun from June 20 to July 14, 1988. (right) Application of this model to the ACRIM observations. Shown are the ACRIM signal, the (ACRIM—Spot) model, and the (ACRIM—Spot—Faculae) model, which results in a flat corrected signal. (from Chapman et al. 1992)

to estimate the projected areas covered by spots and faculae resulting in a photometric facular index (PFI) and a photometric sunspot index (PSI). An empirical formula relates the bolometric irradiance changes to these two indices. There is a third contribution from the overall bright network, but this varies mostly on a solar cycle time period, not on a solar rotation period. The overall solar irradiance variations can be quite well accounted for by facular/plage brightening and sunspot darkening. For example, the relationship between increasing PSI and total irradiance decrease is shown in Figure 5.

Figure 3 (bottom) shows the ACRIM data over the declining phase of cycle 21 from the time of launch of SMM in February 1980 through the maximum phase of cycle 22 in July 1989 until the reentry of the satellite in December 1989 (from Willson 1994). The overall solar cycle change is seen to be about 0.15 percent.

These ACRIM observations reflect the absolute minimum level of variability of the Sun in that they account for the entire solar spectrum. In specific bandpasses the Sun can be highly variable: several orders of magnitude in X-rays during flares, about an order of magnitude in non-flaring X-rays over a solar cycle, factors of two or three in the ultraviolet. No measurements at the ACRIM-precision level exist for the Sun solely in the optical, i.e. a FRESIP-like band. Presumably variations could be a factor of two or more enhanced over the bolometric ACRIM variations.

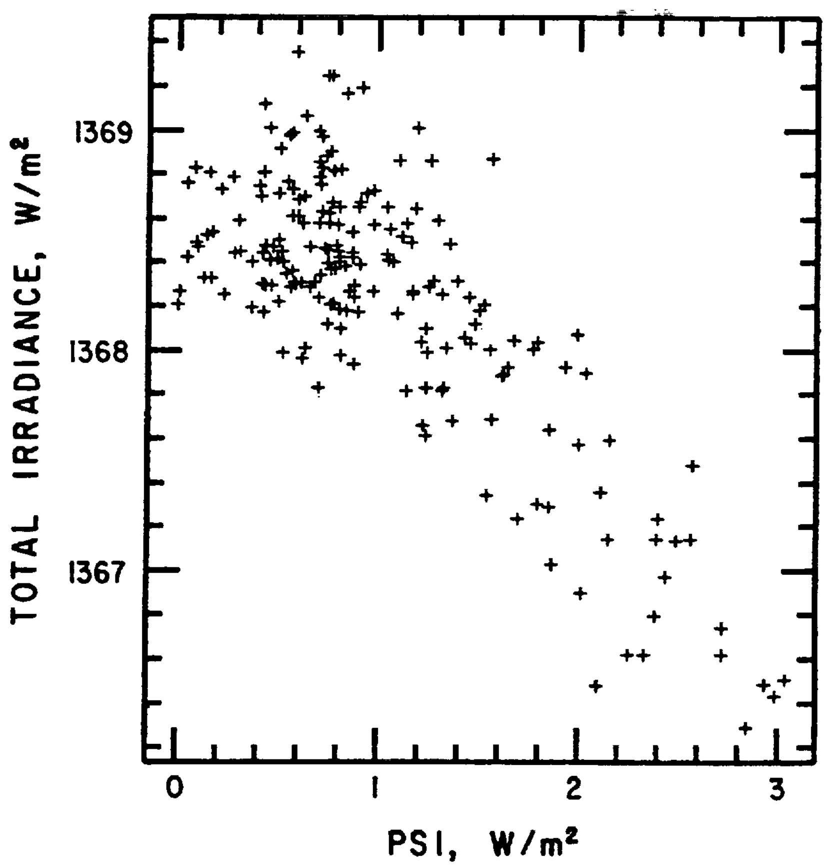


Figure 5. Correlation between increasing sunspot area as measured by the photometric sunspot index (PSI) and decreasing solar irradiance as measured by ACRIM. About half the ACRIM variation is adequately accounted for by the PSI changes. (from Hudson 1988)

3. STELLAR VARIABILITY

Significantly greater changes are expected and have been seen on other stars, with up to 10–100 times the range of the solar variability. It should be easily possible to obtain stellar rotation periods from analysis of such data for a significant fraction of the FRESIP sample. Over a 6 year mission stellar cycle variations should also be measureable in many cases.

