Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 59 (2017) 366–378

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

A study of the possible relation of the cardiac arrhythmias occurrence to the polarity reversal of the solar magnetic field

H. Mavromichalaki [a,*], P. Preka-Papadema [b], A. Theodoropoulou [c], E. Paouris [b], Th. Apostolou [d]

[a] Nuclear and Particle Physics Department, Faculty of Physics, National and Kapodistrian University of Athens, 15784 Athens, Greece
[b] Astrophysics, Astronomy and Mechanics Department, Faculty of Physics, National and Kapodistrian University of Athens, 15784 Athens, Greece
[c] Environment and Health. Capacity Building for Decision Making, School of Medicine, National and Kapodistrian University of Athens, Athens, Greece
[d] 2nd Cardiological Department, St. Panteleimon General Hospital of Nicaea, Piraeus, Greece

Received 1 September 2015; received in revised form 13 August 2016; accepted 22 August 2016
Available online 31 August 2016

Abstract

The biological human system is probably affected by the solar and geomagnetic disturbances as well as the cosmic ray variations. In this work, the relation between the solar activity and cosmic ray variations and the cardiac arrhythmias over the time period 1997–2009 covering the solar cycle 23, is studied. The used medical data set refers to 4741 patients with cardiac arrhythmias and 2548 of whom were diagnosed with atrial fibrillation, obtained from the 2nd Cardiological Clinic of the General Hospital of Nicaea, Piraeus, in Greece. The smoothing method on a 365-day basis and the Pearson *r*-coefficient were used in order to compare these records with the number of sunspots, flares, solar proton events, coronal mass ejections and cosmic ray intensity. Applying a moving correlation function to ±1500 days, it is suggested that a change of the correlation sign between the medical data and each one of the above parameters occurs during a time interval of about 2–3 years. This interval corresponds to the time span of the polarity reversal of the solar magnetic field of this solar cycle, which always takes place around the solar cycle maximum. After then a correlation analysis was carried out corresponding to the rise (1997–2001) and the decay (2002–2009) phases of the solar cycle 23. It is noticeable that the polarity reversal of the solar magnetic field coincides with the period where the sign of the correlation between the incidence of arrhythmias and the occurrence number of the solar eruptive events and the cosmic ray intensity, changes sign. The results are comparable with those obtained from the previous solar cycle 22 based on medical data from another country.

Keywords: Cosmic ray intensity; Solar magnetic field; Cardiac arrhythmias; Atrial fibrillation

1. Introduction

As it is known, Space Weather refers to the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of space borne and ground-based systems and services or endangers property or human health (ESA, 2014). Space weather is caused by solar eruptive events such as solar flares and coronal mass ejections (CMEs) which in turn produce radiations, energetic particles and waves propagating into the interplanetary space and they affect the Earth's magnetosphere and the terrestrial environment. The helio-geomagnetic dis-

* Corresponding author.
E-mail addresses: emavromi@phys.uoa.gr (H. Mavromichalaki), ppreka@phys.uoa.gr (P. Preka-Papadema), theod.rina@gmail.com (A. Theodoropoulou), evpaouris@phys.uoa.gr (E. Paouris).

http://dx.doi.org/10.1016/j.asr.2016.08.024
0273-1177/

turbances seem to affect, directly and indirectly, the human physiology as well as the human health (Palmer et al., 2006). Recent studies indicate a significant association between space weather parameters and the human physiology and health (Stoupel, 1999; Cornèlissen et al., 2002; Palmer et al., 2006; Stoupel et al., 2007a,b; Azcárate et al., 2012).

Various researchers have studied the impact of helio-geomagnetic activity on cardiovascular diseases (e.g. Stoupel and Shimshoni, 1991; Dorman et al., 2001; Oinuma et al., 2002; Dimitrova, 2008). Palmer et al. (2006) reported that 75% of geomagnetic storms are followed by an increase of 50% of hospital neurological and cardiological cases. Also, a good correlation between helio-geomagnetic activity and heart attacks has been indicated by Breus et al. (1989). Moreover, variations in hard cosmic ray flux constitute a prognostic indicator of changes in the number of cardiovascular cases (Styra et al., 2005). It is noticeable that the number of deaths due to heart attacks was increased in Minnesota by 5% during the maximum phase of the solar cycle, studying a 29-year period, while it was decreased in the solar minima (Cornèlissen et al., 2002).

Furthermore, Stoupel et al. (2005) noted a relationship between the death rate, especially due to acute myocardial infractions and space weather's parameters. It was also suggested that the monthly rates of them, in the time periods 1983–1999 and 2003–2005, are correlated with the cosmic ray activity and anti-correlated with the solar sunspot activity (Stoupel et al., 2007a,b). Recently, an increase of the incidents occurrence with Acute Coronary Syndromes was noticed during the recovery phase of some intense geomagnetic storms (Katsavrias et al., 2013).

Papailiou et al. (2011) using data from a number of 4011 aviators, showed a significant correlation between heart rate variations and high levels of geomagnetic activity as well as cosmic ray intensity decreases. Moreover, changes in human physiological parameters such as arterial systolic and diastolic pressure and heart rate during geomagnetic and cosmic ray intensity activities have been reported (Dimitrova, 2008; Papailiou et al., 2012).

It is known that cardiac arrhythmia (ARRY) is any change from the normal sequence of the electrical impulses of the heart (AHA, 2014). It is any disorder of the heart beat and usually it is expressed as a bradycardia or a tachycardia (Kremastinos, 2005). As a result of this disorder, heart does not work properly and does not pump the blood effectively. On account of this heart malfunction, damage may be incurred in brain, lungs and other organs (AHA, 2014). Atrial fibrillation (AF) is the most common arrhythmia in clinical practice (Zimetbaum and Falk, 2013). It is affecting an estimated population of 33 million worldwide, with an associated prevalence of approximately 1% (Chugh et al., 2013). Furthermore, 2.3 million Americans and 4.5 million people in the European Union are estimated to have AF, which is responsible for one-third of cardiac hospitalizations annually (Baez-Escudero and Valderrábano, 2014). Although AF is frequently asymptomatic, it is also a strong factor for increased stroke risk (Chugh et al., 2013; Ferguson et al., 2014) and has an associated 2-fold increase in mortality (Chugh et al., 2013).

Several studies have investigated the relation between the heart rhythm disturbances and the helio-geomagnetic activity (Stoupel and Shimshoni, 1991; Gigolashvili et al., 2010; Papailiou et al., 2011). Stoupel et al. (1994), in a period of 1185 consecutive days with low geomagnetic activity from January 1990 to March 1993, noticed that patients with paroxysmal atrial fibrillation presented a greater number of electrical heart instability events. Moreover, in such periods with low geomagnetic activity the number of ventricular extra systoles and supraventricular extra systoles, both of which are types of cardiac arrhythmias, increased (Stoupel and Shimshoni, 1991). Gigolashvili et al. (2010) showed the existence of a periodicity of 27 days in cardiac arrhythmias patients' number. In the same work a possible relation between the sector structure and the polarity sign of the interplanetary magnetic field during a Bartel rotation and the occurrence of the incidences with arrhythmia and especially those with multiple supraventricular paroxysmal tachycardia and ventricular extra systolic arrhythmias, is presented. Recently, Giannaropoulou et al. (2014) extended this work and focused on the possible relationship between the polarity reversal of the solar magnetic field that occurs 2–3 years around the solar maximum and the above occurrence number of referred types of arrhythmias, such as supraventricular extrasystols (S), supraventricular paroxysmal tachycardia (Ps), ventricular single extrasystols (V1) and ventricular multiple extrasystols (Vm). This work refers to a group of 1902 patients from Tbilisi, Georgia, covering the time period 1983–1992 (solar cycle 22). It was concluded that the polarity reversal of the solar magnetic field was connected with the sign and the value of the relation of the patients' number with the above types of arrhythmias and the solar, cosmic ray and geomagnetic parameters. Moreover, from that study it was resulted that the patients' number with types V1 and Vm of cardiac arrhythmias seems to be more sensitive to the changes of polarity sign of the solar magnetic field.

