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TECHNICAL COMMENTS

Stellar Variability and Global Warming

Stellar observations (*1, 2*) suggest that the sun is less variable in its total light output than other stars of comparable magnetic activity. In his report (*3*), Peter Foukal offers an interpretation of this result in terms of a model for solar variability. It appears, however, that this model does not account completely and correctly for the stellar observations.

Foukal argues that the broadband variability of a star like the sun is explainable in terms of two types of discrete magnetic features on its surface, namely bright faculae (in both active regions and the magnetic network) and dark sunspots. A central feature of his interpretation of the stellar observations is the expectation that the variation in total light must be dominated by the dark (spot) component when the average activity exceeds some level.

This model can, indeed, explain the high amplitude brightness variability of stars that are considerably younger than the sun. Such stars have time-averaged magnetic activity several times greater than that of the present-day sun. Their total light output also characteristically varies inversely with their emission in the resonance lines of ionized calcium (widely accepted as a proxy for the bright faculae), a fact implying that their net broadband variability is driven by the dark (that is, spot) component, consistent with Foukal's expectation.

Stars similar in age to the sun, however, have time-averaged magnetic activity comparable to that of the present-day sun (*4*). They show calcium emission variations on the time scale of the 11-year solar activity cycle ranging from about one-half to twice that of the corresponding solar variation. Their broadband variability ranges from 0.1%, which is characteristic of the sun, to values as much as ten times larger. The broadband cyclic variation of the sun seems to be a factor of 3 or 4 below what one would expect for a star with this average magnetic activity, despite the fact that the amplitude of the sun's calcium emission variation appears to be fairly typical.

These stars, including the sun, characteristically share a property that clearly distinguishes them from younger stars: Their total light output varies directly with their calcium emission, rather than inversely. In terms of the two-component model, this means that, regardless of its amplitude, the net broadband variability of these stars is dominated by the bright (facular) component. Thus, Foukal's argument that the dark (spot) component is driving the net broadband variability of some of these stars (the more strongly varying, in particular) is not correct. Accordingly, his interpretation does not explain, in a fundamental, qualitative way, the behavior of those stars he is most concerned with, namely, stars with average magnetic activity comparable to that of the present sun, but with broadband variability amplitudes that are several times larger.

Furthermore, the behavior of some of these solar analogs appears to pose quantitative difficulties for the two-component model of solar and stellar variability itself. Consider, for example, the star HD 10476. Its average magnetic activity is only 6% greater than that of the sun. The decadal variation of its calcium emission, however, exceeds that from the sun by a factor of almost two. If the proportionality between calcium emission and the bright (facular) component is similar for both the sun and its stellar analogs (*5*), then the contribution to HD 10476's broadband variation from the bright component must also be about twice the corresponding solar value, or 0.4%. Photometric measurements show that its net broadband variation, which reflects the contribution from the dark as well as the bright component, is about 0.6%, six times the solar value. In conjunction, these two measured relations imply that the "dark" component must make a *positive* contribution of 0.2% to the decadal variation of this star, which is, of course, contradictory.

In total, somewhat more than one-third (5 of 13) of the observed sample of close solar analogs pose similar difficulties. If we include stars that are clearly less active than the sun, the situation remains about the same: 8 of 21 stars in the augmented sample are discordant. Perhaps solar-stellar variability does involve "other mechanisms than modulation by photospheric magnetism . . ." (*3*, p. 239). For example, there may be some large-scale phenomenon going on that is not accounted for by a two-component model that views variability as the sum of contributions from small-scale features alone (*6*).

In any case, it seems evident that such problems in explaining the behavior of solar analog stars must also cast doubt on conclusions about the range of possible solar variability and the consequent implications for studies of global warming. I disagree with the suggestion that the observation of relatively large amplitude variability among sun-like stars is not particularly relevant to "the explanation or prediction of Earth's climate anomalies in the immediate past or future" (*3*, p. 238). Were the sun simply to regress to the mean defined by its stellar analogs, it would experience variations in its total light output several times larger than those measured during the past 15 years, without any accompanying change in its average magnetic activity. Until we have a consistent explanation for the observed behavior of solar analog stars, it would seem imprudent to dismiss the clues that stellar observations are providing us about the range of possible solar behavior.

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Response: The main issue addressed in my report (*1*) was whether results from stellar photometry substantially increase the evidence that the sun's luminosity may have varied enough over the past century to explain the global warming reported since the 1880s. My analysis suggested that, at the present early stage of analysis of these interesting stellar data, the answer is probably negative. I do not believe that the points raised by Radick alter this conclusion.

Even the most sunlike of the more highly variable stars in the sample of Lockwood *et al.* (such as HD 10476) appear to differ from the present sun in ways that make similar solar irradiance behavior unlikely. The behavior of HD 10476 can be explained in terms of photospheric magnetic activity (that is, the "two-component" model consisting of spots and faculae). For instance, the photosphere of HD 10476 could carry only dark spots and no faculae. In such a star, both the CaK band and total luminosity could rise and fall in phase, as one observes on HD 10476. This interpretation would be quite consistent with the arguments given in my report.

Alternatively, the behavior of HD 10476 could be explained if its surface were covered mainly by faculae; the intensity enhancement ratio of faculae in chromospheric versus photospheric radiations was three times higher than on the present sun, and the modulation in facular area (over decadal time scales) was twice that of the present sun. There is no direct observational evidence for a constant value of the ratio described above, common to all sunlike stars. On the contrary, there are sound reasons to expect this value (which expresses the ratio of nonthermal to thermal energy transport through the photosphere) to vary substantially, even between similar stars.

I agree that in the second interpretation given above, the luminosity variation of HD 10476 would not be dominated by sunspots. But a more important point is that both of the above explanations of HD 10476's behavior model describe a star with photospheric magnetic structures quite different from those observed on the present sun. We must ask: How likely is it that these parameters on the sun could change from their present solar values to HD 10476–like values over the relevant global warming time scale?

No measurements exist of the chromospheric to photospheric intensity ratio of faculae over the past century. But the remarkable fit of two-component models to the active cavity radiometer irradiance monitor (ACRIM) radiometry between 1980 and 1990 indicates that, at least over the declining phase of cycle 21 and ascending phase of cycle 22, that ratio did not change significantly. It seems unlikely (although not impossible) that this ratio increased over the last century by a factor of 3, which would be required to reach HD 10476–like values, given that this would imply a roughly 300% change in the ratio of the sun's nonradiative to radiative power outputs. I conclude that whichever model (sunspot or facula-dominated) describes HD 10476, the main point is that the sun is unlikely to behave like HD 10476 in our epoch (*3*).

I agree with Radick that climatologically significant irradiance variations in the present sun cannot be ruled out by evidence at our disposal, and I pointed this out in the last paragraph of my report. Unfortunately, this important qualification was not emphasized in the summary that appeared in the "This Week in Science" section of that issue or in the newspaper reports that followed.

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