Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 43 (2009) 523–529
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Cosmic ray variations of solar origin in relation to human physiological state during the December 2006 solar extreme events

M. Papailiou [a,*], H. Mavromichalaki [a], A. Vassilaki [a], K.M. Kelesidis [b], G.A. Mertzanos [b], B. Petropoulos [c]

[a] Nuclear and Particle Physics Section, Physics Department, University of Athens, 15771 Athens, Greece
[b] Cardiological clinic of the KAT Hospital, Kifissias 4, Athens, Greece
[c] Research Center of Astronomy and Applied Mathematics, Academy of Athens, Sorianou Efesiou 4, 11527 Athens, Greece

Received 28 December 2007; received in revised form 22 February 2008; accepted 3 August 2008

Abstract

There is an increasing amount of evidence linking biological effects to solar and geomagnetic disturbances. A series of studies is published referring to the changes in human physiological responses at different levels of geomagnetic activity. In this study, the possible relation between the daily variations of cosmic ray intensity, measured by the Neutron Monitor at the Cosmic Ray Station of the University of Athens (http://cosray.phys.uoa.gr) and the average daily and hourly heart rate variations of persons, with no symptoms or hospital admission, monitored by Holter electrocardiogram, is considered. This work refers to a group of persons admitted to the cardiological clinic of the KAT Hospital in Athens during the time period from 4th to 24th December 2006 that is characterized by extreme solar and geomagnetic activity. A series of Forbush decreases started on 6th December and lasted until the end of the month and a great solar proton event causing a Ground Level Enhancement (GLE) of the cosmic ray intensity on 13th December occurred. A sudden decrease of the cosmic ray intensity on 15th December, when a geomagnetic storm was registered, was also recorded in Athens Neutron Monitor station (cut-off rigidity 8.53 GV) with amplitude of 4%. It is noticed that during geomagnetically quiet days the heart rate and the cosmic ray intensity variations are positively correlated. When intense cosmic ray variations, like Forbush decreases and relativistic proton events produced by strong solar phenomena occur, cosmic ray intensity and heart rate get minimum values and their variations, also, coincide. During these events the correlation coefficient of these two parameters changes and follows the behavior of the cosmic ray intensity variations. This is only a small part of an extended investigation, which has begun using data from the year 2002 and is still in progress.

Keywords: Cosmic ray intensity; Heart rate variations; Forbush decreases; Human physiological state

1. Introduction

Over the last years many studies have been carried out concerning the possible effect that solar and geomagnetic activity might have on human physiological state (Stoupel, 1999; Dorman et al., 2001; Cornelissen et al., 2002; Dimitrova, 2006). Even though there is skepticism in the scientific community regarding the possibility that heliogeophysical changes can influence human health, the results are irrefutable. Human physiological status is influenced by environmental factor changes requiring from the organism and its nervous system a large range of adaptation reactions, which are decreased in case of different diseases (Dimitrova, 2006).

It is obvious that solar or geomagnetic variations could not be solely responsible for all the changes or fluctuations of physiological parameters measured in a human organism. The physiological status of a human being and the abnormalities such as myocardial infractions, brain strokes, cardiac arrhythmias etc. that an organism might

* Corresponding author.
E-mail addresses: mpapahl@phys.uoa.gr (M. Papailiou), emavromi@phys.uoa.gr (H. Mavromichalaki).

0273-1177/$34.00 © 2008 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2008.08.009

exhibit are influenced by many factors such as environmental physical activity and social parameters, smoking, age, etc. Nevertheless it is shown that geomagnetic variations of solar origin can influence at some level the human health and cause a chain of serious problems (Villoresi et al., 1998; Stoupel, 2006). It has been shown that, apart from cardiovascular diseases, like myocardial infraction and brain strokes, also train malfunctions of man – related origin can be influenced by space weather parameters, both in short (during Forbush decreases events) and long – term scale (solar activity cycle). These results on man – related train accidents give additional support to the idea that the capability of operators to react correctly to the environmental circumstances can be influenced by space weather parameters. In short – term scale the cosmic ray intensity seems to be the best indicator of such correlation (Dorman et al., 2001).