In this article the possible relation of the number of sunspots Rz, solar flares and CMEs as well as the cosmic ray intensity (CRI) on the occurrence number of patients with ARRY and especially on those with AF, is examined. Our analysis has been applied on medical data obtained from the General Hospital of Nicaea, Piraeus, Greece, for the time period 1997–2009, covering the period of the solar cycle 23. The study is focused on the possible connection between the polarity reversal of the solar magnetic field and the correlation sign between the medical data and the solar and CRI parameters, during solar cycle 23, searching for a corresponding relation similar to that already been noted during solar cycle 22.

2. Data selection and method of analysis

2.1. Medical data

Medical data over the time period 1997–2009 concerning the number of incidents with ARRY and with AF were obtained from the 2nd Cardiologic Clinic, General Hospital of Nicaea, 'St. Panteleimon', Piraeus, Greece. This database includes 4741 patients with cardiac arrhythmias, of whom 2548 were diagnosed with AF. Their ages were varied from 15 to 98 years old. The annual cases during the studied period are given in Table 1. It is noted that this Clinic did not work properly during the year 1998. An increase of cases number is presented, while the population of Piraeus and the neighboring islands of Saronic Gulf, regions that are covered by this hospital, were not changed significantly during the years 2001 and 2011, according to the Hellenic Statistical Authority (EL.STAT.; http://www.statistics.gr/portal/page/portal/ESYE).

2.2. Solar and cosmic ray data

It is known that the 11-years cycle of the solar activity is well described by the sunspot number (Hathaway, 2010). The solar cycle consists of the rise phase, the solar maximum and the decay phase according to the rise and the fall of the sunspot number. A solar flare, which is a sudden release of energy appearing as electromagnetic radiation over an extremely wide range and also as mass, particle, wave and shock-wave motions, is an eruptive phenomenon of the solar activity (Kenneth, 1995) associated with the sunspots. CMEs are large eruptions of magnetized plasma which are blasted off from the solar corona.

A solar proton event (SPE) is characterized by an abrupt increase of the population of the solar protons with $E > 10$ MeV and $J > 10$ pfu at the Earth's orbit (Belov et al., 2005a,b).

Daily values of the sunspots and flares number were obtained from the National Geophysical Data Center (NOAA, http://www.ngdc.noaa.gov/stp/SOLAR/ftp-sunspotnumber.html). The daily number of flares was grouped into C-, M- and X-class flares according to GOES classification (http://www.ngdc.noaa.gov/stp/solar/solarflares.html).

The daily number of CMEs, based on SOHO/LASCO CME catalogue (http://cdaw.gsfc.nasa.gov/CME_list/), is provided by Paouris et al. (2012). It is noted that the SOHO/LASCO catalogue has a data gap during the months July–September 1998 and January 1999 and therefore our study was performed for the period February 1999–December 2009.

Unfortunately, during this period of data gap there are no CMEs data from other sources.

Solar proton events (SPEs) were obtained from the Solar Proton Events Database of the Athens Cosmic Ray Station (http://cosray.phys.uoa.gr/index.php/data/solar-proton-events-database) and from NOAA Space Environment Services Center (http://umbra.nascom.nasa.gov/SEP/).

Daily corrected for pressure and efficiency values of the cosmic ray intensity (CRI) for the aforementioned time period were obtained from Oulu Neutron Monitor Station, University of Oulu (http://cosmicrays.oulu.fi/).

It is noted that the aim of this work is to study the possible relation of the solar magnetic field polarity reversal with the appearance of cardiac arrhythmias. For this reason we examine only the solar eruptive phenomena (CMEs and flares) which are correlated with the sunspot number connected to the solar magnetic field. The effect of the heliomagnetic activity (ICMEs, CIR, HSSWSs, Dst and Ap indices, etc.) to the cardiological cases may be examined in another work.

2.3. Solar magnetic field polarity reversal

It is known that the polarity of the solar magnetic field reverses sign approximately every 11-years around the period of solar maximum. Thus this reversal of polarity is related to the sunspot number expressed the solar activity and the solar modulation is the process in which the irregularities in the interplanetary magnetic field, which impede the passage of high energy particles toward Earth, are great, when the Sun is most active and are small, when the Sun is quite (Forbush, 1958; Longair, 1992; Mavromichalaki et al., 1998).

As regards the solar cycle 23, the north polar reversal has been reported to be in February 2001 and the south polar reversal in September 2001 (Durrant and Wilson, 2003). According to Bilenko (2002), the north polar reversal of the Sun occurred in May 2001 and the south polar reversal in January 2002. During the time period 2000–2002, the magnetic field strength had shown an "unsettled behavior" with several short-duration reversals (Gopalswamy et al., 2003). Also, Dikpat et al. (2004) supports that the north polarity was reversed during the time period of June–September of 2000, while the south one was reversed during the period of May–August of 2001. Thus, it is outlined that the polarity reversal of the solar

Table 1
Annual number of cardiac arrhythmias (ARRY) and of atrial fibrillation (AF) cases for the period 1997–2009.

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
ARRY	231	198	256	313	349	395	396	429	419	463	446	437	409
AF	91	83	127	131	132	161	194	287	241	319	259	260	263

magnetic field during the solar cycle 23 occurred from September 2000 up to end of 2002.

2.4. Method of analysis

The Adjacent-Averaging method of smoothing was used and the Pearson *r*-coefficients were calculated in order to examine the possible relation of the number of sunspots, solar flares, CMEs and solar proton events as well as the cosmic ray intensity variations, on the occurrence rate of the patients with ARRY and especially with AF recorded in the General Hospital of Nicaea, Piraeus, Greece. The statistical method of Adjacent-Averaging smoothing was applied on a 365-day basis (1 year) using the program Origin Pro 8.5, Origin Lab Corporation, 1991–2010. The statistical package STATISTICA ver.6, StatSoft Inc. 2001, was used for the calculation of all correlation coefficients and *p*-values. It is important to refer that correlation coefficients are significant at $p < 0.0500$.

Moreover in order to calculate the time lag of each parameter with respect to the ARRY and AF, the cross correlation coefficients between these parameters with varying time-lags from 0 to ±1500 days for the time interval 1997–2009 have been calculated. Finally, the statistical analysis of data is repeated after having removed the trends of the time series in order to robust our previous results.

3. Data analysis

Time profiles of the daily smoothing values of the sunspot number (Rz) together with the corresponding daily smoothing values of the ARRY and the AF cases for the period 1997–2009, are presented in the upper panel of Fig. 1. Also, the daily smoothing values of the CRI with the corresponding daily smoothing values of ARRY and AF, for the same time period are presented in the lower panel of Fig. 1. Cosmic rays modulated by the solar activity expressed by the sunspot number are in inverse relation (Forbush, 1958) and it is well presented in this figure. The dotted vertical lines indicate the time span of the polarity reversal of the solar magnetic field for the examined solar cycle, while the solid vertical line separates the descending phase from the ascending and the maximum phases of this cycle.

During the rise phase of the solar cycle 23 (1997–2001) an increase on both, the number of medical cases and the sunspot number was recorded. On the contrary, during the decay phase (2002–2009) and after the polarity reversal of the solar magnetic field (September 2000 till the end of 2002) there was an expected decrease of the sunspot number, while the number of medical cases continued to increase. Respectively, an increase of the medical cases during the decreasing of CRI in the period 1997–2001 is recorded, while during the increasing of CRI (2002–2009), the medical cases were increased. It is noticeable that a similar behavior appeared during solar cycle 22, using medical data from another country (Giannaropoulou et al., 2014).

The daily smoothing values of the number of solar flares and of the number of ARRY and AF cases for the same time period is presented in the upper panel of Fig. 2. The results are similar to the ones for the sunspot number and the medical cases. Moreover, examining the possibility of a different behavior between the various types of solar flares expressed by the X-ray flux, we analyzed separately the C-class flares, which are the main population of the solar flares and also, the intense flares with classification ⩾M-class (M- and X-flares). We also examined separately the solar proton events characterized as SPEs. The daily smoothing values of the number of C- flares, ⩾M-class flares and SPEs together with ARRY and AF daily smoothing cases for the same time period are presented in Fig. 3. However, there is not any different behavior, comparing them with the previous results (see Fig. 2). Finally, the daily smoothing values of the CMEs number together with the corresponding daily smoothing values of ARRY and AF cases are presented in the lower panel of Fig. 2. The time series of medical cases compared with the time series of CMEs number, presented a similar behavior with that between the medical data and the time series of the solar flares number and the sunspot number (and vice versa with CRI).

