Stellar Luminosity Variations and Global Warming

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Recent studies indicate that variation in the sun's luminosity is less than that observed in many other stars of similar magnetic activity. Current findings also indicate that in more active stars, the attenuation by faculae of sunspot luminosity modulation is less effective than in the sun at present. The sun could thus become photometrically more variable (and dimmer) if its magnetic activity exceeded present levels. But the levels of solar activity required for this to occur are not observed in carbon-14 and beryllium-10 records over the past several millennia, which indicates that such an increase in amplitude of surface magnetism–driven variations in solar luminosity is unlikely in the present epoch.

Lockwood *et al.* (*1*) have recently presented evidence that the sun is significantly less variable in total light output than are other stars of similar magnetic activity, as measured by a proxy of surface magnetic flux based on those stars' chromospheric emissions in the resonance line of ionized calcium. This evidence is relevant to the controversy over solar and anthropogenic contributions to global warming (*2, 3*) if it implies that the sun could achieve similar levels of luminosity variation in the present epoch.

Here I show that the greater variation in luminosity seen in many stars with a mass and age similar to that of the sun is likely to be a consequence of luminosity modulation by photospheric magnetic activity, a model that explains most of the variation in solar irradiance observed over the past 15 years. I then show that the sun's transition to those higher levels of irradiance variation would probably require an increase in solar magnetic activity to levels that have not occurred in the past few millennia. This reduces the likelihood that the mechanism most probably responsible for the greater variation in luminosity of many sun-like stars is relevant to the explanation or prediction of Earth's climate anomalies in the immediate past or future.

Most of the photometric variability of the sun that has been measured over the past one and a half 11-year sunspot cycles (*4–6*) is caused by the evolution and rotation across the solar disk of dark magnetic sunspots and of bright magnetic structures called faculae. Their contributions are opposite in sign and similar in magnitude, so they tend to cancel when averaged over at least a few solar rotation periods [this is the time scale of the stellar photometric variations discussed by Lockwood *et al.* (*1*)]. The increase in total irradiance of about 0.07% that was measured between the minimum and maximum of cycle 21 seems to have been the result of a dimming of about the same magnitude (estimated from the areas and photometric contrasts of cycle 21 sunspots) that was more than compensated for by a brightening of about twice that magnitude, caused by faculae in active regions and in the magnetic network (*7*).

It follows that the sun would become photometrically more variable if sunspot and facular contributions did not cancel as effectively. In particular, if the ratio A_F/A_S of facular to sunspot area is lower in stars with greater magnetic activity, luminosity modulation by spots in such stars should be more evident. For instance, in solar cycle 21, if the magnetic flux had formed only sunspots and no faculae, the amplitude of irradiance variation could have reached three times the value actually observed. Lockwood *et al.* note that the photometric variability of somewhat more magnetically active stars exceeds the sun's photometric variation by a factor of about 3 to 5. At the same time, the variability in the strength of the resonance line of ionized calcium, which is dominated by the evolution and rotation of faculae across the solar disk, should decrease in stars with a lower value for A_F/A_S. This helps to explain why Lockwood *et al.* find the sun to be about average in its calcium-line variability relative to the same sample of stars.

Recent results indicate that a decline in A_F/A_S does occur as the sun becomes more active (*8*). The evidence for this behavior is based on analysis of the 103-year daily record of faculae and spots observed in white light by the Royal Greenwich Observatory (RGO) between 1874 and 1976. Figure 1 shows a plot of annual mean A_F versus A_S for this entire database. It can be seen that this relation is roughly linear when solar activity is low. However, the slope declines steadily with increasing A_S and changes sign when sunspot activity is greatest. The ratio A_F/A_S has decreased by more than a factor of 2 at the highest values of A_S.

Analysis of the RGO data shows further that the decline in A_F/A_S seen in the disk-averaged, annual mean data plotted in Fig. 1 can be traced to a reduction in the relative areas of faculae found in individual active regions containing the largest spots. Active regions can also be characterized by the areas of the plages, visible in Ca K-line emission, that overlie the faculae; such studies show a similar decline in A_F/A_S (*8, 9*).

The most evident difference between facular and sunspot magnetic fields is the higher flux density of the magnetic field in the spots (*10*). Thus, a likely explanation of the decline in A_F/A_S is the increase in the area-filling factor of magnetic flux tubes in active regions as the overall level of photospheric magnetic flux rises. Such an increase is also consistent with results from the study of late-type stars over a range of activity levels (*11*).

My interpretation of the Lockwood *et al.* result is made more plausible by their additional finding [see figure 1c in (*1*)] that the sun lies near the transition between less magnetically active stars with intermediate-band photometric variations that are in phase with their brightness variations in the calcium line and more active stars whose intermediate-band and calcium-line variations are out of phase by π. The interpretation given (*12*) is that in the less active stars, the faculae that account for the calcium-line variations also dominate the variability seen in intermediate-band photometry. This agrees with my evidence in Fig. 1 that the transition to a regime of sunspot dominance of irradiance variation seems to set in already near the upper end of the range of magnetic activity found in the sun at present.