In the last decades, many scientists have worked on the impact of space weather parameters, through the geomagnetic field, on different diseases (Dorman et al., 2001; Stoupel, 2002; Gmitrov and Ohkubo, 2002; Gmitrov and Gmitrova, 2004; Dimitrova et al., 2004). It has been revealed that cardiovascular circulatory, nervous and other functional systems react under changes of geophysical factors (Kay, 1994; Watanabe et al., 1994; Persinger and Richards, 1995; Gurfinkel et al., 1995; Zhadin, 2001; Cornelissen et al., 2002). It has long been claimed that geomagnetic storms and other electromagnetic variations are associated with changes in the incidence of various diseases, myocardial infractions and strokes (Halberg et al., 2000). Some evidence has also been accumulated on the association between geomagnetic disturbances and increases in work and traffic accidents (Reiter, 1955; Ptitsyna et al., 1996; Dorman, 2005).

Recent studies consider the links between life threatening cardiac arrhythmias, sudden cardiac deaths and the level of environmental physical activity factors like geomagnetic activity and cosmic ray and high energy proton flux (Stoupel, 2006). Moreover, a new field, called 'Clinical Cosmobiology', is slowly developing. This field studies the relationship between the frequency of total deaths, cardiac arrhythmias, occurrence of acute myocardial infraction, risk related cardiovascular parameters, deaths from cardiovascular diseases, temporal distribution of sudden cardiac death, stroke, life threatening cardiac arrhythmias, homicide and suicide and the level of major environmental physical activity factors (Stoupel, 2006).

In this work, the problem of the possible synchronization of the sudden changes in cosmic ray intensity with the ones of heart rate variations on a daily basis is considered. Cosmic ray intensity data from the Athens Neutron Monitor for December 2006 are used. A comparison of these with those involving the heart rate variations of thirty persons with no symptoms and hospital admission, which have been obtained by the method of Holter electrocardiogram, also in Athens region, is performed.

2. Data selection and methods

The time period from 4th to 24th December 2006, being very close to the end of the 23rd solar cycle was characterized by extreme solar and geomagnetic activity. In this study hourly, pressure corrected, data of the hadronic component of the cosmic ray intensity obtained from the Cosmic Ray Station of the University of Athens (Super 6NM-64) have been used. This station is located 260 m above sea level and detects particles with a cut-off rigidity of 8.53 GV. It is operational since November 2000 providing high quality real-time data through Internet (http://cosray.phys.uoa.gr). These data have a time resolution of 1 h, 1 min and 1 s as well, unique in the world (Mavromichalaki et al., 2001, 2005). The statistical error is smaller than 0.30% on hourly data.

Data are also used concerning solar flares registered by GOES satellites. Moreover, data for the X-ray flux and the geomagnetic index K_p (http://spidr.ngdc.noaa.gov/spidr/index.jsp) have been used for the time period under study. The geomagnetic index Dst from the World Data Center for Geomagnetism, Kyoto (http://swdcwww.kugi.kyoto-u.ac.jp/) is also used for December 2006 (Fig. 1, bottom panel).

A series of solar flares of classes M and X was registered starting from 6th December until 14th December. The hourly X-ray flux data from GOES – 12 satellite concerning this period were plotted and the most important solar flares are shown in Fig. 1 (top panel). We are mostly interested in the two big solar flares on 13th and 14th December 2006. The first flare was of class X3.4/4 B with maximum at 2:40 UT and the second one was a solar flare of class X1.5 and maximum at 22:15 UT. These flares produced energetic solar cosmic rays that were guided towards the Earth and resulted in an increase in the count rates of the ground based cosmic ray detectors. The middle panel in the same figure shows the variations of the geomagnetic K_p index. On 15th December K_p had a value of 8^+ that means that a geomagnetic storm occurred.

The data concerning the heart rate variations came from a group of patients, who were not admitted to the hospital and had no symptoms, but had some cardiovascular problems and that is why they were monitored by the hospital using the method of Holter electrocardiogram. This method records, on a 24-h base, the heart rate variations while the patient carries out his/her routine activities. The results, then, are gathered and analyzed by computer. The Holter electrocardiogram can detect many cardiovascular irregularities, such as arrhythmias and ischemic strokes. Our group consisted of thirty people (ranged from 35 to 88 years old) and our measurements refer to the period of December 2006.