Figure 6 shows an example of major stellar variability over a broadband. Hartmann et al. (1981) used the Harvard archival plate collection to examine the $B-$band behaviour of the dK5e star BD +26°730 going back to the turn of the century. The old data were, of course, photographic, but have been converted to the standard Johnson photometric $B-$band. The star is thought to be viewed pole-on, thus eliminating any rotational modulation which would obscure the long-term cyclic variability.

More detailed discussion of stellar activity related variability observations and modeling may be found in the contributions by Dempsey and by Radick in these proceedings.

4. FLARES

White light flares on the Sun are short-lived (typically a few minutes) and cover a small

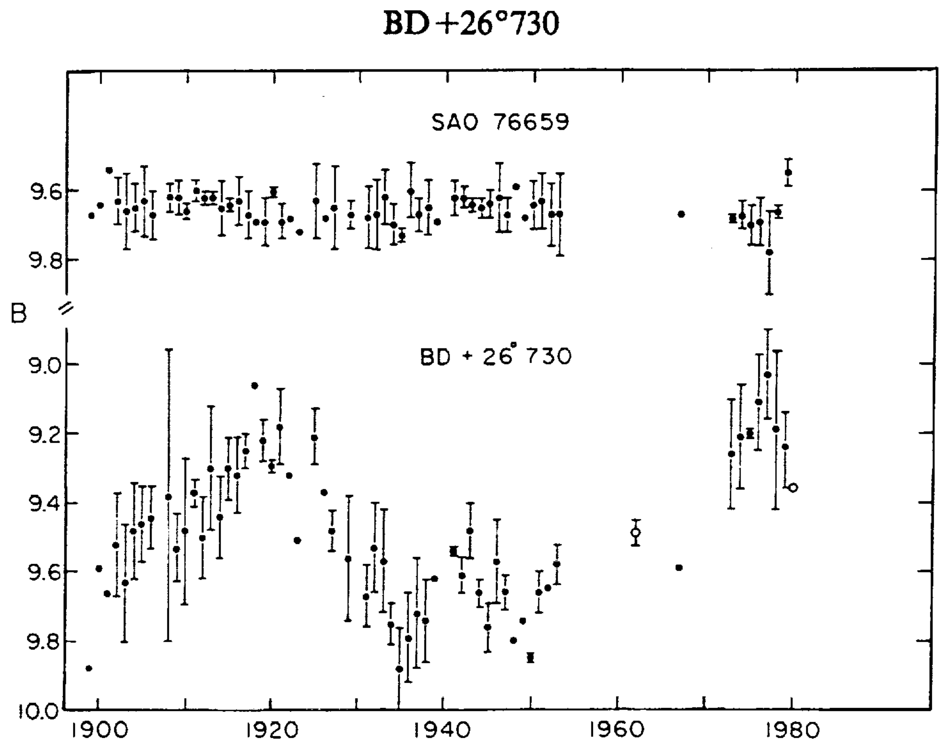


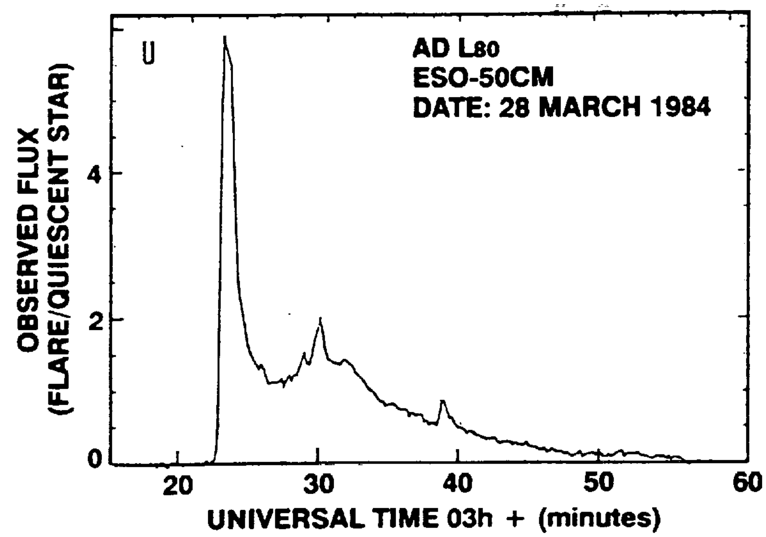
Figure 6. Long-term variability of the dK5e star BD+26°730 referenced to a nearby comparison star. (from Hartmann et al. 1981)

area on the Sun (see Haisch, Strong and Rodonò 1991 for a review of solar and stellar flares). The most energetic solar white light flare amounted to $\sim 2 \times 10^{29}$ ergs s^{-1}, which is only 0.005 percent of the bolometric luminosity, $L_{\odot} = 3.8 \times 10^{33}$ ergs s^{-1}. Note that the $V-$band luminosity is much less than the bolometric: $L_V = 0.12 L_{\odot}$, and so depending on the actual white light band used to detect the flare, the change could be several times higher than 0.005 percent. However ACRIM did not, in fact, detect any solar flares.

