# Towards solar activity maximum 24 as seen by GOLF and VIRGO/SPM instruments

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**Abstract.** All p-mode parameters vary with time as a response to the changes induced by the cyclic behavior of solar magnetic activity. After the unusual long solar-activity minimum between cycles 23 and 24 –where the p-mode parameters have shown a different behavior than the surface magnetic proxies– we analyze the temporal variation of low-degree p-mode parameters measured by GOLF (in velocity) and VIRGO (in intensity) Sun-as-a-star instruments on board SoHO. We then compared our results with other activity proxies.

# 1. Introduction

GOLF and VIRGO/SPM instruments have been used since 1996 to study the characteristics of low-degree, solar-acoustic modes [1] and even to unveil the asymptotic properties of dipole gravity modes [2, 3]. Thanks to their high-quality observations, we were able to measure all the pmode properties with very high precision not previously attainable, including mode asymmetries [4]. Moreover, the temporal variations of the p-mode parameters during cycle 23 were studied [5, 6, 7]. The unexpected long activity minimum between cycles 23 and 24 [8] reminds us that the physical processes governing the magnetic activity in the Sun are not yet well understood.

#### 2. Observations and Data Analysis

We analyzed observations collected by the space-based GOLF [9] and VIRGO [10] instruments onboard SoHO. A total of 6000 days were analyzed covering nearly 16.5 years between 1996 and 2012. These datasets were split into contiguous 365-day subseries, with a one-fourth overlap. The

power spectrum of each subseries was fitted to extract the mode parameters using a standard likelihood maximization function (power spectrum with a  $\chi^2$  with 2 d.o.f. statistics). Each mode component was parameterized using an asymmetric Lorentzian profile [11]. The temporal variations of the frequency shifts were defined as the difference between reference values (taken as the average over 1996-1997) and the parameters of the corresponding modes observed at different dates. Subseries with duty cycles less than 90% (around the SoHO vacation) were not taken into account for this analysis. The weighted averages over the central part of the 5-min oscillation power –from 2200 to 3400  $\mu$ Hz– of the temporal variations of the mode parameters were then calculated. Mean values of daily measurements of the 10.7-cm radio flux were used as a proxy of the solar surface activity. Linear regressions were performed between the temporal variations of the mode parameters and the radio flux using independent points only.

# 3. Frequency Variations of Individual Low-Degree p Modes

In Fig. 1 we show the average temporal variations of the l=0,1, and 2 p-mode frequencies observed by GOLF and VIRGO following [12]. The 11-year solar cycle is clearly visible superimposed to the the 2-year modulation originally described by [13], and fully discussed by [14, 15]. The frequency shifts are anticorrelated with the amplitude of the modes. No significant temporal variations have been found on the rotational splittings in agreement with [16].

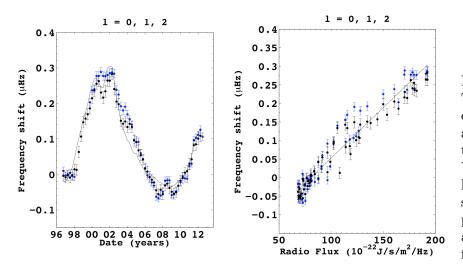


Figure 1. Left panel: Temporal variations of low-degree modes described in the as text; GOLF(black) and VIRGO (blue). The solid lines correspond to the scaled radio flux. Right panel: Frequency shifts as a function of the radio flux at 10.7 cm.

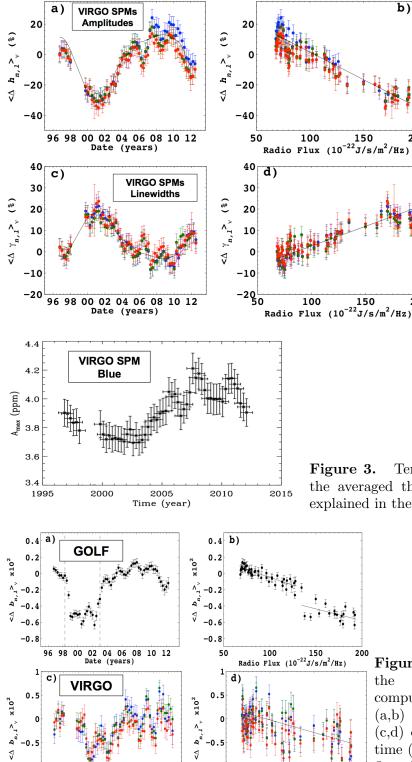
### 4. Mode Excitation and Damping with Solar Activity

The temporal variations of the mode amplitudes,  $\langle \Delta h \rangle$ , and linewidths,  $\langle \Delta \gamma \rangle$ , are shown in Fig. 2 computed using the three VIRGO/SPM channels. Note that due to absolute calibration problems and the changes of the observing wings [17], the GOLF amplitudes and linewidths are not exploitable for the moment for this analysis. A proper calibration is currently underway.