4. Statistical analysis and results

In order to examine how the correlation coefficients of the above analyzed time series vary with time, a moving correlation analysis was used. Results concerning the sunspot number and the CRI with the ARRY and AF medical cases for different time lags are presented in Fig. 4. The medical data (ARRY and AF cases number) with respect to the Rz were mainly examined, because this is related directly to the solar magnetic field polarity reversal. As it is expected, the other solar data correlated to the occurrence number of the medical cases provide analogous results.

Without any time lag, the time series of the sunspot number and the time series of the medical data have an anti-correlation coefficient of −0.42 (ARRY-Rz) and −0.63 (AF-Rz) for the time period 1997–2009 (left panels of Fig. 4). It is underlined that the best correlation coefficient between ARRY data and sunspot number +0.45 corresponds to the time lag of ~1460 days (4 years) until 1500 days (4.5 years) and the best anti-correlation coefficient −0.96 corresponds to a time lag of about −894 days (2.5 years), although a plateau in the maximum anti-correlation coefficient values from −650 to −1460 days is obvious in Fig. 4. The best correlation coefficient between AF data and Rz equal to +0.47 corresponds to a time lag of ~1460 days (4 years) and the best anti-correlation coefficient −0.93 corresponds to the time lag of about −699 days (1.9 years), while a plateau in the maximum anti-correlation coefficient values from −450 to −950 days

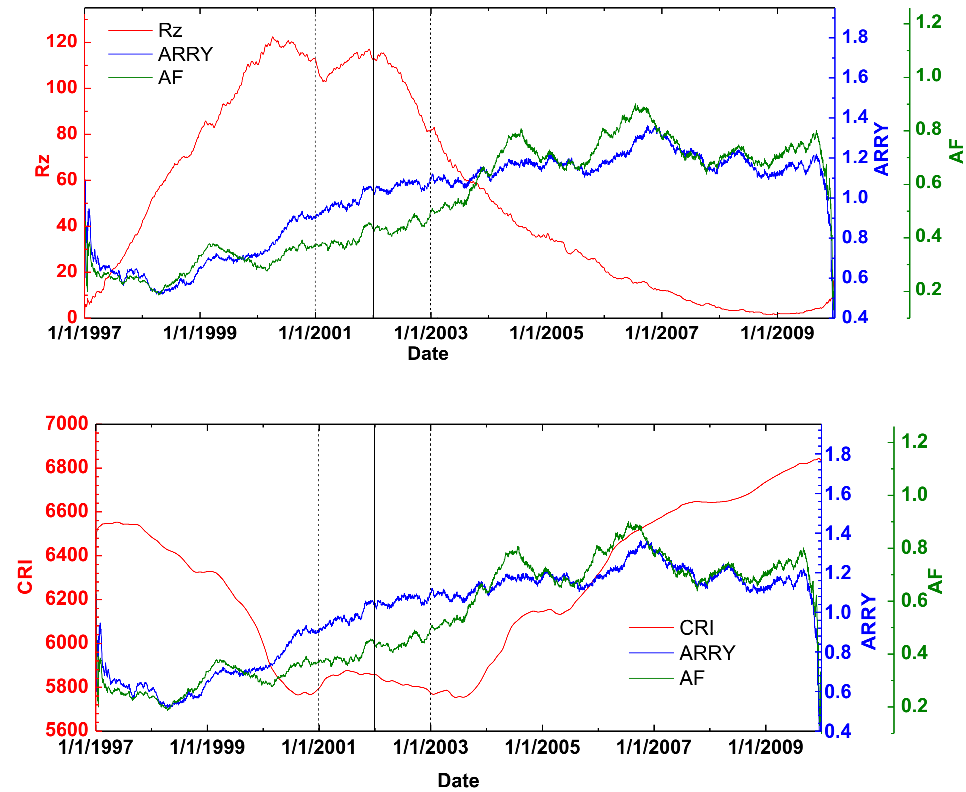

Fig. 1. The daily smoothing values of Rz, ARRY and AF (upper panel) and of CRI, ARRY and AF (lower panel) for the period 1997–2009 are illustrated. The dotted vertical lines indicate the time span of the polarity reversal of the solar magnetic field. The solid vertical line separates the ascending phase from the maximum and the ascending phases of the examined solar cycle.

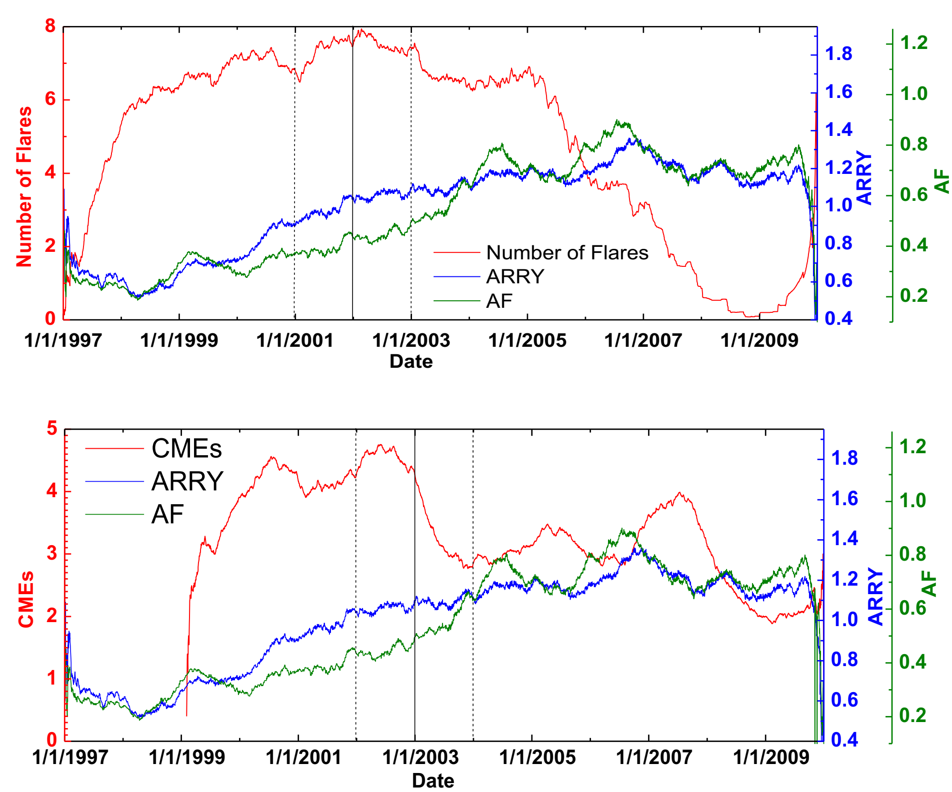

Fig. 2. Daily smoothing values of number of flares, ARRY and AF cases (upper panel) and daily smoothing values of CMEs, ARRY and AF (lower panel) for the period 1997–2009. The time-series of CMEs start from February 1999.