3. Results and discussion

One of the biggest problems of biogeomagnetics is to determine those characteristics of solar and geomagnetic

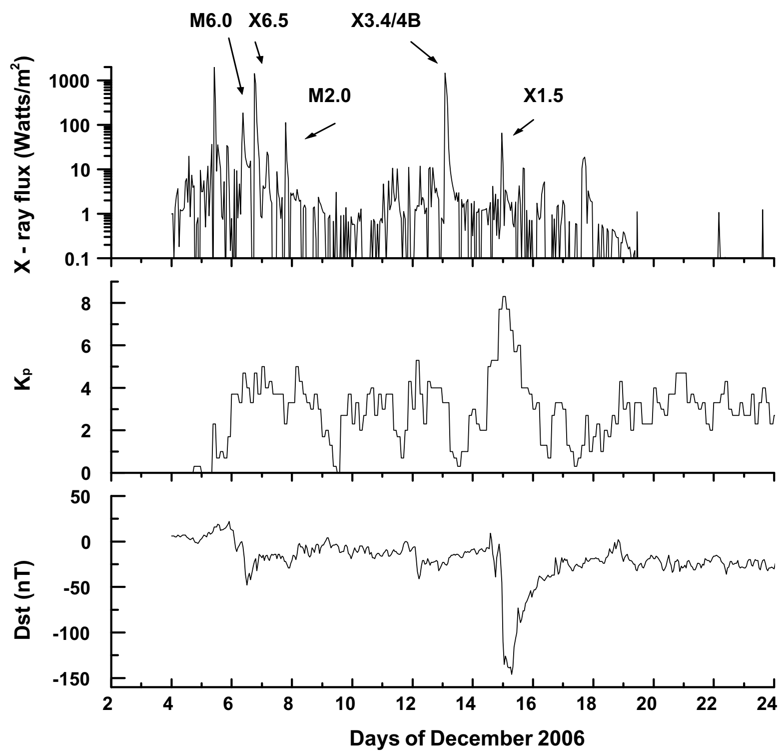

Fig. 1. The X-ray flux as measured by GOES – 12 satellite (top panel), the K_p index (middle panel) and the variation of the Dst index (bottom panel) during December 2006 are illustrated.

activity with the greatest effect on human health. Indices of interplanetary disturbances, which are connected to geomagnetic activity and short-term cosmic ray intensity variations, are used for the research on biological rhythms variations. In Villoresi et al. (1994a,b, 1998), Ptitsyna et al. (1996), Dorman et al. (1999) it is shown that Forbush decreases are the most sensitive indicators of the connection between geomagnetic field disturbances and health parameters, as incidence of ischemic strokes, myocardial infractions and vehicular traffic accidents. The most remarkable and statistically significant effects have been observed during days of geomagnetic perturbations defined by the days of the declining phase of Forbush decreases in cosmic ray intensity.

Using the hourly data of the cosmic ray intensity recorded at the Cosmic Ray Station of the University of Athens, the normalized cosmic ray intensity variations were calculated using the relation $\Delta I = \frac{I - \bar{I}}{\bar{I}}$, where I is the hourly cosmic ray intensity and $\bar{I}$ is the average cosmic ray intensity. These results are plotted for 4th–24th December 2006 and are shown in Fig. 2 (continuous grey line).

Intense cosmic ray events were recorded during this period, such as a series of Forbush decreases started on 6th December and lasted until the end of the month and a solar proton event causing a Ground Level Enhancement (GLE) of the cosmic ray intensity on 13th December. A sudden decrease of the cosmic ray intensity on 7th December was recorded in Athens neutron monitor station with amplitude of 3%. Cosmic ray intensity started decreasing on 7th December at 09:00 UT (0.02%), took its minimum value (−0.01%) on 8th December, at 17:00 UT and then the recovery phase started. Then another Forbush decrease was recorded with amplitude of 4% starting from 14th December at 12:00 UT and taking its minimum value on 15th December, at 02:00 UT. The cosmic ray intensity reached the pre-decrease level on 23rd–24th December.