Many late-type main sequence stars exhibit much more energetic flaring than the Sun. Figure 7 is an example of two stellar flares. The AD Leo flare was part of a coordinated. multiwavelength observing campaign by Rodonò et al. 1994. The AD Leo flare is on an arbitrary scale, but the actual peak was $\Delta U = -2.1$ mag, i.e. a factor of 7 increase in brightness. The brightest, impulsive part of this flare lasts less than 100 s.

The optical flare radiation is very approximately similar to photospheric radiation from a 25000–30000 K star, i.e. like a B-star with $(U-B) = -1$ and $(B-V) = -0.3$, with a bolometric correction of $BC = -2.8$. The colors of a star like AD Leo are $(U-B) = +1.55$, $(B-V) = +1.25$. From these colors we can estimate the corresponding ΔV for this event: $\Delta V = \Delta U + (U-B)_* + (B-V)_* - (U-B)_f - (U-B)_f = 2.0$, i.e. in the $V-$band the flare would be two magnitudes fainter than the star, corresponding to a brightness change of around 16 percent.

There are also observations of dips in the optical emission associated with flares, and these are taken as evidence of prominence eruptions or other mass ejections associated with flares. Such an example is shown in the EQ Peg flare. According to Giampapa et al. "...the brightness of the star decreases at roughly 0.1 mag per minute for 2.7 minutes,



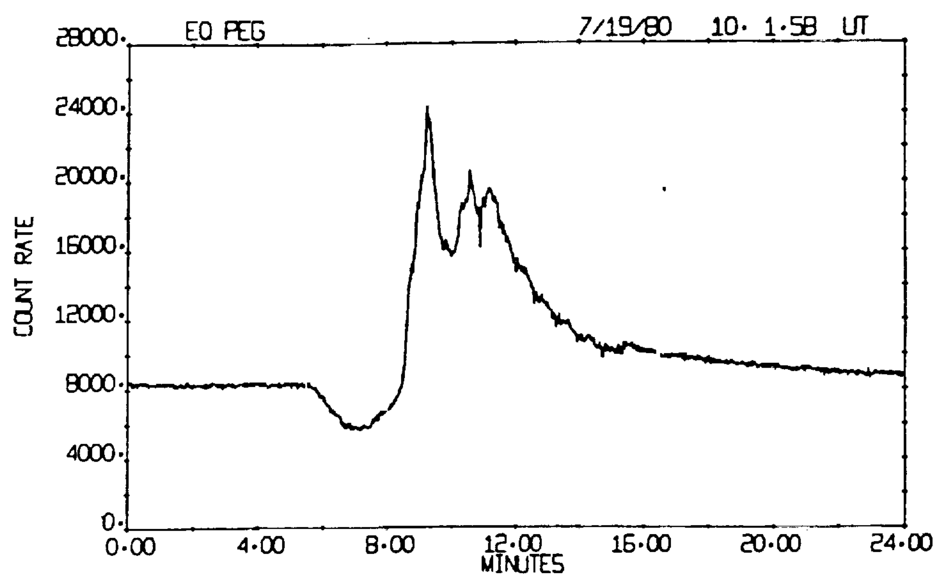


Figure 7. $U-$band flares on AD Leonis and EQ Pegasi (from Giampapa et al. 1982).

then levels off at 75 percent of the quiescent brightness for 1 minute before the flare begins.

Moreover there are relations between the energy of a flare and the frequency of occurrence: $E(\nu)$. As a first approximation, the $E(\nu)$ relation has the same shape but a different overall level from stars of differing activity states, i.e. $E(\nu) \sim 10^4 E(\nu)_\odot$ for some very flare-active stars. This guarantees that FRESIP will see many optical flares with flux changes exceeding several percent on time scales of minutes. Determining the $E(\nu)$ function for hundreds of flaring stars should give us a valuable constraint on coronal heating mechanisms.