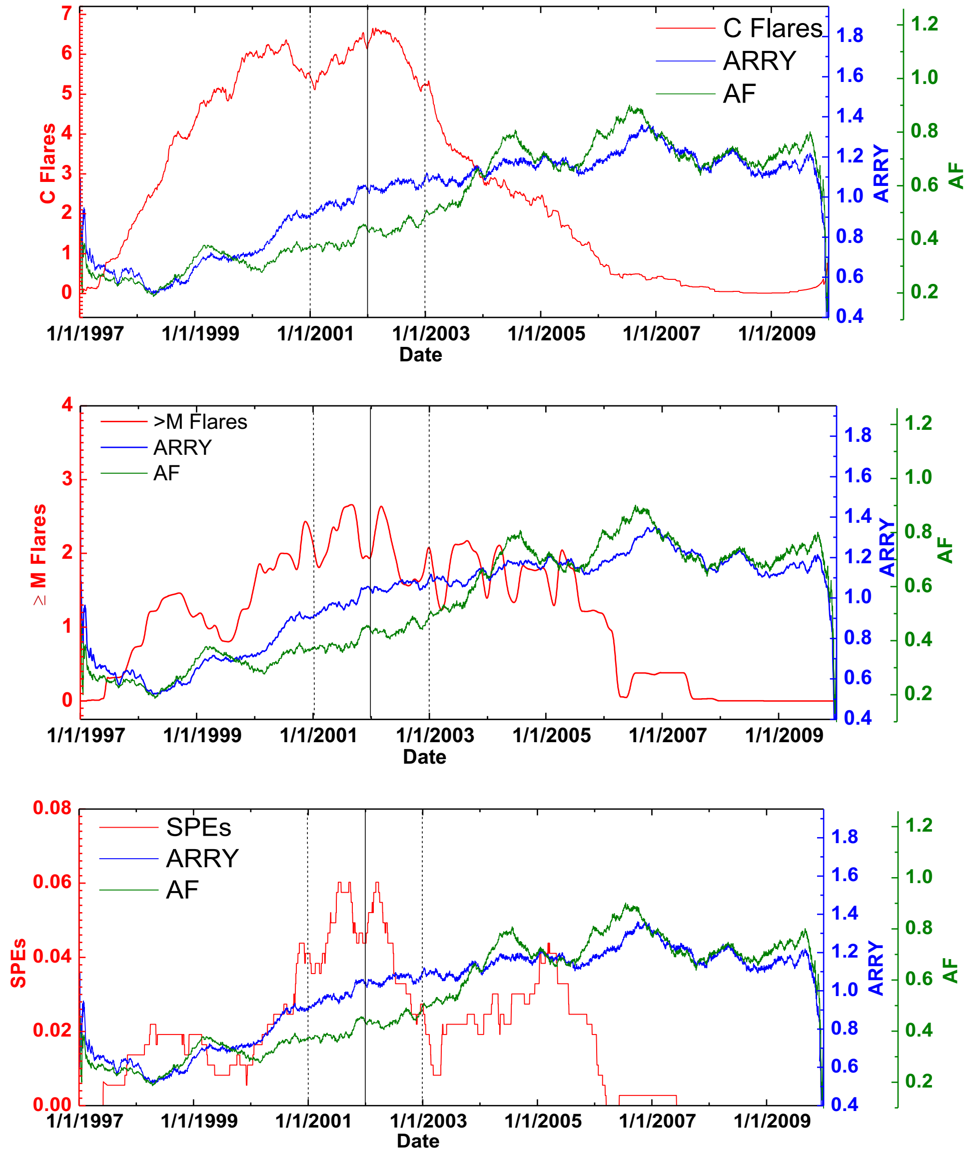

Fig. 3. Daily smoothing values of C-flares, ARRY and AF (upper panel), daily smoothing values of ⩾M flares, ARRY and AF (middle panel) and daily smoothing values of SPEs, ARRY and AF (lower panel) for the period 1997–2009.

is obvious. It means that a time lag of approximately half of the solar cycle gives the best correlation coefficient or anti-correlation coefficient. Furthermore, the correlation coefficient between sunspot number and medical cases number is equal to zero and the correlation changes sign from negative to positive, in a time lag of 633 days (1.7 years) and 1009 days (2.8 years) for ARRY and AF cases, respectively. This time interval of 1.7–2.8 years (mean value 2.2 years) is comparable to the time period of the solar magnetic field polarity reversal. Combining both the last results, we conclude that the correlation coefficient's sign changes around the solar maximum during a period of 2–3 years that is in agreement with the period of the solar magnetic field polarity reversal.

In the right panels of Fig. 4, the time series of the CRI and of the medical data without a time lag are presented. A correlation of +0.07 (ARRY-CRI) and +0.32 (AF-CRI), for the time period 1997–2009 is calculated. The best correlation coefficient +0.93 (ARRY-CRI) corresponds to a time lag of ~ 1460 days (4 years) up to 1500 days (4.5 years) and the best anti-correlation coefficient −0.76 (ARRY-CRI) corresponds to a time lag of −1355 days (3.7 years) up to 1500 days (4.5 years). The best correlation coefficient between the AF and CRI data +0.95 corresponds to the time lag of ~ 1460 days (4 years) and the best anti-correlation coefficient −0.86 corresponds to a time lag of −1046 days (2.9 years). Moreover, the correlation coefficient between CRI and medical cases number is zero and the correlation changes sign from positive to negative, in a time lag of 75 days and 390 days for ARRY and AF cases, respectively. According to Paouris et al. (2012) the hysteresis effect between CRI and Rz has been found to

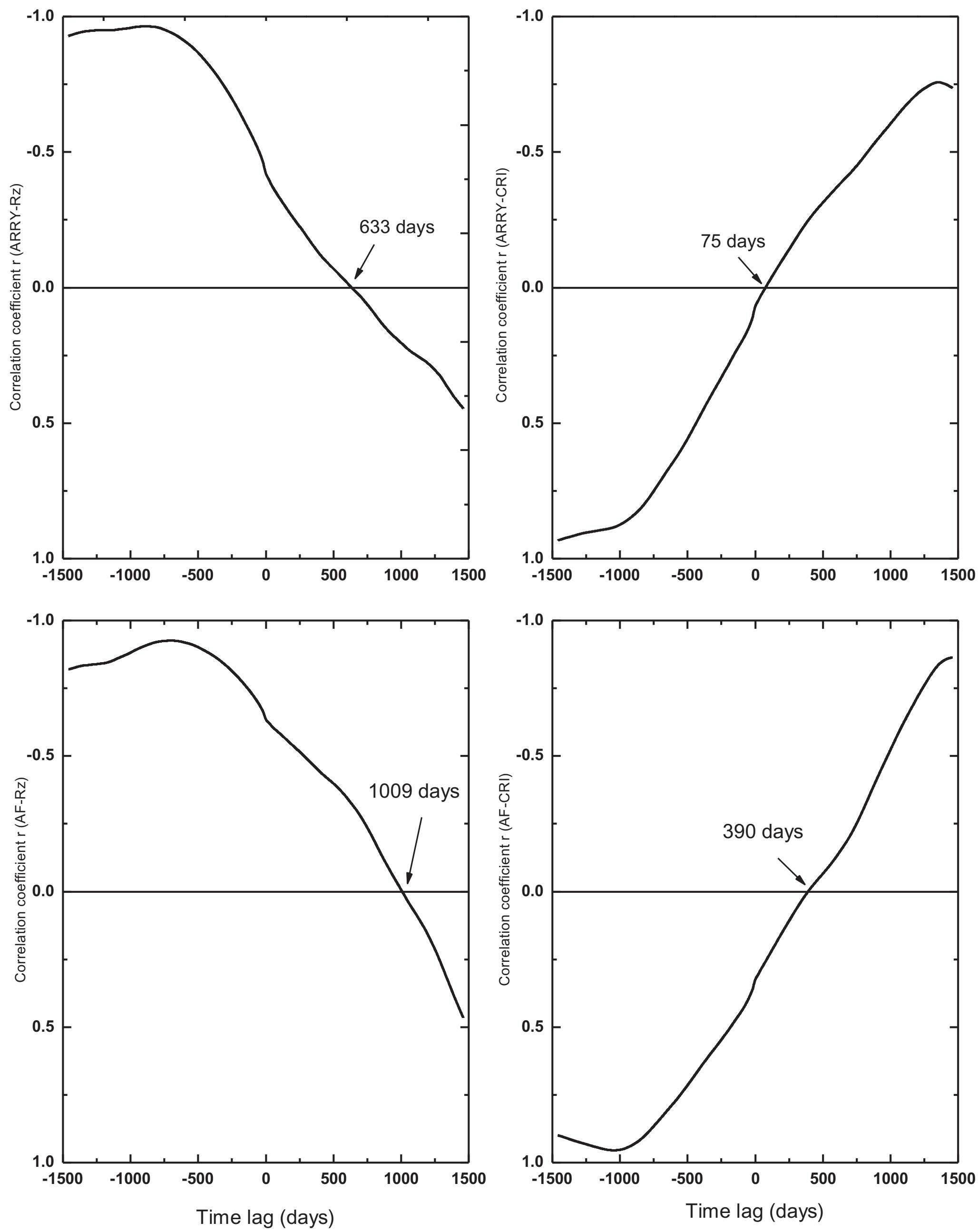

Fig. 4. Cross-correlation coefficients between the ARRY (upper panels) and AF (lower panels) data and the examined variables of Rz (left panels) and CRI (right panels) respectively with different time lags for the time period 1997–2009. The anti-correlation of the CRI against the Rz is obvious. The change of the correlation sign is also indicated.

be equal to 13.6 ± 0.4 months during the solar cycle 23. This is comparable to the time lag of approximately one year obtained from this work.

