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The cycle-dependence of Far-UV and Middle-UV solar emission: EMD analysis of SOLSTICE and Mg II signals

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SOLAR PHYSICS UTOV

https://www.fisica.uniroma2.it/~solare/en/

Abstract: The solar Far-UV and Middle-UV variability is extremely relevant for the stratospheric ozone concentration and dynamics. We investigate solar UV variability at decennial time scale using the data of SOLar-STellar Irradiance Comparison Experiment (SOLSTICE) on SORCE and Bremen Mg II composite signal. The Empirical Mode Decomposition (EMD) technique has been applied to Mg II and UV signals to separate intrinsic solar components and focus on 11-y variability. The analysis shows that the star changes the UV spectral distribution during 11-y cycle with a different behavior during the descending phase of cycle 23 and growing phase of cycle 24. The observed UV major evolution can provide empirically-motivated UV predictions over the cycles. On the other hand, the observed minor differences during the ascending and descending phase of solar cycle can be attributed to physical changes in solar emission or described by an uncorrected time-dependent performance of SOLSTICE UV channels. We shortly discuss both possibilities.

The radiative and particle output of the Sun is variable on different time scales, from seconds to the evolutionary scale of the star. These fluctuations, due to instabilities and non-stationary processes related to solar magnetic field dynamics and evolutionary mechanisms, affect the energy balance of the Earth's surface and atmosphere, thus influencing our climate (e.g. Haigh, 2007).

Fluctuations of the total (TSI) and spectral (SSI) solar irradiance indicate that the main feature of solar variability, at least in the last centuries, is the 11-years Schwabe cycle. This cycle is distinctly observed with different physical (e.g., TSI, SSI, Mg II or F10.7 fluxes) and synthetic (e.g., sunspot number) indices.

Over this cycle, changes in the TSI are about 0.07% with different spectral intervals contributing differently; indeed, the UV emission varies by a few percent in the range 200÷300 nm to up to 100% around the Lyman-alpha line at 121.6 nm (Krivova, Solanki & Floyd , 2006).

Magnesium II index dataset

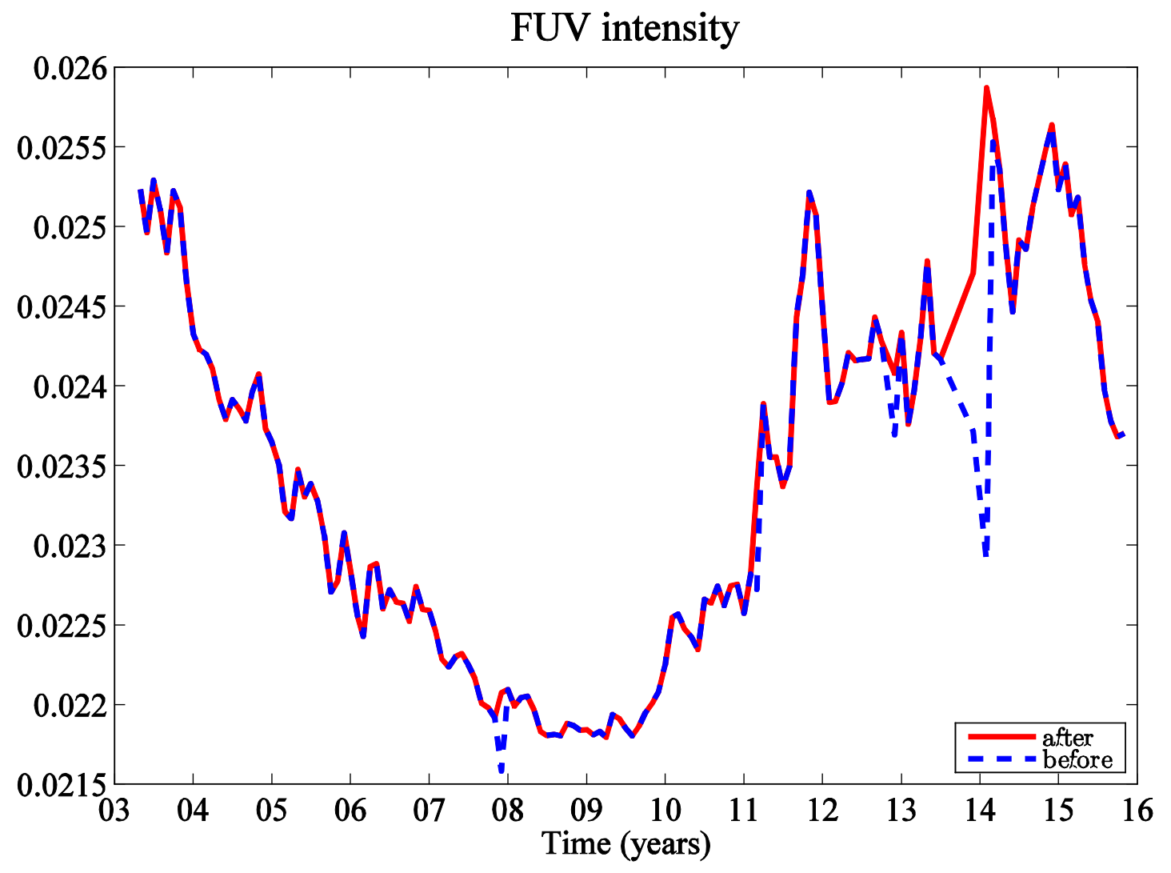
The Mg II core-to-wing ratio is a good proxy for the solar UV and facular component of the TSI (e.g. Dudok deWit et al., 2009). TheMg II index is calculated as the ratio between h and k emission doublet at 280 nm, which originates in the solar chromosphere, and a reference continuum intensity at specific wavelengths in the wings of the Mg II absorption band. The continuum around the doublet is originated in the photosphere. More in detail, the Mg II index was calculated first by (Heath & Schlesinger , 1986) as the:

