Mem. S.A.It. Vol. 74, 603

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Modeling solar irradiance variations through full-disk images and semi-empirical atmospheric models

I. Ermolli[1], B. Caccin[2], M. Centrone[1], and V. Penza[2]

[1] INAF Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monte Porzio Catone, Italia e-mail: ilaria@mporzio.astro.it

[2] Dipartimento di Fisica Università degli Studi "Tor Vergata", Via della Ricerca Scientifica, 00133 Roma, Italia

Abstract. We summarize the results of both accurate measurement and models calculations carried out with the aim of understanding the physical origins of the solar irradiance variability arising from variations of surface structures through the solar activity cycle. In particular, we used the new high-quality measurements of the photospheric contrast of facular regions and the network, together to the accurate description of the temporal variation of their disk coverage since the last solar minimum obtained analyzing the archive of daily observations carried out with the PSPT at the Rome Observatory. We used these image analysis results together to the output of semi-empirical models of solar features to compute variations of the solar irradiance during periods spanning from few weeks up to the full ascending phase of the current solar cycle. We present the comparison of the computed variations with those measured by Virgo radiometers on board of SOHO.

Key words. Solar Atmosphere – Solar variability – Atmosphere models

1. Introduction

Radiometers on board satellites launched during the last two decades have revealed that the total solar irradiance changes on a variety of time-scales. Solar irradiance variations on scales of days up to the solar activity cycle length are closely related to the evolution of the solar surface magnetic field, because the emergence and evolution of active regions on the solar surface is reflected in the irradiance records. Space-based irradiance records have also established a variation of about 0.1% of the irradiance in phase with the 11 year solar activity cycle, giving as a result a brighter Sun around activity maximum. The origin of the long-term increase of the irradiance between activity minimum and maximum is still widely debated. It is expected that small- scale magnetic elements that compose the enhanced and quiet network contribute substantially to

Send offprint requests to: I. Ermolli
Correspondence to: INAF OAR, Via Frascati 33, 00040 Monte Porzio Catone

the observed irradiance increase during activity maximum. However, uncertainties in the measurements of small scale magnetic region properties in time are yet one of the major sources of errors in the modeling of long-term irradiance variations and incidentally, because of these errors it is still debated whether other mechanism of non-magnetic origin may contribute significantly to the measured irradiance variations. Among these, are listed in literature temporal changes in the latitude-dependent surface temperature of the Sun, cyclic variations of the effective temperature of the Sun, structural changes in the convection zone during the solar cycle, and effects of the changing internal magnetic field. Models of the solar irradiance became possible as consistent time-series observations came along, and were improved or discarded as errors and uncertainties in the representation of their components went down. Note, in literature a model is defined as a mathematical expression for the solar irradiance as a function of time in some units, the solar spectral irradiance as a function of wavelength at some resolution and time in some units. Published expressions that go into models range all the way from direct observations, to phenomenological representations, all the way to theoretical terms. The initial context for models suggested that the explanations of irradiance variations should only take into account sources or mechanisms from the photospheric layers and above, i.e. where measurements originate. So, to first order, effects of both dark and bright features on the solar disk have been modeled through Photometric Indexes. These indexes were largely based on the use of proxies, i.e. measured or inferred values representing the component to be modeled. Common examples are the Calcium 1 Å index and the MgII core-to-wing ratio as proxies for the facular component. For a detailed review of all the subjects presented see the AGU Geophysical Monograph XXX, 2002. In the course of this modeling and the pursuit of accurately accounting for dark and bright features indicated that while the balance seemed promising at first it did not match the observations in a consistent manner. In particular, there are both phase shift between the rise of the modeled solar activity and that of the measured irradiance time series during the current ascending phase of the solar cycle, as well as discrepancies around the solar maxima where solar activity tends to a plateau and the measured irradiance time series does not. In general, scaling formulae obtained from regression analyses between irradiance time series and the main properties of solar observed magnetic features often presented in literature to estimate the solar irradiance lack in physical matter. So, the existing discrepancies between measured and modeled irradiance variations point to missing "physics" or the inability of existing proxies to represent a physical process. At present, no single proxy model account for all, or even most, of the existing time series on time scales longer than a rotation. To really understand the physical origins of the irradiance variability arising from variations of the surface magnetic fields, a modeling of the energy balance in and around magnetic regions along the cycle is need.

2. Models of solar features

Near simultaneously to the beginning of irradiance measurements the work on stellar atmosphere constituting the Kurucz's ATLAS code (1979) started to be applied to model the solar visible and infrared spectrum. Around the same time, Avrett and colleagues were continuing to develop semi-empirical atmosphere models for different solar features, i.e. quiet sun, network, faculae and plage, each of which having been observed to have different spectral characteristics. The latter models are different from the first ones, mainly because they take empirically into account the temperature chromospheric increase as a result of energy dissipation on the deeper layer. Besides, while the Kurucz models are theoretical and in LTE, the latter (VAL models) are semi-empirical meaning that they depends on the temperature structure determined to reproduce set of observations in different features. Each models component (from mod A describing faint supergranule cell interior to mod S representative of sunspot umbra) is treated separately as a plane-parallel atmosphere taking into account that models have to represent only medium scale surface features, greatly exceeding the heights of formation of both lines and continua. The most recent work on these models has been developed by Fontenla and co-workers (Fontenla et al. 1999 for a review) to improve the physical consistency of the models and to increase the agreement with the updated observations (FAL models). In the most recent years, also Solanki and colleagues developed simpler synthesis models which utilizes the Kurucz flux spectra calculation and a limited set of solar features to model the solar spectrum and its variability (Solanki, Fligge and Unruh 2001 for a review). Their models differ from the former mainly in the region of the temperature increase, where a linear extrapolation of the photospheric relation log(T) vs log(P) replaces the temperature increase.

