# Deep-seated modulation of the quiet-sun irradiance by the solar magnetic cycle

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The solar-cycle-driven modulation in the surface coverage of various photospheric magnetic structures is known to be responsible for the observed solar radiative variability on timescales ranging from minutes to years. On the other hand, the possibility that deep-seated modulation of the quiet sun luminosity contributes significantly to the variability on timescale of the activity cycle and longer remains conjectural. Such a modulation would have its roots deeper within the solar convection zone, and may entail changes in the sun's radius, pole-equator temperature contrast, and/or radial temperature gradient in subphotospheric layers. Helioseismology has revealed cyclic changes of $p$-mode oscillation frequencies on the same 11-yr timescale as the magnetic activity cycle, pointing to structural changes localized mostly in subsurface layers, although a deep-rooted contribution cannot be ruled out.

In this talk I will present global magnetohydrodynamical simulations of solar convection that generate a well-organized large-scale magnetic component undergoing regular polarity reversals, in a manner solar-like in many aspects (Ghizaru et al. 2010, *Astrophys. J. Lett.*, **715**, L133; Passos & Charbonneau 2014, *Astron. Astrophys.*, **568**, A113). I will show that this large-scale magnetic cycle modulates the convective luminosity of the simulation, the simulation being slightly brighter during the maximum phase of the magnetic cycle (see Figure 1), just as the total solar irradiance peaks at activity maximum. In the simulation, this modulation can be detected all the way down to the base of the convectively unstable layers, and traced to magnetically-mediated changes in the character of convection. The detected modulation arises not from direct, magnetically-mediated systematic changes in convective velocities via the Lorentz force, but rather from changes in the degree of correlation between convective speeds and temperature perturbations. More specifically, the modulation of convective energy flux originates in the (non-Gaussian) tails of the statistical distribution of turbulent heat fluxes. In particular, we find that the presence of a strong ($\sim 0.1\,\mathrm{T}$) magnetic field well-organized on large spatial scales reduces turbulent entrainement and enhances the number of "hot spots", i.e., strong convective plumes which, although relatively rare, carry a lot of heat across many scale heights in the simulation. This markedly non-local pattern of energy transport is very different from what one would infer from diffusive, mixing-length-based arguments, whereby heat transport is simply proportional to the local temperature

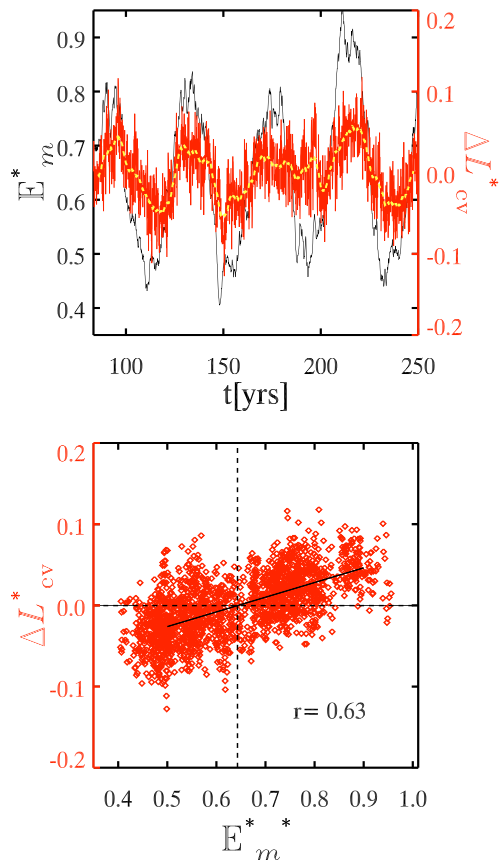


Fig. 1.— Time variations of magnetic energy (black ) and convective luminosity (red), with the yellow line a running mean of the latter. Taken from Cossette et al. 2013, *Astrophys. J. Lett.*, **777**, L29 (Figure 3).

gradient (see, e.g., Foukal et al. 2006, *Nature*, **443**, 161; and references therein).

The detected modulation in convective energy flux also leads to changes in the thermodynamic structure of the statistically stationary state, as required to explain changes in $p$-mode oscillation frequencies. Unfortunately, because our simulation reaches only out to $r/R = 0.96$, we cannot at this point predict the corresponding magnitude or phase of the frequency shifts. Nonetheless, because the modulation exhibits a significant latitudinal dependency, an observational signature may be detectable, although at this writing it remains to be quantified. Overall, our simulation results support, in a qualitative sense, the thesis according to which part —or even all— of the observed total solar irradiance variations on time scales decadal and longer could be attributed to a global modulation of the Sun's internal thermal structure by magnetic activity.