These findings suggest three main conclusions. First, the relatively large luminosity fluctuations seen in stellar photometry seem to require a level of solar magnetic activity that has not been observed since reliable daily sunspot records began about 150 years ago. Therefore, the solar dimming we would expect as dark spots overwhelm faculae could not have played any role in determining changes in climate over

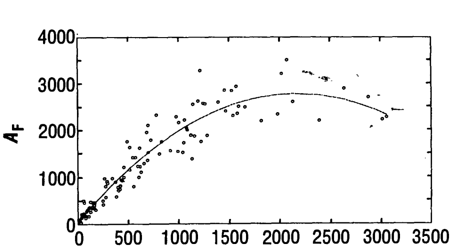

Fig. 1. A plot of A_F versus A_S for annual mean data over the entire RGO facular database, 1874–1976. The values of A_F and A_S have been corrected for foreshortening and are given as millionths of the surface area of one solar hemisphere. The curve represents a quadratic least squares fit to the data.

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the past 150-year period of reported global warming.

Second, historical information on solar activity obtained from the C^{14} and Be^{10} records indicates that the present level of activity is about as high as any reached in the past several millennia (*13*). This reduces the likelihood that a future increase in solar activity beyond present levels might make the sun dimmer, decreasing its average output to levels that might fall below the 0.3% lower total irradiance estimated for the 17th-century Maunder Minimum (*7, 14*).

Finally, if transient magnetic activity levels much exceeding that of the sun at present are encountered in the future (or are shown to have occurred in the past), they are most likely to be associated with a dimming of the sun. This dimming should occur if the time scale of magnetic activity increase is short compared with the radiative relaxation time of layers storing the heat blocked by sunspots. This time scale could be as long as the radiative relaxation time of the solar convection zone, on the order of 10^5 years. Over longer time scales, one would expect the sun's luminosity to return to its average value, which is determined by nuclear burning rates and is unaffected by photospheric thermal impedances (*15, 16*). This suggests that a closer look at climate perturbations that may be associated with periods of anomalously high solar activity before the past few millennia might help to explain episodes of more pronounced climatic cooling than was produced by the Little Ice Age.

Higher (and lower) levels of solar irradiance may be achieved by other mechanisms than modulation by photospheric magnetism (*16*), and these could account for the correlations found between the Earth's temperature variations and several indices of solar activity (*17–19*). But further study of results from stellar photometry will be required to determine whether there exist sun-like stars exhibiting large luminosity variations that cannot be ascribed to photospheric magnetic activity. Discovery of such stars would be an important event for climate studies, because the imminent occurrence of such large solar luminosity variations would be much harder to rule out. Techniques for identifying such stars might include comparison of luminosity variation amplitudes measured on rotational time scales with those observed on much longer time scales. More detailed comparisons between the calcium-line variability and the photometric variability could also help in the discrimination.

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Trends in Stomatal Density and $^{13}C/^{12}C$ Ratios of *Pinus flexilis* Needles During Last Glacial-Interglacial Cycle

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Measurements of stomatal density and $\delta^{13}C$ of limber pine (*Pinus flexilis*) needles (leaves) preserved in pack rat middens from the Great Basin reveal shifts in plant physiology and leaf morphology during the last 30,000 years. Sites were selected so as to offset glacial to Holocene climatic differences and thus to isolate the effects of changing atmospheric CO_2 levels. Stomatal density decreased ~17 percent and $\delta^{13}C$ decreased ~1.5 per mil during deglaciation from 15,000 to 12,000 years ago, concomitant with a 30 percent increase in atmospheric CO_2. Water-use efficiency increased ~15 percent during deglaciation, if temperature and humidity were held constant and the proxy values for CO_2 and $\delta^{13}C$ of past atmospheres are accurate. The $\delta^{13}C$ variations may help constrain hypotheses about the redistribution of carbon between the atmosphere and biosphere during the last glacial-interglacial cycle.

Variations in atmospheric CO_2 affect the physiology and leaf morphology of C_3 plants, which dominate the terrestrial biosphere (*1*). These effects have been studied primarily in growth chamber experiments but also should be evident in fossil leaves from times in the past when CO_2 levels are known to have fluctuated. Evidence from ice cores indicates that ambient CO_2 levels varied from 190 to 200 parts per million by volume (ppmv) during glacial maxima to 270 to 280 ppmv during interglacials; relatively rapid increases have accompanied deglaciation (*2, 3*). The ice core evidence has inspired controlled experiments that simulate plant growth at glacial to present CO_2 concentrations (*4*). It also prescribes a reinterpretation of late Quaternary vegetation changes that acknowledges direct CO_2 effects, such as improved water use efficiency (WUE) at elevated CO_2 concentrations (*4*).

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An abundance of leaves has been preserved in fossil pack rat middens from the western United States. These middens span the last 40,000 years with excellent coverage during deglaciation (5). We measured the stomatal density and $\delta^{13}C$ of fossil leaves of limber pine. During the last glacial period, this C_3 species dominated large expanses of open woodland in the lowlands of the Great Basin and the Colorado Plateau (5). Stomatal density and $\delta^{13}C$ are closely linked to carbon fixation and water status in C_3 plants and should be influenced by variations in CO_2 levels.

Stomatal densities decrease markedly as atmospheric CO_2 levels are increased from preindustrial (270 ppmv) to current values (350 ppmv), as seen in leaves from controlled experiments (*6, 7*) and herbarium specimens collected during the past 200 years (*7, 8*). Variations in stomatal densities have been used as a paleobarometer of atmospheric CO_2 variations during the last