3. Observations and method

The image analysis performed on the full archive of daily observations carried out with the PSPT at the Rome Observatory summarized by Centrone and Ermolli (2002) and Ermolli, Berrilli and Florio (2002) allowed new high-quality measurements of both the photospheric contrast and disk coverage of magnetic regions on the solar disk since the last solar minimum. In brief, the images analyzed correspond to the observations acquired each day at the three PSPT band-pass centered at CaIIK (393.3±0.25nm), Blue (409.2±0.25nm) and Red continua (607.1±0.5nm) with a 2k × 2k CCD camera (Ermolli et al. 1997, Centrone et al. 2001). We merged the results of the PSPT image analysis with the output results of spectrum synthesis per-

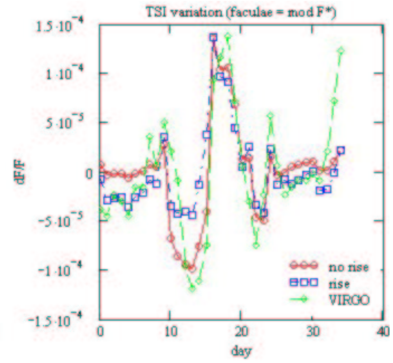

Fig. 1. Comparison between the measured (diamond) and the modeled (square) irradiance variations for a period at the minimum of the current solar cycle (15 July - 24 August 1996).

formed by Caccin and Penza (2002) using FAL semi-empirical models of the main solar features. They were able to calculate the spectral irradiance associated to each model feature at any wavelength band in the spectrum, in particular at the wavelength bands of PSPT's observations. The comparison of PSPT image analysis results and model's calculations performed for the PSPT bands of observations, in particular concerning the center to limb variation of both active (faculae) and quiet (network) bright magnetic feature contrasts on the disk are briefly presented in Caccin and Penza (2002).

4. Results

We tried to describe the variations of the bolometric flux of the integrated solar disk during periods spanning from few days up to the full ascending phase of the current solar cycle, weighting the contributions of all the different solar features observed with the PSPT on the solar disk. In particular, we assumed that the total solar irradiance variations are equal to flux variations described by $\frac{\delta S}{S} = \frac{\Sigma_i \phi_i(t)(F_i - F_0)}{F_0}$ where $\phi_i(t)$ is the disk coverage of the $i-th$ solar feature obtained by the PSPT image analy-

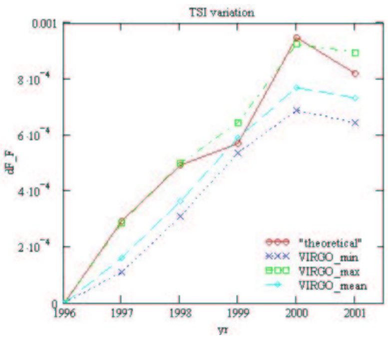

Fig. 2. Comparison between the measured (square) and the modeled (circle) irradiance variations for the full ascending phase of the current solar cycle (Summer 1996 - December 2001).

sis and F_i the flux of the semi-empirical model of the $i-th$ solar feature (i=0 is quiet model) calculated with the ATLAS9 code. The comparison of our modeling results with experimental data, i.e. measurements of irradiance performed by VIRGO radiometers on SOHO, gives us an evaluation of the capability of our modeling to reproduce the effective solar emergent spectrum. In figure 1 we show the comparison between the measured and the modeled irradiance variations for two periods of few days each, occurring at the beginning and at the maximum of the latest solar cycle, respectively during Summer 1996 and Summer 2001. Note, that comparison was optimized using mod F of semi-empirical FAL models to represent facular features, and distinct values for umbra-penumbra disk coverage as well as their associated fluxes for sunspot regions. In figure 2 we show the comparison between the measured and the modeled irradiance variations for the full ascending phase of the current solar cycle, from Summer 1996 to December 2001. Note, that comparison was optimized weighting the contributions of quiet Sun (mod C), network pattern (mod E), facular regions (mod F), sunspot umbra (mod S) and sunspot penumbra (0.76· mod C) with the disk coverage values obtained by the PSPT image analysis.

5. Discussion

Solar irradiance modeling has significantly changed over the past 20 years and especially in the latest years. Proxy models have found a large place in modeling the solar irradiance and a decennial experience on the use of selected proxies overcame those based on regression analyses. The use of physics based models, like those used in this paper, is the most promising for a deep understanding of solar irradiance variability and in particular toward the nature of the relation to solar (surface and perhaps sub-surface) activity on a variety of time scales. However, these models have uncertainties in a number of areas, for example the assumption of plane-parallel atmosphere, the atomic data and the missing lines used in the model synthesis. The results presented here summarize a substantial amount of work on accurately decomposing the Sun into structures important to irradiance modeling, as well as the optimization of model synthesis to improve the physical consistency of the models and to increase their agreement with the newest observations.

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