$$I = \frac{4[E_{279.8} + E_{280.0} + E_{280.2}]}{3[E_{276.6} + E_{276.8} + E_{283.2} + E_{283.4}]}$$

The Mg II Bremen composite, downloaded from the University of Bremen website (http://www.iup.uni-bremen.de/gome/gomemgii.html), gives us daily Mg II index values, from which we calculated montly mean values.

SORCE SOLSTICE dataset

The accurate investigation of SSI in the 115 to 2400 nanometer spectral (wavelength) range was not quite possible until 2003 with the launch of the NASA's SORCE satellite (Rottman,Woods & Sparn, 1993).
The two data sets, FUV and MUV, are downloaded from LASP SORCE website http://lasp.colorado.edu/home/sorce/data/. The SOLSTICE data obtained from the LASP SORCE website is version 15 data that includes data up to October 2015. SSI measurements present zero values corresponding to missing data, which leads to non physical gaps in the monthly means of the intensities in both spectral regions. A preliminary data interpolation is required.



Monthly means of FUV intensity radiation before (dashed line) and after the interpolation (solid line).

The two noticeable gaps occurring in 2008, 2013 and 2014 have been corrected.

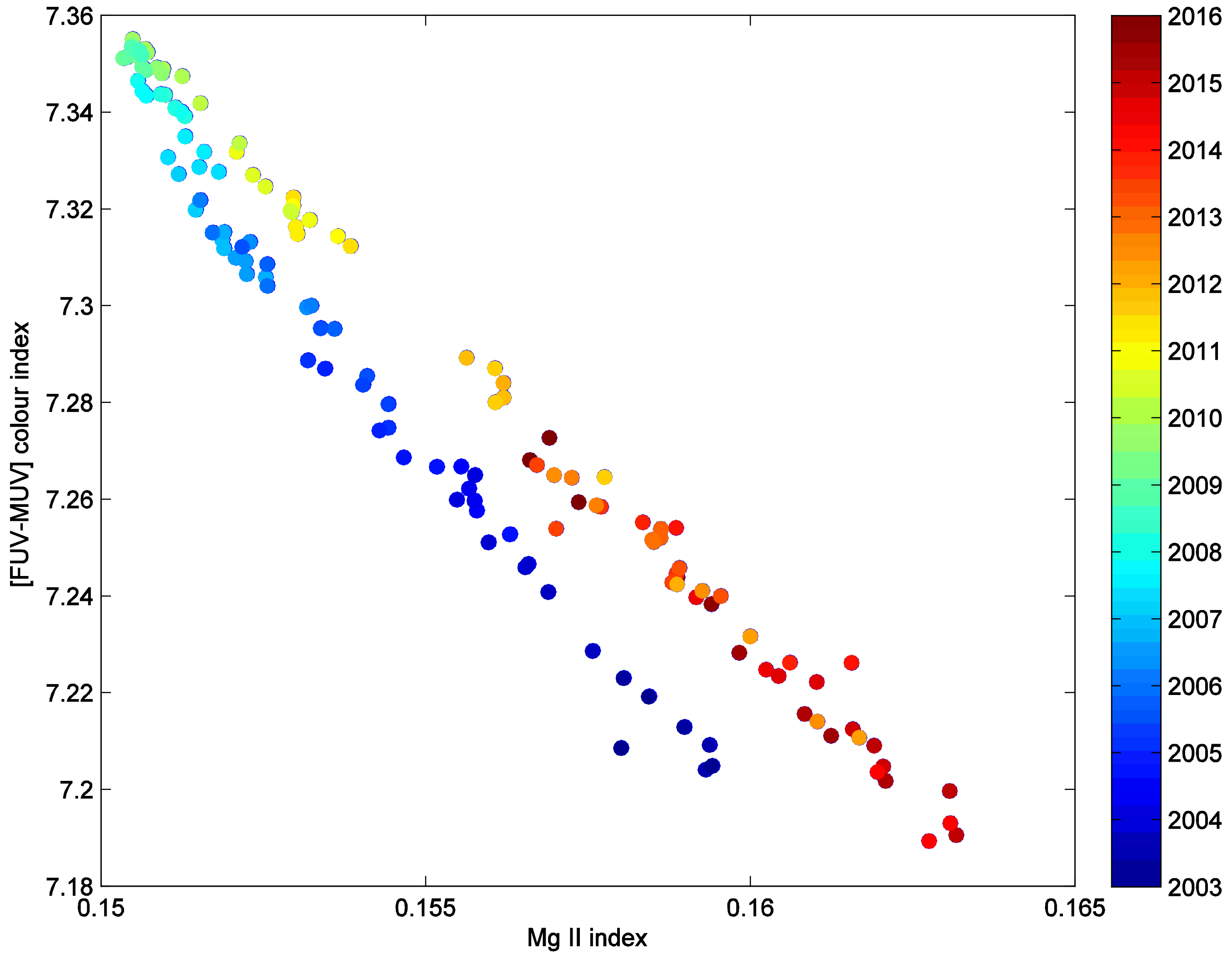
The [FUV-MUV] colour index

The FUV and MUV monthly means are used to analyze the behavior of the [FUV-MUV] colour index. The colour index is calculated by the difference between the measurements of the magnitude of the Sun at two different wavelengths (i.e., 147.5nm and 245nm, for FUV and MUV, respectively), the value found at the longer wavelength being subtracted from that found at the shorter. The zero points of our magnitude scale, which is arbitrary, are set to zero. Therefore, [FUV-MUV] colour is defined as:

$$[FUV - MUV] = -2.5log \frac{\lambda_{\rm FUV}}{\lambda_{\rm MUV}} \frac{e^{\frac{hc}{\lambda_{\rm MUV} KT}} - 1}{e^{\frac{hc}{\lambda_{\rm FUV} KT}} - 1}$$

The local slope permits to derive the colour temperature, i.e., the temperature for which the [FUV-MUV] colour of a blackbody radiator fits the solar one.

The figure shows the dependence of the colour on both Mg II index and time. The data sets cover the time between May 2003 and October 2015. The figure clearly shows strong correlation between the colour index and Mg II index, meaning that the UV slope is sensitive to solar activity on the time scale of 11 years. Moreover, we point out the existence of two separate slopes, which merge during the solar minimum in 2008 and 2009. Starting from this minimum the Mg II index is seen to increase while the colour index decreases. Around the maximum in 2013, the Mg II index reaches a maximum of 0.163 and colour index is at the minimum observed value of 7.19. From this point, until the date of last observation, the colour index dependence on Mg II index is retracing the same path in parameter space in reverse. The two di_erent slopes can be due to some physical e_ect in the solar atmosphere, or due to the SOLSTICE instrument degradation (e.g. Snow et al., 2014).