During the examined here time interval the index K_p reached the value of 8^+ on 15th December (Fig. 1, middle panel) and also the index Dst reached its minimum value (−146 nT) on the same day, which means that a geomagnetic storm was recorded. It is known that a geomagnetic storm occurs when $K_p > 5$ and Dst < -100 nT. The variations of the Dst index for December 2006 are presented in Fig. 1 (bottom panel).

Studying in detail the solar, interplanetary and geomagnetic activity of periods connected with Forbush decreases recorded by neutron monitor, during the examined here time interval, very interesting results have been obtained. The hourly variations of the cosmic ray intensity on a daily basis compared to the average heart rate variations of patients are given in Fig. 3 for the cases of the above mentioned Forbush decreases. Generally it seems that the heart rate variations coincide with the cosmic ray intensity ones (Petropoulos et al., 2006). The correlation diagrams along with the regression line between these two parameters, with a significance level of 95%, are shown in Fig. 4. The correlation coefficients for some of the cases under study during December 2006 are presented in Table 1.

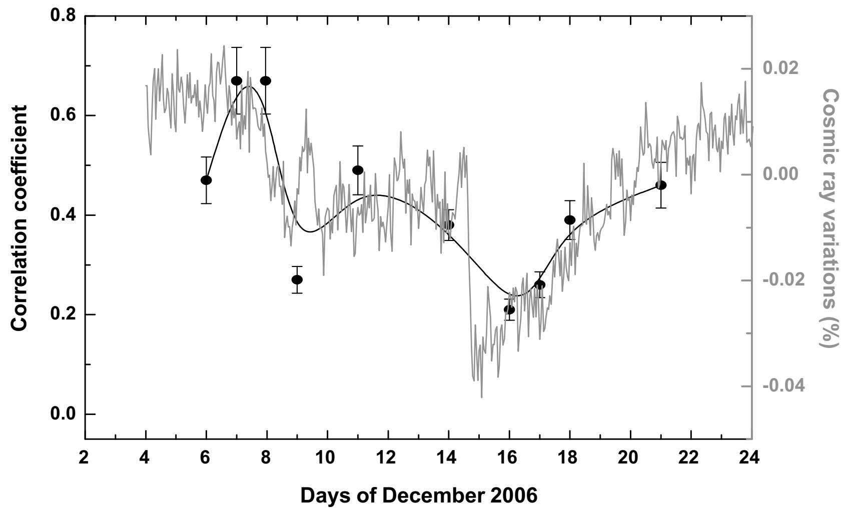

Fig. 2. The percentage variation of the cosmic ray intensity as measured by the Athens Neutron Monitor from 4th to 24th of December 2006 (grey line) and the correlation coefficient of cosmic ray intensity and heart rate variations (black line) are presented.

The two parameters, heart rate variations and cosmic ray intensity, under study coincide during Forbush decreases and the restoration phase of Forbush events. But for time periods when a strong event is detected we are not only interested in the correlation coefficient's absolute value but also its variation during the days of the cosmic ray event. It is noticed (Petropoulos et al., 2006) that the correlation coefficient decreases during the descending phase of a Forbush decrease and increases during the restoration phase of a Forbush decrease. Fig. 2 shows this behavior of the correlation coefficient variations in comparison to the cosmic ray variations. The cosmic ray intensity started to decrease on 6th December and had its minimum value on 15th December. The same variations are, also, noticed for the Dst index (Fig. 1, bottom panel). On the other hand the correlation coefficient's decrease started on 7th December and had its minimum value on 16th December (Fig. 2, continuous black line). A time delay is noticed. This delay might be due to the fact that our group of patients is rather small and consists of only thirty people. The correlation coefficient shows the same behavior, as described here, with no significant time delay in a wider investigation, which uses a sample of 250 people and data from 2002 (Petropoulos et al., 2006).