The correlation coefficients among the daily smoothing values of ARRY or AF cases and the daily smoothing values of CRI, Rz, flares, C- and $\geqslant$M-class flares, SPEs and CMEs are calculated. All these data were divided into two time periods, 1997–2001 and 2002–2009, based on the time period of the solar magnetic field polarity reversal during the solar cycle 23. The calculated correlation coefficients of all the used parameters for these two time periods are given in Table 2. It is noted that all the obtained results are statistically significant ($p < 0.05$). The medical cases have a positive correlation coefficient with all the solar events and a negative one with the CRI, during the period 1997–2001. On the contrary, in the period 2002–2009, the correlation between ARRY and AF cases and the CRI is positive, although the correlation between the solar events and medical cases is negative. It is noted here that the sunspot number and the CRI are anti-correlated (Forbush, 1958). It is obvious from this Table that the change of the correlation coefficient sign takes place during the time

Table 2
Correlation coefficients and p-values of the solar and medical data for the two time periods, 1997–2001 and 2002–2009.

Type of arrhythmias	Rz	Total number of Flares	C-Flares	⩾M-Flares	SPE	CRI (counts/s)	CMEs[a]
ARRY (1997–2001)	0.57 $p = 0.00$	0.36 $p = 0.00$	0.54 $p = 0.00$	0.58 $p = 0.00$	0.71 $p = 0.00$	−0.76 $p = 0.00$	0.55 $p = 0.00$
ARRY (2002–2009)	−0.42 $p = 0.00$	−0.29 $p = 0.00$	−0.37 $p = 0.00$	−0.29 $p = 0.00$	−0.30 $p = 0.00$	0.29 $p = 0.00$	−0.54 $p = 0.00$
AF (1997–2001)	0.53 $p = 0.00$	0.36 $p = 0.00$	0.51 $p = 0.00$	0.45 $p = 0.00$	0.50 $p = 0.00$	−0.60 $p = 0.00$	0.70 $p = 0.00$
AF (2002–2009)	−0.76 $p = 0.00$	−0.51 $p = 0.00$	−0.68 $p = 0.00$	−0.53 $p = 0.00$	−0.52 $p = 0.00$	0.52 $p = 0.00$	−0.78 $p = 0.00$

[a] CMEs were studied for the period February 1999–December 2009.

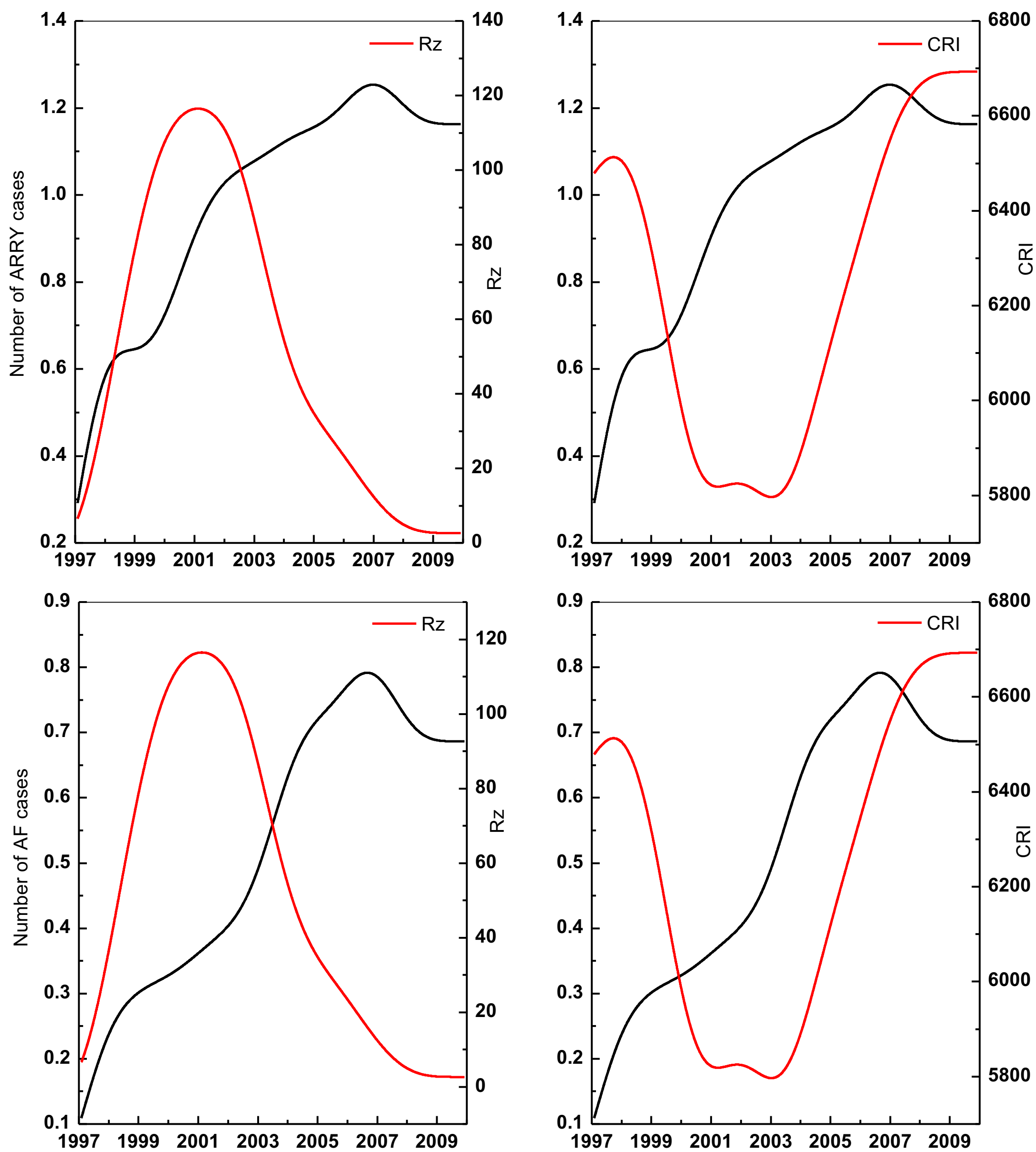

Fig. 5. After removing any trends from the time series, time profiles of the filtered data of ARRY (upper panels) and AF (lower panels) cases together with Rz (left panels) and CRI (right panels) data, for *all* the examined time period 1997–2009, are presented.