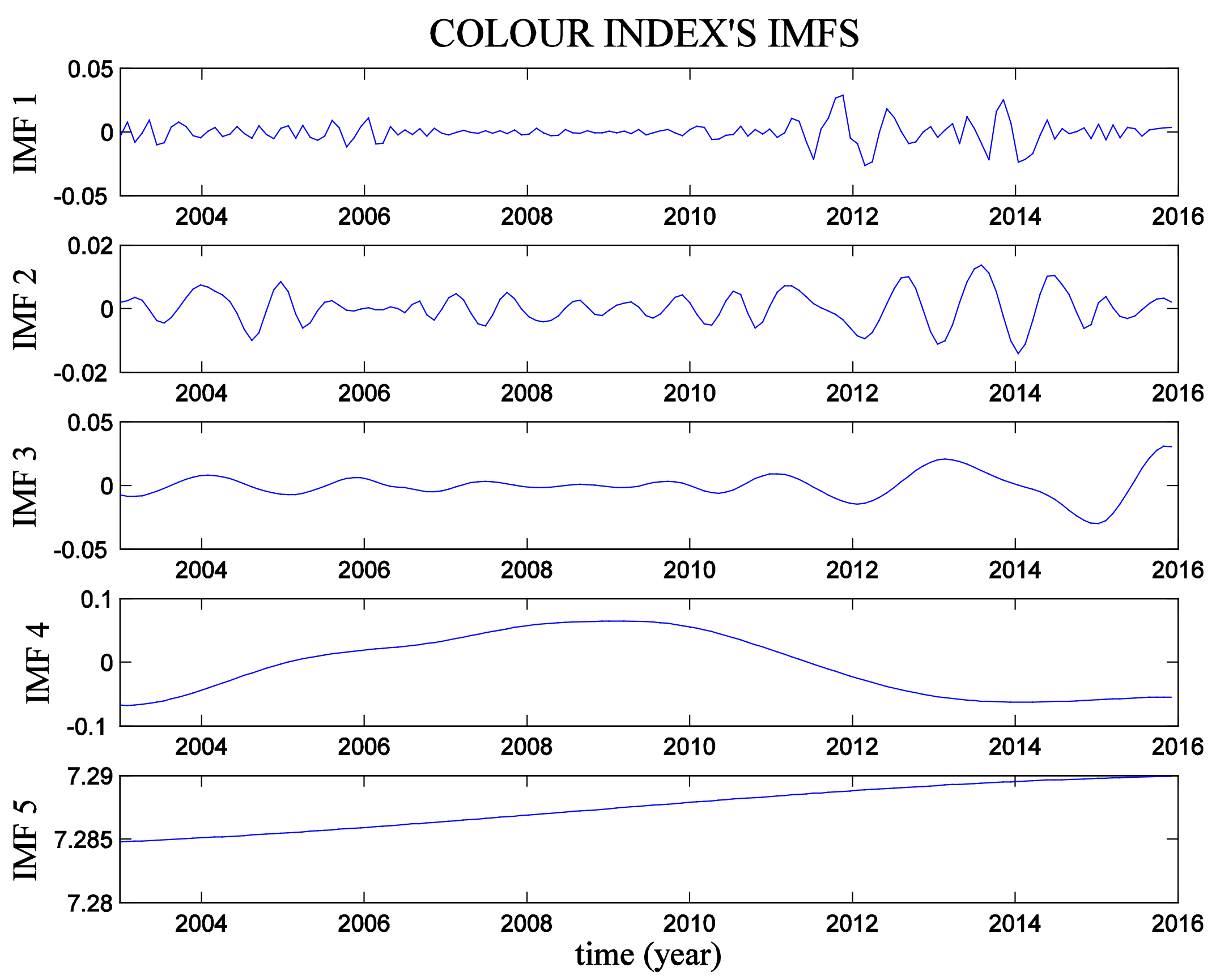


Empirical Mode Decomposition analysis

The signals associated to [FUV-MUV] colour index and Mg II flux have been studied for the time period between May 2003 and October 2015. Their variability derives form activity of the Sun which is non-stationary and nonlinear, like signals of climate variability, therefore an adaptive analysis is required. The Empirical Mode Decomposition (EMD) analysis is a standard signal processing technique developed by Huang et al. (1998) to especially analyze nonlinear, chaotic, and non-stationary types of signals. The EMD's main aim is to synthesize any signal as the sum of a finite number of functions, (Intrinsic Mode Functions or IMFs) computed a posteriori directly from the signal by an algorithm called the sifting process (Huang et al., 1998).