Another interesting result is that this correlation is much stronger in women than in men. For the group of people under study the 40% of women and only the 20% of men had a correlation coefficient over 0.25. Gender differences in acute coronary syndromes, atherogenesis, concomitant pathologies, like diastolic heart failure, hypertension, diabetes, heart rupture, outcomes in coronary revascularization are widely discussed (Stoupel et al., 2005). Unfortunately women show higher risk in revascularization procedures, more heart failure and higher mortality in acute coronary syndromes (Stoupel et al., 2005). When geomagnetic and cosmic ray activity is correlated with the irregularities mentioned above it seems that in women those links are much stronger. In Stoupel et al. (2005) it is mentioned that 'like in many other fields, older women are more susceptible to environmental physical activity compared to younger men with the same pathology'.

4. Conclusions

In our days there is an increasing amount of evidence linking biological effects to solar and geomagnetic conditions. Stoupel (1999) has published a series of studies of changes in human physiological responses and the natural history of various pathological events at different levels of daily and monthly geomagnetic activity. Over the last decades many researches have taken place involving biogeomagnetics and the effect of Space weather, through the geomagnetic field, on some diseases (Dorman et al., 2001; Stoupel, 2002; Palmer et al., 2006).

In the last decades, many scientists have worked on the impact of space weather parameters, through the geomagnetic field, on different diseases (Dimitrova et al., 2004). Changes in the geomagnetic activity level are related to fluctuations in solar activity and are involved in climate regulation and various animals (Wiltschko and Wiltschko, 1995, 2005) and human behaviour (Babayev and Allahverdiyeva, 2007). The living species examined, including man, have adapted to normal variation in geomagnetic activity (Stoupel, 1999). Cosmic ray Forbush decreases, which are connected to interplanetary disturbances, can be used as indicators of the relationship between the geomagnetic field fluctuations and health parameters (Dorman et al., 2001). The most important results are those concerning cardiovascular diseases and diseases of the nervous system, especially strokes, myocardial infarctions and traffic accidents as well (Villoresi et al., 1994a,b; Ptitsyna et al., 1996; Dorman et al., 1999). It is proved that the monthly number of acute myocardial infraction is significantly related to solar, geo-