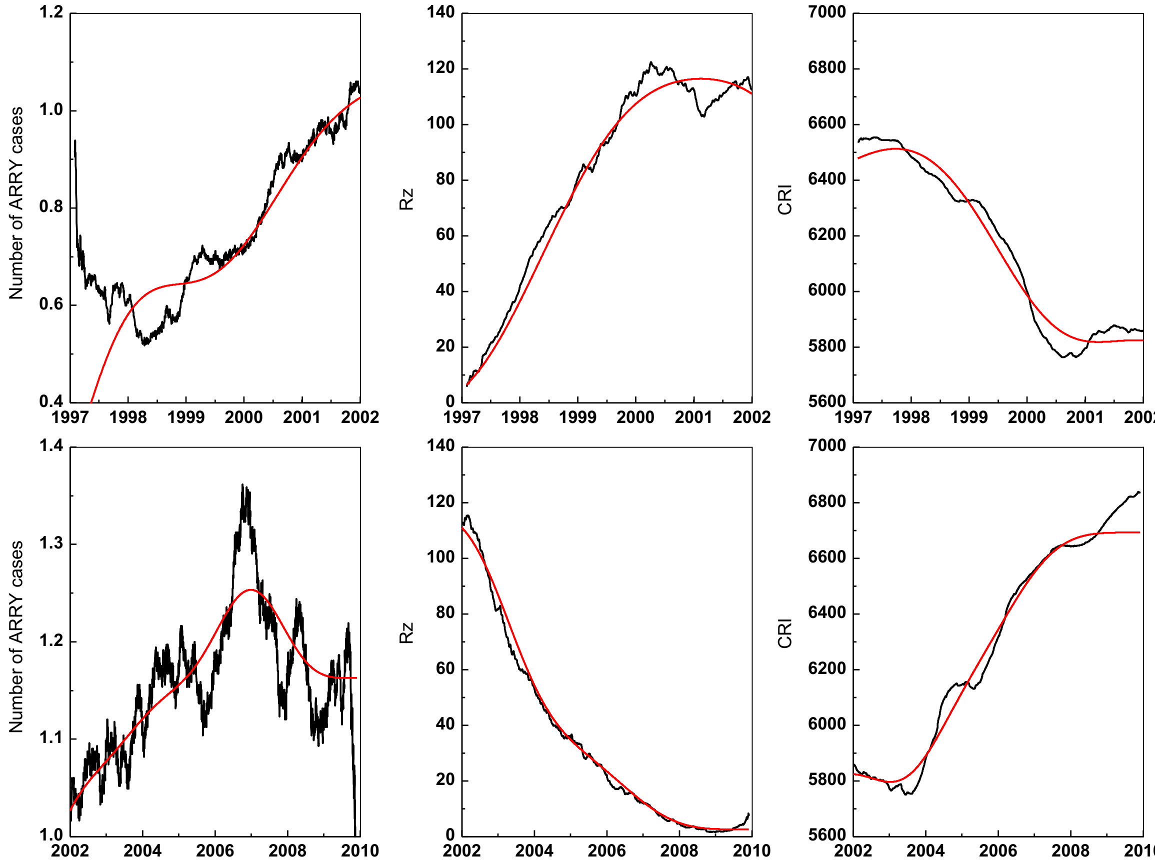

Fig. 6. Time profiles of the data (ARRY cases, Rz and CRI) before (black line) and after removing the trends (red line) for the time period 1997–2001 (top panels) and 2002–2009 (bottom panels). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

period of the solar magnetic field polarity reversal (Bilenko, 2002; Gopalswamy et al., 2003).

A very good correlation (>70%) between ARRY cases and SPEs as well as CRI, during the rise phase, is obtained. Also, a very good correlation (>70%) between AF cases and CMEs number, during the rise and the decay phases, as well as between AF cases and Rz, and AF and C-flares, during the decay phase, is observed. The correlation coefficients with values $r \geqslant 0.50$ consist a percentage up to 50% for the ARRY cases and up to 86% for the AF cases, respectively.

In general, it is outlined that the correlation coefficients associated with the ARRY cases during the rise phase of the solar cycle are better than the ones of the decay phase, with only an exception of those related to the CMEs number. Also, the correlation coefficients associated with the AF cases during the decay phase are better than the ones of the rise phase, with exception of those that are related to CMEs number and SPEs number which is retained in almost the same levels.

Furthermore, for more accurate results the trends from the studied time series were removed applying a low-pass band Butterworth filter with a cut-off period at 3 years. It is a conventional methodology before the calculation of the correlation coefficients and thus, there is a direct comparison only of large-scale variations between the parameters examined in this work. After removing any trends from the time series, the time profiles of the filtered data of ARRY (upper panels) and AF (lower panels) cases together with Rz (left panels) and CRI (right panels) data, for all the examined time period 1997–2009, are presented in Fig. 5. It is noteworthy that, there is a positive relation between medical data and sunspot number (Rz) during the rise phase of this solar cycle and a negative one during the decay phase. Certainly, the vice versa results were obtained in the case of the CRI. It is obvious that this change of the relation of the ARRY and AF cases time series with the Rz and the CRI ones is observed during the period 2000–2003. However, this time interval coincides with the period of magnetic field polarity reversal of the solar cycle 23.

More specifically, this behavior separately for the two time periods 1997–2001 and 2002–2009 is shown in Figs. 6 and 7. After removing the trends from the examined time series, the time profiles of the smoothed and the filtered data of ARRY cases, Rz and CRI for the time period 1997–2001 (upper panels) and for the period 2002–2009 (lower panels) are presented in Fig. 6. The corresponding time-series for the AF cases, Rz and CRI, for the same time periods are given in Fig. 7. The calculated correlation

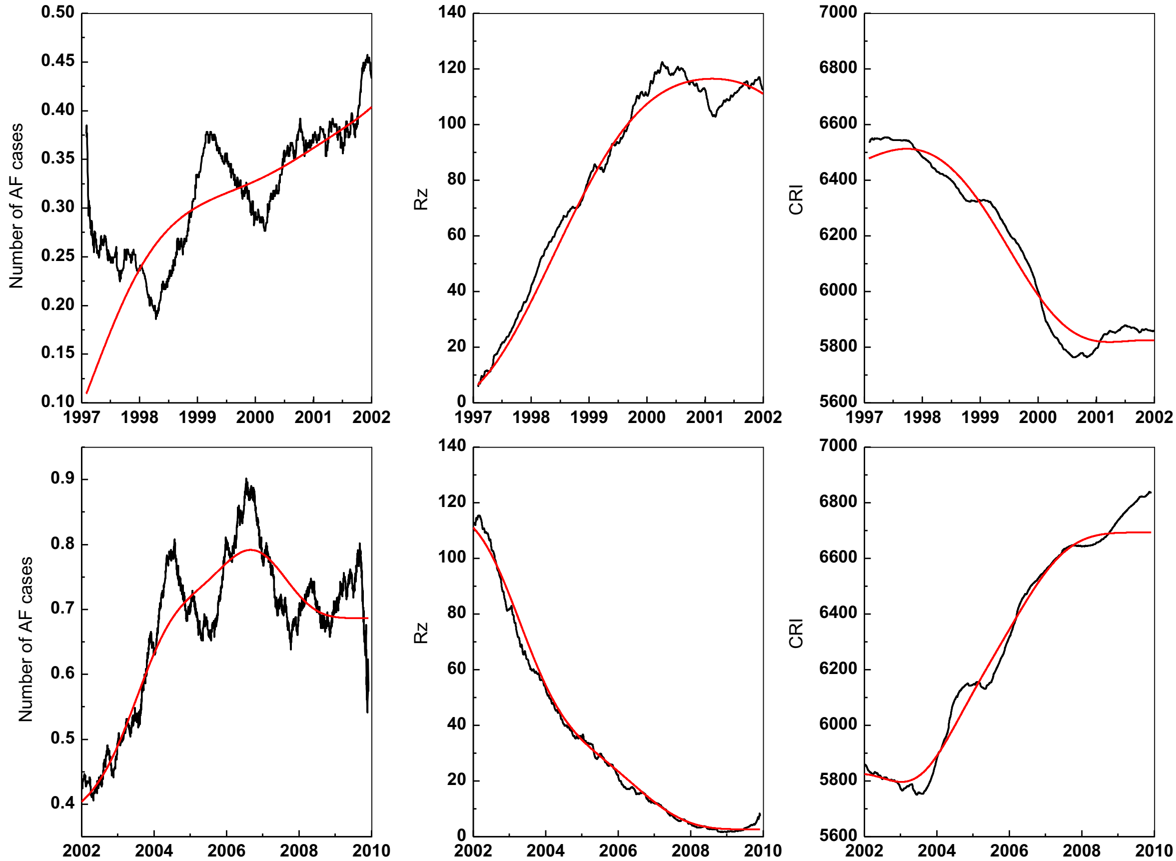

Fig. 7. Time profiles of the data (AF cases, Rz and CRI) before (black line) and after removing the trends (red line) for the time period 1997–2001 (top panels) and 2002–2009 (bottom panels). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Correlation coefficients and p-values after removing the trends of the corresponding time-series of Table 2.

Type of arrhythmias	Rz	CRI (counts/s)
ARRY (1997–2001)	+0.89 $p = 0.00$	−0.86 $p = 0.00$
ARRY (2002–2009)	−0.90 $p = 0.00$	+0.79 $p = 0.00$
AF (1997–2001)	+0.96 $p = 0.00$	−0.88 $p = 0.00$
AF (2002–2009)	−0.88 $p = 0.00$	+0.72 $p = 0.00$

coefficients and the corresponding p-values of these time series, after removing the trends (Figs. 6 and 7), are given in Table 3.