EMD is applied to Mg II monthly mean time series and to [FUV-MUV] colour index, resulting in 4 components for the Mg II index and 5 component for [FUV-MUV] colour index (figure shows the result of the EMD applied to [FUV-MUV] colour index). We got two important results:

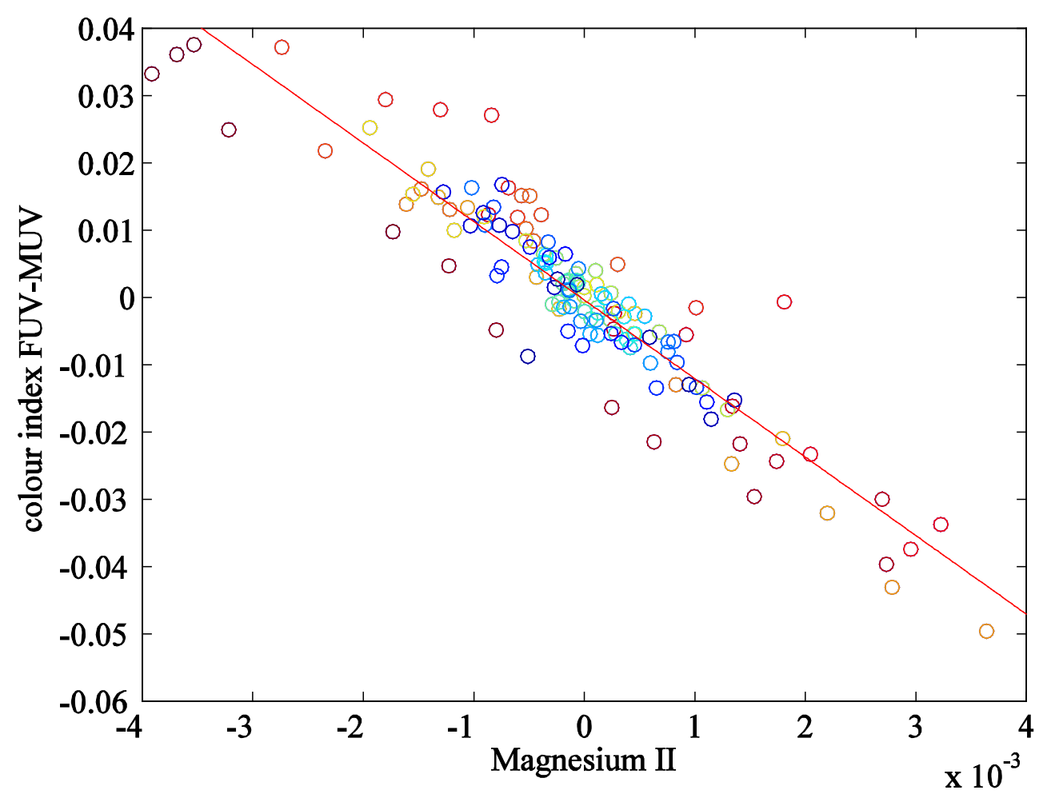
- phase opposition is clearly relating the IMFs of the two indices;
- the components are representative of solar magnetic activity cycle

EMD is applied to Mg II monthly mean time series and to [FUV-MUV] colour index, resulting in 4 components for the Mg II index and 5 component for [FUV-MUV] colour index (next figure shows the result of the EMD applied to [FUV-MUV] colour index).