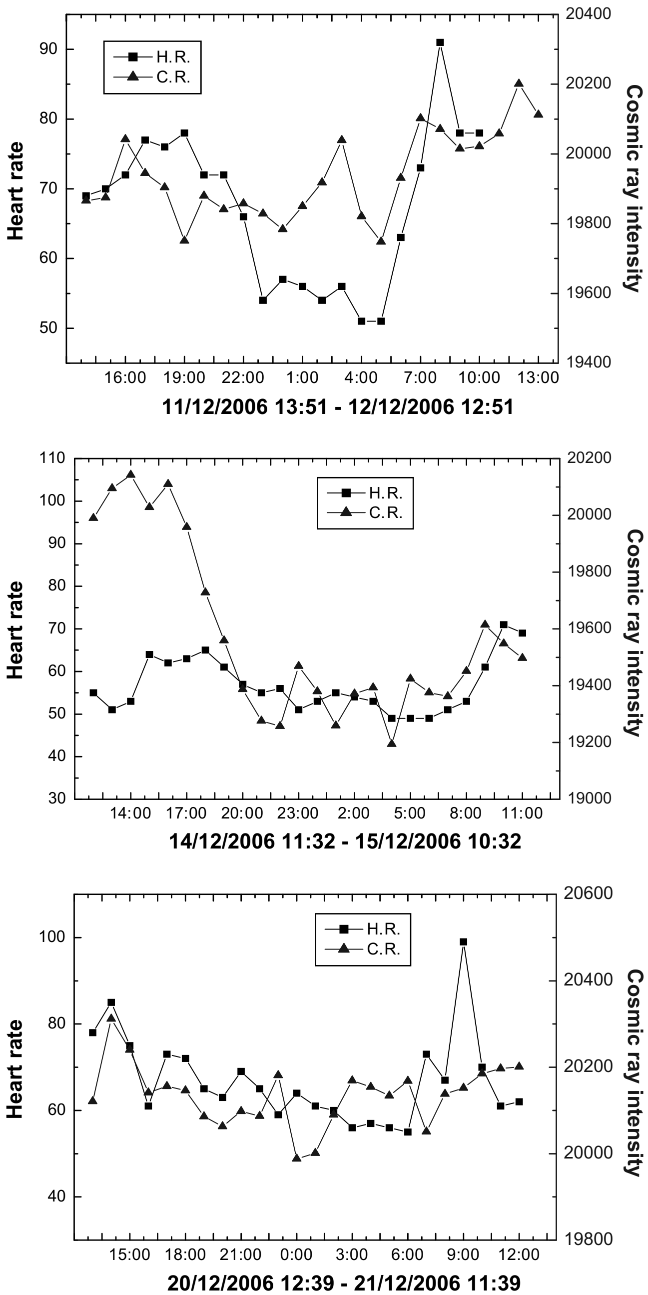

Fig. 3. Time profiles of the hourly values of cosmic ray intensity (triangle) and heart rate (square) of different persons for the days 11, 14 and 20 of December 2006.

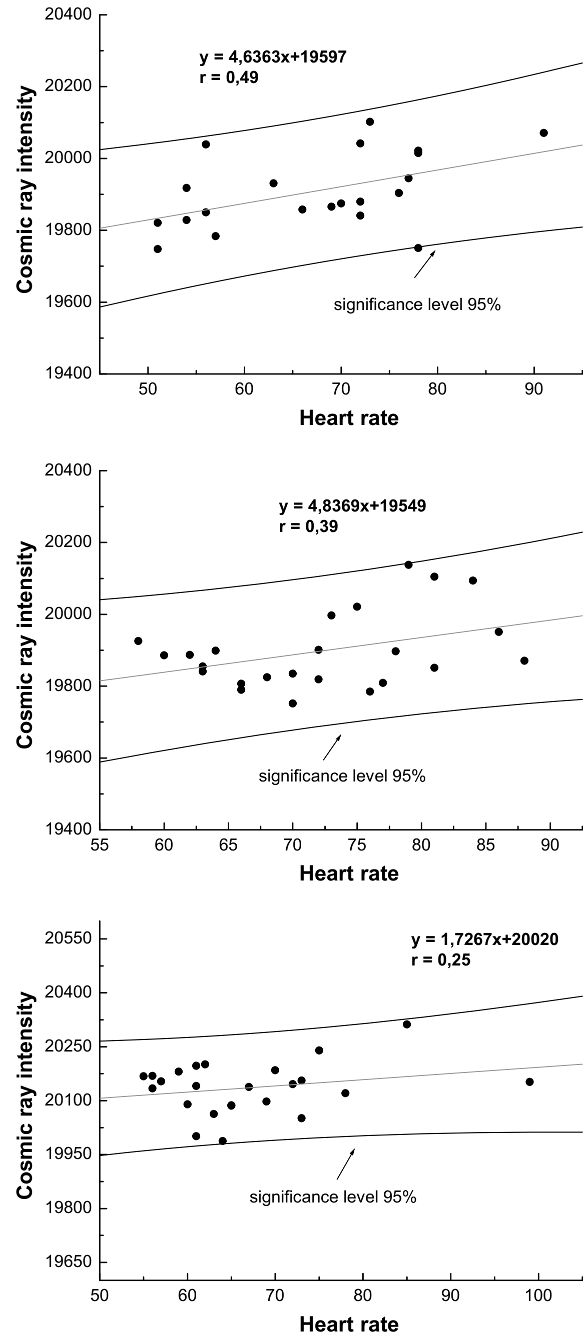

Fig. 4. The equivalent correlation diagrams of the cases given in Fig. 3 with a significance level of 95%.

magnetic and cosmic ray activity (Stoupel et al., 2005; Stoupel et al., 2007).

Solar, geomagnetic and cosmic ray activities and their changes have an influence on human health. Comparison of the monthly sudden cardiac death data revealed a significant and inverse correlation with solar activity indices and with geomagnetic activity indices. A positive correlation was found for cosmic ray activity (Stoupel et al., 2006).