It should be mentioned that during at the rise phase of this solar cycle (1997–2001), a clear correlation between the occurrence of patients (ARRY and AF) and the sunspot number Rz_ appeared. Also, at the decay phase (2002–2009) an anti correlation between the occurrence of patients (ARRY and AF) and the sunspot number Rz appeared. The anti-correlation between the occurrence of patients and CRI during the rise phase and the correlation between them during the decay phase are also presented. These results are consistent to the results presented in Table 2.

The coefficients after removing the trends are better than the ones before removing the trends.

This is reinforcing the initial assumption that the change of polarity of the solar magnetic field seems to affect the manifestation of arrhythmias, because the existence of trends, expressing the presence of smaller periodicities involved in the 11 years cycle, cause some confusion in comparing time series. Nevertheless it seems that the correlation is strong enough and it is not covered by the existence of trends.

The same conclusion applies to the comparison of analogous medical data and Rz, CRI, etc. during the previous solar cycle (Giannaropoulou et al., 2014), as those time series, without removing trends, gave similar results.

5. Discussion and conclusions

In this work medical data of ARRY and AF were analyzed in comparison with the solar magnetic field polarity reversal and the occurrence of solar eruptive events (flares and CMEs) as well as with the CRI. These data were recorded within the time period 1997–2009 covering the solar cycle 23, which is considered as a very active and peculiar solar cycle. A number of strong helio-geomagnetic events as intense flares, fast CMEs, Forbush decreases, GLEs, geomagnetic storms, etc. appeared especially during the declining phase of this solar cycle (e.g. Belov et al., 2005a,b; Papaioannou et al., 2009; Plainaki et al., 2010). The polarity of the solar magnetic field reverses sign approximately every 11 years near the maximum of the solar activity or the minimum of the CRI (Mavromichalaki et al., 1998). It is noticeable that the correlation between the daily smoothing values of ARRY and AF with the corresponding values of sunspots, solar flares, CMEs, SPEs and CRI changes sign during the time period of this reversal.

The examined arrhythmia cases (and especially the AF cases) present a good relation or anti relation with the occurrence number of eruptive solar phenomena (flares and CMEs) which affect directly or indirectly the terrestrial environment, during the rise or the decay phase of the solar cycle 23. This means that the correlation or anti-correlation depends on the polarity reversal of the solar magnetic field, which happens during the maximum phase in each solar cycle.

The same result has been already underlined during the solar cycle 22, using medical cases obtained from Tbilisi, Georgia, while the ones of the solar cycle 23 were recorded in the area of Piraeus, Greece. Giannaropoulou et al. (2014) have shown that the change of the sign of the solar magnetic field polarity of the solar cycle 22 seems to be related with the reverse of the sign of the correlation between the arrhythmias cases and the helio-geomagnetic variations as well as the CRI. This research refers to the years 1983–1992 including the maximum of the solar cycle 22, and was based on a group of 1902 patients. Moreover, the authors concluded that the arrhythmias types V1 and Vm seem to be more sensitive in the changing of the sign of the solar magnetic field polarity comparing to the arrhythmias types S and Ps. Furthermore, according to Gigolashvili et al. (2010) the rate of arrhythmias and especially of paroxysmal tachycardia and ventricular multiple extra systoles can be affected by the change of the polarity sign of the solar magnetic field. In this research the possible influence of solar activity and interplanetary magnetic field changes on different types of cardiac arrythmias was studied. The method of Fourier spectral analysis and the method of superposing epochs for the study of the periodic changes in the solar activity, were used in a sample of ischemic heart disease patients. The results revealed a correlation between the periods of incidence of arrythmias and the main periods of solar and interplanetary magnetic fileds. It is noteworthy that the same results have been also outlined for the solar cycle 22 by Stoupel et al. (1994). They noticed that patients with paroxysmal AF presented a greater number of electrical heart instability events, in a period of low geomagnetic activity from January 1990 to March 1993 that coincides with the polarity reversal of the solar magnetic field of the solar cycle 22. It is obvious that this result is consistent with the work by Giannaropoulou et al. (2014) where a possible effect of this magnetic field polarity reversal to the examined four types of cardiac arrhythmias was noticed.

The AF cases present a good correlation or anti correlation with the solar activity expressed by the number of sunspots, flares and CMEs during the rise or the decay phase of the solar cycle, respectively. Also a good anti-correlation or correlation with the CRI during the rise or the decay phase of the solar cycle is respectively noticed. Almost all correlation coefficients (86% of them) are higher or lower than 0.50 or -0.50 and this association seems to be better during the decay phase rather than the rise phase of the solar cycle. During the decay phase, the AF cases and the Rz or the number of C-class flares which are the main occurrence number of flares appear to have a good anti-correlation ($\sim$0.70). Additionally, the AF cases have a correlation ($>$0.70) or anti correlation (-0.70) with the CMEs number, during the rise or the decay phase of the solar cycle, respectively. The CMEs via solar wind affect the terrestrial magnetosphere and cause geomagnetic storms that mean the high correlations between the examined AF cases and the occurrence number of CMEs indicate a possible affect of the geomagnetic disturbances on the AF cases, as a further aggravating environmental factor. We remind that the purpose of this work is the study the possible relation of the solar magnetic field polarity reversal with the appearance of cardiac arrhythmias examining only the solar eruptive phenomena (CMEs and flares) which are correlated with the sunspot number that is connected to the solar magnetic field.

When the set of the medical cases was enriched with all the types of arrhythmias (ARRY), then the correlation coefficients between the number of ARRY and the number of each one of the solar phenomena during the rise phase of the solar cycle, seem to be higher than 0.50 with the only exception of that one of the total number of flares. During the decay phase, ARRY cases and CMEs occurrence number have a good anti correlation ($>$0.50). Also, during the rise phase, ARRY cases appear a very good correlation ($>$0.70) with SPEs and an anti correlation (<-0.70) with CRI. The same correlation coefficient between the examined medical cases and SPE or CRI, during the rise and the decay phase, is in accordance with the known association between the CRI and the SPEs. The high correlation coefficient between the ARRY cases and the occurrence of SPEs or the CRI, during the rise phase, indicates a possible relation between the increased arrhythmias cases and the arrival of energetic solar protons in the Earth's environment (magnetosphere and ionosphere) as well the increased dose of CRI.

As a conclusion, the solar magnetic field polarity reversal seem to affect the correlation between the number of cardiac arrhythmias and atrial fibrillation cases and the occurrence of solar eruptive events and the cosmic ray intensity. The connection between the produced geomagnetic disturbances caused by the solar activity which modulate the cosmic ray intensity as it is recorded by ground based detectors as the neutron monitors is noted.

It is noted that this study is in the direction of the affection of the environmental factors on the cardiac arrhythmias. Except from the atmospheric parameters such as temperature and pressure it seems that the terrestrial electromagnetic environment (e.g. cosmic rays) also affects the heart operation. In the future an extended work with more medical data around the solar maxima of other solar cycles beyond the cycles 22 and 23 would be helpful for a better understanding of the influence of the solar and geomagnetic activities to the human cardiac physiological parameters.

Acknowledgments

The authors thank the cosmic ray data providers of the High Resolution Neutron Monitor Database (NMDB) and those ones of the solar and interplanetary data. The authors from the University of Athens thank the Special Research Account for supporting the Cosmic Ray Research. Moreover the authors express their thanks to the PhD students Christos Katsiavrias and Dimitra Lingri of the University of Athens for assistance provided. Thanks are also due to the anonymous referees for their useful suggestions improving this manuscript.

References

AHA, 2014. American Heart Association. <http://www.heart.org/> (retrieved November 15, 2014).

Azcárate, T., Mendoza, B., Sánchez de la Pena, S., Martínez, L.J., 2012. Temporal variation of the arterial pressure in healthy young people and its relation to geomagnetic activity in Mexico. Adv. Space Res. 50, 1310–1315.

Baez-Escudero, L.J., Valderrábano, M., 2014. Cardiac pacemakers and resynchronization therapy. In: Levine, Glenn N., Saunders, W.B. (Eds.), Cardiology Secrets, Philadelphia, fourth ed., pp. 278–283 (Chapter 37).

Belov, A., Baisultanova, L., Eroshenko, E., Mavromichalaki, H., Yanke, V., Pchelkin, V., Plainaki, C., Mariatos, G., 2005a. Magnetospheric effects in cosmic rays during the unique magnetic storm on November 2003. J. Geophys. Res. 110 (9), A09S20.