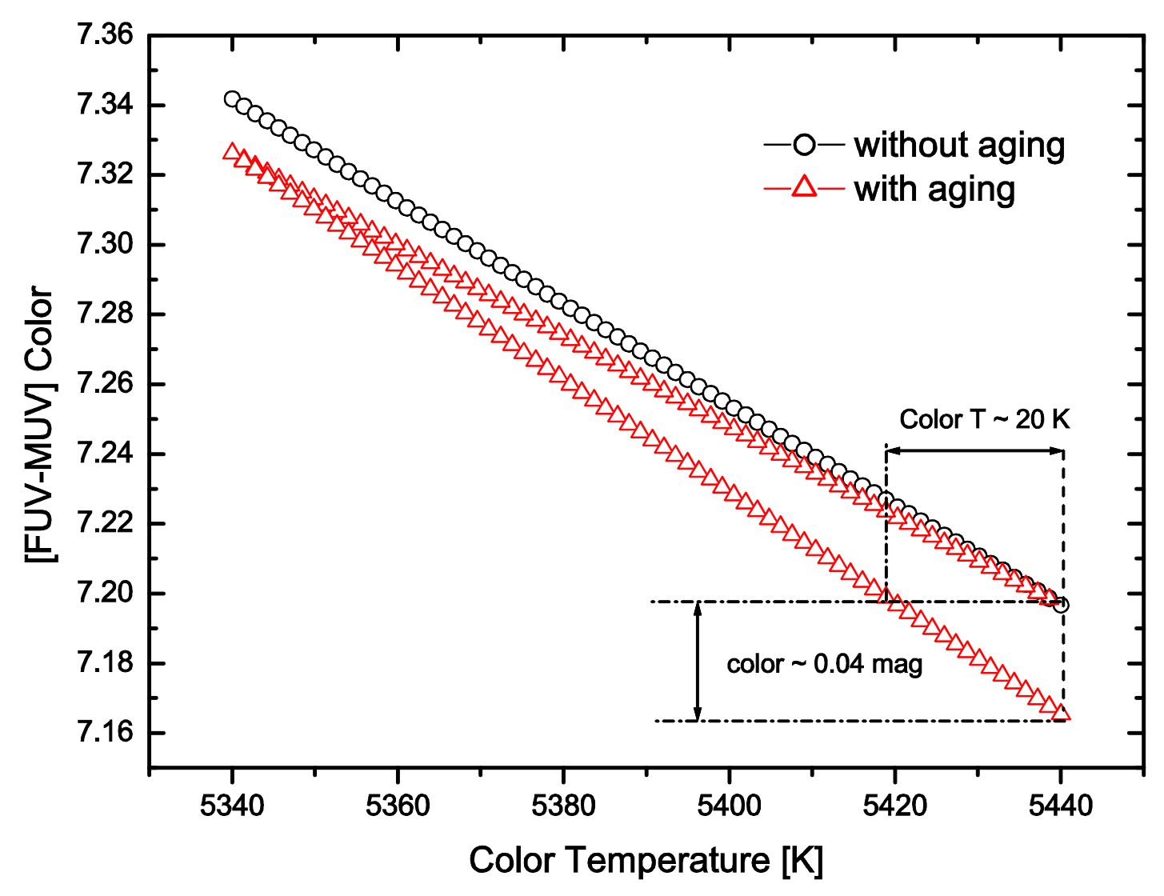


The IMFs of the colour index [FUV-MUV] are shown from the first (highest frequency) to the last (lowest frequency) starting from the top. The data sets cover the time between May 2003 and October 2015. IMF4 corresponds to 11-years Schwabe cycle.

The first two components have the highest frequencies thus they are likely affected by "solar noise", so they haven't been considered in this work focused on the dependence on 11-years Schwabe cycle. Quasi biennial variation seem to rule the third components, while data trend is contained in the fourth components and corresponds to the solar cycle 11-years period, as we would expect from data covering 12 years of solar activity.



Scatter plot between the two indices synthesized without the undecennal components. The circles represent the data, while the line represents the linear correlation. Data colour goes from blue to red and reflects the temporal evolution. We see that a unique slope has been recovered.



The colour index dependence on colour temperature assuming a linear dependence during the solar cycle. Black symbols show the relation without FUV channel ageing. Red symbols show the colour index variation considering a FUV channel ageing of a factor 0.0002 per month. This corresponds to a total reduction of 2.8% during the period of 142 months and produces an apparent colour temperature change of about 20 K.