In this study, we have examined a group of thirty persons for the period 4th–24th December 2006 and the following conclusions are outlined:

- A significant correlation of cosmic ray activity level with heart rate variations exists. These results are in agreement with those ones noticed also by Stoupel et al. (2005) for the time interval 1983–1999.
- The correlation coefficient between cosmic ray intensity and heart rate variations seems to decrease during the declining phase of strong cosmic ray events, such as Forbush decreases and increase during the ascending phase of such events.
- The correlation between cosmic ray intensity and heart rate variations is stronger when women are concerned.

Table 1
The date, the time interval, the gender, the age and the correlation coefficient between cosmic ray intensity and heart rate variations for a group of patients under study

	Start of measurement		End of measurement		Gender	Age	Correlation coefficient
	Date	Time	Date	Time			
1	6/12/06	11:58	7/12/06	10:58	M	70	0.47
2	6/12/06	6:12	7/12/06	5:12	F	77	0.47
3	7/12/06	21:43	8/12/06	22:43	M	53	0.67
4	9/12/06	20:36	10/12/06	19:36	F	88	0.27
5	11/12/06	13:51	12/12/06	12:51	F	58	0.49
6	11/12/06	15:22	12/12/06	14:22	F	80	0.32
7	14/12/06	11:32	15/12/06	10:32	M	70	0.31
8	17/12/06	11:12	18/12/06	10:12	F	50	0.26
9	18/12/06	14:53	19/12/06	13:53	F	51	0.39
10	21/12/06	18:47	22/12/06	17:47	F	70	0.46

Over the last years many scientists have tried to connect solar and geomagnetic activity to changes of human physiological state. We are mostly concerned about how cosmic ray variations may influence heart rate variations and the effect they may have on different cardiovascular diseases. As there seems to be a connection between these two parameters, it is important to continue this investigation using a larger group of patients during a wider period of time.

Acknowledgements

Thanks are due to our colleagues from the Neutron Monitor stations who have kindly provided us with their cosmic ray data and the cardiological clinic of the KAT Hospital for the heart rate data. We are grateful to the Special Account of Research of Athens University for supporting this study. The authors thank the referees for improving significantly this paper with their comments.

References

Babayev, E.S., Allahverdiyeva, A.A. Effects of geomagnetic activity variations on the physiological and psychological state of functionally healthy humans: some results of Azerbaijani studies. Adv. Space Res. 40, 1941–1951, 2007.

Cornelissen, G., Halberg, F., Breus, T., et al. Non-photic solar associations of heart rate variability and myocardial infraction. J. Atmos. Solar Terr. Phys. 64, 707–720, 2002.

Dimitrova, S., Stoilova, I., Cholakov, I. Influence of local geomagnetic storms on arterial blood pressure. Bioelectromagnetics 25, 408–414, 2004.

Dimitrova, S. Relationship between human physiological parameters and geomagnetic variations of solar origin. Adv. Space Res. 37, 1251–1257, 2006.

Dorman, L.I., Iucci, N., Ptitsyna, N.G., et al. Cosmic ray Forbush decreases as indicators of space dangerous phenomena and possible use of cosmic ray data for their prediction. Proc. 26th ICRC (Salt Lake) 6, 476–479, 1999.

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

Dorman, L.I. Space weather and dangerous phenomena on the Earth: principles of great geomagnetic storms forecasting by online cosmic ray data. Ann. Geophys. 23, 2997–3002, 2005.

Gmitrov, J., Ohkubo, C. Artificial static and geomagnetic field interrelated impact on cardiovascular regulation. Bioelectromagnetics 23, 329–338, 2002.

Gmitrov, J., Gmitrova, A. Geomagnetic field effect on cardiovascular regulation. Bioelectromagnetics 25, 92–101, 2004.

Gurfinkel, Iu.I., Liubimov, V.V., Oraevskii, V.N., et al. The effect of geomagnetic disturbances in capillary blood flow in ischemic heart disease patients. Biofizika 40, 793–799, 1995.

Halberg, F., Cornelissen, G., Otsuka, K., et al. Cross-spectrally coherent $\sim$10.5- and 21-year biological and physical cycles, magnetic storms and myocardial infarctions. Neuroendocrinol. Lett. 21, 233–258, 2000.