ACKNOWLEDGEMENTS

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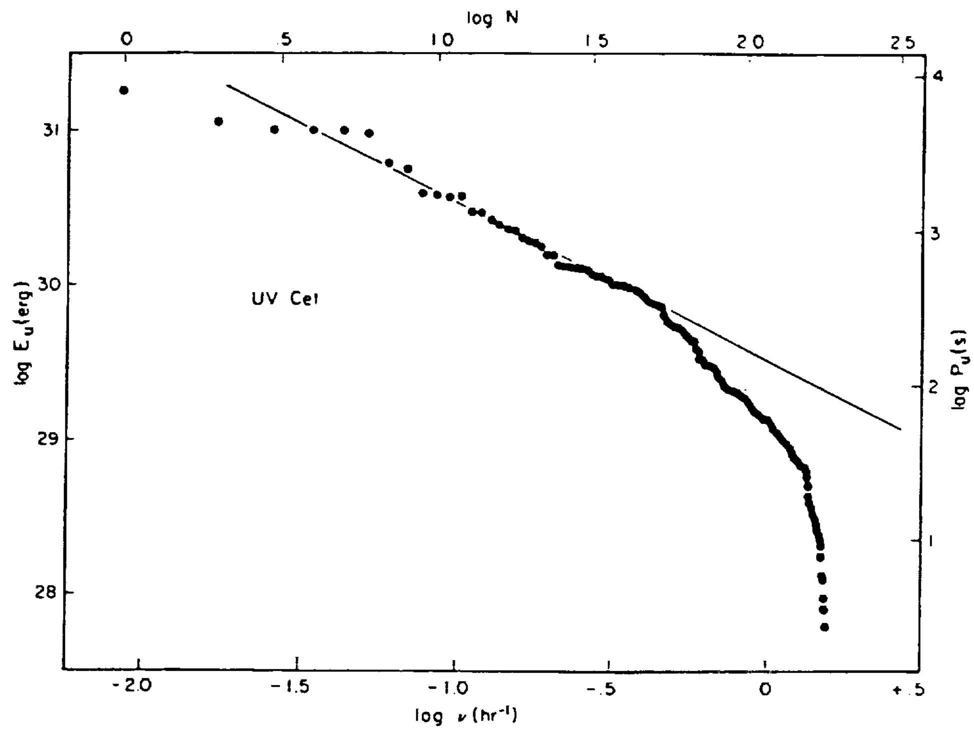

Figure 8. Cumulative frequency diagram of total flare energy vs. occurrence rate. (from Lacy et al. 1976)

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Probing Surface Structure on Late-type Stars With FRESIP

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Abstract.

We discuss possible secondary scientific results obtainable with the FRESIP satellite in regards to surafce features on solar-like stars.

1. Introduction

Currently, for only one star, our Sun, is it possible to resolve surface features such as sunspots and plages. In the case of the Sun these features are well studied. For example, it is clear that the dark sunspots never cover more than 1% of the surface and tend to develop at mid latitudes with formation occurring closer to the equator as the 11-year solar cycle progresses. Through the remarkable work of the Mt. Wilson project we now know many stars possess surfaces covered unevenly with plage-like regions (Wilson 1978) and that stellar activity levels may undergo cyclic variations similar to the solar cycle (Baliunas & Vaughn 1985). Noyes et al. (1984) demonstrated the connection of the Ca II emission flux to the magnetic dynamo believed to be operating in rapidly rotating, convective stars. In general, the Ca II emission is strongest for stars with $P_{rot} \approx$ 1-3^d and gradually decreases as P_{rot} increases. Similar relationships have been observed in other diagnostics (e.g., Simon & Fekel 1987; Strassmeier et al. 1990) and the rotation-activity relationship is now firmly established, at least for single stars.

Numerous late-type stars show photometric amplitude modulation which is believed to result from large, sunspot-like regions rotating in and out of view as the star rotates. The light curves of a few dozen stars have been modeled successfully using simple spot models (see Dempsey et al. 1992 for references).

may be? More systems must be studied to answer these questions.

2. FRESIP

A major benefit of the FRESIP project will be the ability to detect and monitor surface features *on thousands of stars.* An immediate result of this is that a statistically significant number of stars of all spectral types can be sampled. Since the program stars will be dwarfs this will allow us to study the advent of spots in objects earlier than the Sun and to see how far down the main sequence such phenomena persist, i.e. do fully convective M stars posses spots. If possible, it would be desirable to include a sample of 200-300 class IV and III objects. This allows us to probe the characteristics of the future Sun.

In particular, surface features on the longer period ($P > 10 - 20^d$), less active systems will be studied in detail for the *first time.* This results from the fact that FRESIP will be able to detect photometric variations with periods greater than several weeks more easily than can be done from the earth. Earth based observations are limited by short observing seasons, weather and evolution of the surface features on timescales less than P_{rot}. A typically poor light curve is shown in Fig 1. Since it has also been established that the rotation period generally determines the activity level, the longer period systems will be less active and more solar-like than those studied to date. Therefore, the millimag precision of FRESIP will allow us to probe to lower thresh