In Fig. 3, we show the variations of  $A_{max}$  [18] as it is usually done in asteroseismology to track down activity cycles [19] computed following [20]. The results are comparable to the average of the individual mode amplitudes as shown in Fig.2a.

## 5. Variation of Asymmetry

In Fig. 4, the temporal variations of the peak asymmetry  $\langle \Delta b \rangle$  of the modes observed by GOLF and VIRGO/SPM are shown. Due to the change in the GOLF observing configuration between the blue and the red wings [17], the variations (gradient) with the cycle are different (see Fig.4b).



-1

50

96 98 00 02 04 06 08 10 12 Date (years) 100 150 Radio Flux (10<sup>-22</sup>J/s/m<sup>2</sup>/Hz)

200

Figure 2. Average of the amplitudes (a,b) and linewidths (c,d) of the modes l = 0, 1 and 2 obtained using the three independent VIRGO channels: blue, green, and red as a function of time (left panels) and the radio flux (right panels). The solid lines correspond to the scaled radio flux.

Figure 3. Temporal variation of  $A_{max}$  using the averaged three VIRGO/SPM channels as explained in the text.

200

200

Figure 4. Average of mode asymmetries the computed using GOLF and VIRGO/SPM (a,b)(c,d) data as a function of time (left panels) and radio flux (right panels). The solid lines correspond to the scaled radio flux.

# 6. Solar Activity Proxy with GOLF and VIRGO/SPM

By correcting the raw VIRGO/SPM averaged data using the algorithms used to process *Kepler* data [21], we are able to measure the time evolution of the rotation signature produced by the sunspots crossing the visible solar disk. The projection of the wavelet power spectrum [22] in the range 6 to 60 days onto the time domain, provides us with a proxy of the 11-year magnetic activity cycle. This methodology could be use to track magnetic activity cycles in other stars.

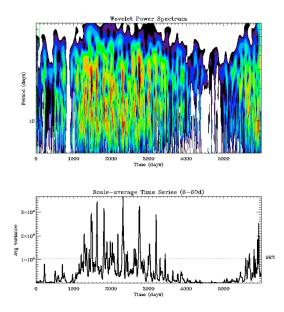


Figure 5. Top: Wavelet power spectrum of VIRGO/SPM computed using [22, 20]. Bottom: Projection onto the time axis as explained in the text. the dotted line is the 99% confident level.

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#### References

- [1] Toutain T, Appourchaux T, Baudin F et al. 1997 Solar Phys. 175 311
- [2] García R A, Turck-Chièze S, Jiménez Reyes S J et al. 2007 Science 316 1591
- [3] García R A , Jiménez A, Mathur S et al. 2008 Astron. N. 329 476
- [4] Thiery S, Boumier P, Gabriel A H et al. 2000 Astron. & Astrophys. 355 743
- [5] Gelly B, Lazrek M, Grec G, et al. 2002 Astron. & Astrophys. 394 285
- [6] Jiménez-Reyes S J, García R A, Jiménez A, Chaplin W J 2003 Astrophys. J. 595 446
- [7] Jiménez-Reyes S J, Chaplin W J, Elsworth Y et al. 2007 Astrophys. J. 654 1135
- [8] Salabert D, García R A, Pallé P L, Jiménez-Reyes S J 2009, Astron. & Astroph. 504 L1
- [9] Gabriel A H, Grec G, Charra J et al. 1995 Solar Phys. 162 61
- [10] Frohlich C, Romero J, Roth H et al. 1995 Solar Phys. 162 101
- [11] Nigam R & Kosovichev A G 1998 Astrophys. J. 505 L51
- [12] Salabert D, Chaplin W J, Elsworth Y, New R, Verner G A 2008, Astron. & Astrophys. 463 1181
- [13] Broomhall A M, Chaplin W J, Elsworth Y, Fletcher S T, New R 2009 Astrophys. J. 700 162
- [14] Fletcher S T, Broomhall A M, Salabert D et al. 2010 Astrophys. J. 718 19
- [15] Simoniello R, Finsterle W, Salabert D et al. 2012 Astron. & Astroph. 539 135
- [16] Broomhall A M, Salabert D, Chaplin W J et al. 2012 MNRAS 422 3564
- [17] García R A, Turck-Chièze S, Boumier P et al. 2005 Astron. & Astroph. 442 385
- [18] Kjeldsen H, Bedding T R, Arentoft T et al. 2008 Astrophys. J. 682 1370
- [19] García R A, Mathur S, Salabert D et al. 2010 Science 329 1032

- [20] Mathur S, García R A, Régulo C et al. 2010 Astron. & Astroph. 511 46
  [21] García R A, Hekker S, Stello D, et al. MNRAS 414 L6
- [22] Torrence C & Compo G P 1998 *BAMS* **79** 61