Kay, R.W. Geomagnetic storms: association with incidence of depression as measured by hospital admission. Br. J. Psychiatry 164 (3), 403–409, 1994.

Mavromichalaki, H., Sarlanis, C., Souvatzoglou, G., et al. Athens neutron monitor and its aspects in the cosmic-ray variations. Proc. 27th ICRC 2001 (Hamburg) 10, 4099–4102, 2001.

Mavromichalaki, H., Papaioannou, A., Petrides, A., et al. Cosmic-ray events related to solar activity recorded at the Athens neutron monitor station for the period 2000–2003. Int. Mod. J. Phys. A 20, 6714–6716, 2005.

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

Persinger, M.A., Richards, P.M. Vestibular experiences of humans during brief periods of partial sensory deprivation are enhanced when daily geomagnetic activity exceeds 15–20 nT. Neurosci. Lett. 194 (1–2), 69–72, 1995.

Petropoulos, B., Mavromichalaki, H., Papailiou, M., et al. The effect of the daily anisotropy of the cosmic ray intensity on the heart rate frequency variations. Praktika Acad. Athens 81, 51–106, 2006.

Ptitsyna, N.G., Villoresi, G., Kopytenko, Y.A., et al. Coronary heart diseases: an assessment of risk associated with work exposure to ultra low frequency magnetic fields. Bioelectromagnetics 17, 436–444, 1996.

Reiter, R. Bio-meteorologie auf physikalischer basis. Phys. Blatter 11, 453–464, 1955.

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

Stoupel, E. The effect of geomagnetic activity on cardiovascular parameters. Biomed. Pharmacother. 56, 247–256, 2002.

Stoupel, E., Domarkiene, S., Radishauskas, R., et al. In women myocardial infraction occurrence is much stronger related to environmental physical activity than in men-a gender or an advanced age effect? J. Clin. Basic Cardiol. 8, 59–60, 2005.

Stoupel, E. Cardiac arrhythmia and geomagnetic activity. Indian Pacing Electrophysiol. J. 6, 49–53, 2006.

Stoupel, E., Babayev, E.S., Mustafa, F.R., et al. Clnical cosmobiology – sudden cardiac death and daily/monthly geomagnetic, cosmic ray and solar activity – the Baku study (2003–2005). Sun Geosphere 1, 13–16, 2006.

Stoupel, E., Babayev, E.S., Mustafa, F.R., et al. Acute myocardial infarction (AMI) occurrence – environmental links, Baku 2003–2005 data. Medical science monitor. Int. Med. J. Exp. Clin. Res. NY 13, BR175–BR179, 2007.

Villoresi, G., Breus, T.K., Iucci, N., et al. The influence of geophysical and social effects on the incidences of clinically important pathologies (Moscow 1979–1981). Phys. Med. 10, 79–91, 1994a.

Villoresi, G., Kopytenko, Y.A., Ptitsyana, N.G., et al. The influence of geomagnetic storms and man-made magnetic field disturbances on the incidence of myocardial infraction in St. Petersburg (Russia). Phys. Med. 10, 107–117, 1994b.

Villoresi, G., Ptitsyana, N.G., Tyasto, M.I., et al. Myocardial infarct and geomagnetic disturbances: analyses of data on morbidity and mortality. Biofizika 43, 623–631, 1998.

Watanabe, Y., Hillman, D.C., Otsuka, K., et al. Cross-spectral coherence between geomagnetic disturbance and human cardiovascular variables at non-societal frequencies. Chronobiologia 21 (3–4), 265–272, 1994.

Wiltschko, R., Wiltschko, W. Magnetic orientation in animals. Zoophysiology 33, 297, 1995.

Zhadin, M.N. Review of Russian literature on biological action of DC and low frequency AC magnetic fields. Bioelectromagnetics 22, 27–45, 2001.

Wiltschko, W., Wiltschko, R. Magnetic orientation and magnetoreception in birds and other animals. J. Comp. Physiol. A 191, 675–693, 2005.