Belov, A., Garcia, H., Kurt, V., Mavromichalaki, H., Gerontidou, M., 2005b. Proton enhancements and their relation to X-ray flares during the three last solar cycle. Sol. Phys. 229, 135–159.

Bilenko, I.A., 2002. Coronal holes and the solar polar field reversal. Astron. Astrophys. 396 (2), 657–666.

Breus, T., Komarov, F., Musin, M., Naborov, I., Rapaport, S., 1989. Heliophysical factors and their influence on cyclical processes in biosphere. Itogi Nauki I Techniki: Medicin. Geograf. 18, 172–174 (in Russian).

Chugh, S.S., Havmoeller, R., Narayanan, K., Singh, D., Rienstra, M., Benjamin, E.J., Gillum, R.F., Kim, Y., McAnulty, J.H., Zheng, Z., Forouzanfar, M.H., Naghavi, M., Mensah, G.A., Ezzati, M., Murray, C.J.L., 2013. Worldwide Epidemiology of Atrial Fibrillation: A Global Burden of Disease 2010 Study. From PMC: <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC4151302/> (Retrieved November 13, 2014).

Cornèlissen, G., Halberg, F., Breus, T., Syutkina, E., Baevsky, R., Weydahl, A., Watanabe, Y., Otsuka, K., Siegelova, J., Fiser, B., Bakken, E.E., 2002. Non-photic solar associations of heart rate variability. J. Atmos. Sol. Terr. Phys. 64, 707–720.

Dikpat, M., De Toma, G., Gilman, A.P., Arge, N.C., White, R.O., 2004. Diagnostics of polar field reversal in solar cycle 23 using a flux transport dynamo model. Astrophys. J. 601, 1136–1151.

Dimitrova, S., 2008. Different geomagnetic indices as an indicator for geo-effective solar storms and human physiological state. J. Atmos. Sol. Terr. Phys. 70, 420–427.

Dorman, L., Iucci, N., Ptitsyna, N., Villoresi, G., 2001. Cosmic ray as indicator of space weather influence on frequency of infract myocardial, brain strokes, car and train accidents. In: Proc 27th ICRC (Hamburg), pp. 3511–3514.

Durrant, C.J., Wilson, P.R., 2003. Observations and simulations of the polar field reversals in cycle 23. Sol. Phys. 214, 23–39.

ESA, 2014. Environmental Space Agency. <http://swe.ssa.esa.int> (retrieved November 15, 2014).

Ferguson, C., Inglis, C.S., Newton, J.P., Middleton, S., Macdonald, S.P., Davidson, M.P., 2014. Atrial fibrillation: stroke prevention in focus. Aust. Crit. Care 27, 92–98.

Forbush, S.E., 1958. Cosmic ray intensity variations during two solar cycles. J. Geophys. Res. 63, 651–669.

Giannaropoulou, E., Papailiou, M., Mavromichalaki, H., Gigolashvili, M., Tvildiani, L., Janashia, K., Preka-Papadema, P., Papadima, Th., 2014. A study on the various types of arrhythmias in relation to the polarity reversal of the solar magnetic field. Nat. Hazards 70, 1575–1587.

Gigolashvili, M., Ramishvil, G., Janashia, K., Tvildiani, L., Pitiurishvili, P., 2010. Possible Dependence of the Sign Changing of the Polarity of Interplanetary Magnetic Field on Complications of Various Arrhythmias Internal Report. National Astron Observ.

Gopalswamy, N., Lara, A., Yashiro, S., Howard, A.R., 2003. Coronal mass ejections and solar polarity reversal. Astrophys. J. 598, L63–L66.

Hathaway, D.H., 2010. The solar cycle. Living Rev. Sol. Phys. 7, 1–65.

Katsavrias, C., Preka-Papadema, P., Moussas, X., Apostolou, T., Theodoropoulou, A., Papadima, T., 2013. Helio-geomagnetic influence in cardiological cases. Adv. Space Res. 51, 96–106.

Kenneth, J.H.P., 1995. Guide to the Sun. Cambridge University Press, Cambridge.

Kremastinos, D., 2005. Cardiology: Clinical Cardiology, Greek ed. Medical Publications P.X, Pasxalidis, Athens, Greece.

Longair, S.M., 1992. High Energy Astrophysics. Cambridge University Press, Cambridge.

Mavromichalaki, H., Belehaki, A., Rafios, X., 1998. Simulated effects at neutron monitor energies: evidence for a 22-year cosmic-ray variation. Astron. Astrophys. 330, 764–772.

Oinuma, S., Kubo, Y., Otsuka, K., Yamanaka, T., Murakami, S., Matsuoka, O., Ohkawa, S., Cornélissen, G., Weydahl, A., Holmeslet, B., Hall, C., Halberg, F., 2002. Graded response of heart rate variability, associated with an alternation of geomagnetic activity in subartic area. Biomed. Pharm. 56, 284–288.

Palmer, S.J., Rycroft, M.J., Cermack, M., 2006. Solar and geomagnetic activity, extremely low frequency magnetic and electric fields and human health at the Earth's surface. Surv. Geophys. 27, 557–595.

Paouris, E., Mavromichalaki, H., Belov, A., Gushchina, R., Yanke, V., 2012. Galactic cosmic ray modulation and the last solar minimum. Sol. Phys. 280, 255–271.

Papailiou, M., Mavromichalaki, H., Kudela, K., Stetiarova, J., Dimitrova, S., 2011. Effect of geomagnetic disturbances on physiological parameters: an investigation on aviators. ASTRA 8, 1–9.

Papailiou, M., Mavromichalaki, H., Kudela, K., Stetiarova, J., Dimitrova, S., 2012. Cosmic radiation influence on the physiological state of aviators. Nat. Hazards 61, 719–727.

Papaioannou, A., Belov, A., Mavromichalaki, H., Eroshenko, E., Oleneva, V., 2009. The unusual cosmic ray variations in July 2005 cosmic ray resulted from western and behind the limb solar activity. Adv. Space Res. 43, 582–588.

Plainaki, C., Mavromichalaki, H., Belov, A., Eroshenko, E., Andriopoulou, M., Yanke, V., 2010. A new version of the NMBANGLE model applied to the GLE60. Sol. Phys. 264, 239–254.

Stoupel, E., 1999. Effect of geomagnetic activity on cardiovascular parameters. J. Clin. Basic Cardiol. 2, 34–40.

Stoupel, E., Abramson, E., Israelevich, P., Sulkes, J., Harrell, D., 2007a. Dynamics of serum C-reactive protein (CRP) level and cosmophysical activity. Eur. J. Intern. Med. 18, 124–128.

Stoupel, E., Domarkiene, S., Radisauskas, R., Bernotiene, G., Abramson, E., Israelevich, P., Sulkes, J., Breus, T., 2005. Variants of acute myocardial infraction in relation to cosmophysical parameters. Sem. Cardiol. 11, 51–55.

Stoupel, E., Kalediene, R., Petrauskiene, J., Starkuviene, S., Abramson, E., Israelevich, P., Sulkes, J., 2007b. Monthly deaths number and concomitant environmental physical activity: 192 months observation (1990–2005). Sun Geosph 2, 78–83.

Stoupel, E., Martfel, J., Rotenberg, Z., 1994. Paroxysmal atrial fibrillation and stroke in males and females above and below age 65 on days of different geomagnetic levels. J. Basic Clin. Physiol. Pharmacol. 5, 315–329.

Stoupel, E., Shimshoni, M., 1991. Hospital cardiovascular deaths and total distribution of deaths in 180 consecutive months with different cosmic physical activity: a correlative study (1974–1988). Int. J. Biometeorol. 35, 6–9.

Styra, D., Gaspariunas, A., Usovaite, A., Juozulynas, A., 2005. On the connection between hard cosmic ray flux variations and changes in cardiovascular disease in Vilnious city. Int. J. Biometeorol. 49, 267–272.

Zimetbaum, P., Falk, H.R., 2013. Atrial fibrillation. In: Antman, Elliott M., Sabatine, Marc S., Saunders, W.B. (Eds.), Cardiovascular Therapeutics: A Companion to Braunwald's Heart Disease, fourth ed., Philadelphia, pp. 372–382 (Chapter 20).