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REVIEW

Solar and geomagnetic activity, extremely low frequency magnetic and electric fields and human health at the Earth's surface

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Abstract The possibility that conditions on the Sun and in the Earth's magnetosphere can affect human health at the Earth's surface has been debated for many decades. This work reviews the research undertaken in the field of heliobiology, focusing on the effect of variations of geomagnetic activity on human cardiovascular health. Data from previous research are analysed for their statistical significance, resulting in support for some studies and the undermining of others. Three conclusions are that geomagnetic effects are more pronounced at higher magnetic latitudes, that extremely high as well as extremely low values of geomagnetic activity seem to have adverse health effects and that a subset of the population (10–15%) is predisposed to adverse health due to geomagnetic variations. The reported health effects of anthropogenic sources of electric and magnetic fields are also briefly discussed, as research performed in this area could help to explain the results from studies into natural electric and magnetic field interactions with the human

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body.Possible mechanisms by which variations in solar and geophysical parameters could affect human health are discussed and the most likely candidates investigated further. Direct effects of natural ELF electric and magnetic fields appear implausible; a mechanism involving some form of resonant absorption is more likely. The idea that the Schumann resonance signals could be the global environmental signal absorbed by the human body, thereby linking geomagnetic activity and human health is investigated. Suppression of melatonin secreted by the pineal gland, possibly via desynchronised biological rhythms, appears to be a promising contender linking geomagnetic activity and human health. There are indications that calcium ions in cells could play a role in one or more mechanisms. It is found to be unlikely that a single mechanism can explain all of the reported phenomena.

Keywords Cardiovascular system · ELF waves · Geomagnetic activity · Heliobiology · Melatonin · Schumann resonance

1 Introduction

Life on Earth owes its existence to the Sun. During the late 20th and early 21st centuries, with the advent of space-based observatories such as the joint USA/European Solar and Heliospheric Observatory (SoHO), our knowledge of our nearest star has grown considerably. We have characterised many of the Sun's natural variations on a wide range of timescales, from the 5-min oscillations to the 22-year magnetic cycle and beyond (Lang 1999). The Earth's magnetic field has also been essential to the evolution of life, as it provides a protective ''shield'' against cosmic rays and prevents our atmosphere from being eroded away by the solar wind (Van Allen and Bagenal 1999). It is the interaction between the solar wind and the Earth's magnetic field that causes aurorae, but these interactions can also do great damage, such as in March 1989, when geomagnetically induced currents caused the collapse of the Hydro-Québec electrical power distribution system (Pirjola and Viljanen 2000).

The idea that variations on the Sun and in the Earth's magnetic field can affect human health has global implications, but is especially important for those living at high geomagnetic latitudes where the geomagnetic fluctuations have larger amplitudes. The population of these high-latitude areas will grow as the population of the Earth grows, increasing the pressure to exploit previously untapped resources within these areas. Little comparison of possible effects to humans from geomagnetic activity exists between high and low latitudes. This field of research becomes increasingly important in the present context of a consistent weakening of the Earth's magnetic field and the fact that we are statistically overdue for a geomagnetic reversal (Buffet 2000). Civilised humans have not yet experienced such a reversal and the health impacts could be catastrophic. The more we know about the relationship between solar and geomagnetic activity and human health, the better prepared we shall be for any future geomagnetic event, whether it be a strong geomagnetic storm or a further weakening and even reversal of the Earth's magnetic field.

This work attempts to review the previous research carried out in the field of ''heliobiology'', the branch of science that deals with the impact of solar activity on living organisms, especially humans, as well as to investigate the various causal mechanisms which have been suggested to explain the reported associations. Much work has been conducted in Russia and so has not been very accessible to non-Russian-speaking scientists, although reviews such as the joint US/Russian publication (Davydov et al. 1996) have attempted to rectify this problem.

Much of the literature published on the subject of heliobiology is ambiguous and more than occasionally contradictory. Since the human species evolved in the presence of geomagnetic fields, a presence of magnetoreceptors in humans seems likely, but there is little evidence to indicate what they may be or how magnetoreception would work. One of the aims of this work is to identify the ''red herrings'' in the published literature, and to separate them from the real phenomena. In order to achieve this aim we have tried to validate or refute previous results on the basis of their statistical significance. It is hoped that this will lead to a better understanding of which aspects of heliobiology will yield the most useful results in future studies. Not only physiological effects but also mental health effects and possible consequences of altered mental performance, e.g. accidents, are reviewed and discussed herein.

The fundamental difficulty when studying the effect of natural electric and magnetic field variations on human health is the fact that, compared with many anthropogenic sources, the field strengths involved are very small. When the geomagnetic environment is disturbed, it seems plausible that this could have either a direct or indirect effect on human physiology. However, having evolved in the presence of varying natural magnetic and electric fields, it seems inevitable that humans have developed a mechanism for coping with nominal geomagnetic activity conditions. The magnitude of these disturbances, typically 300 nT for a large magnetic storm, is only 1% of the background geomagnetic field (~30,000 nT at the magnetic equator, rising to ~60,000 nT at the magnetic poles); typical directional changes of the field are a fraction of a degree. The small size of the effect poses a significant problem when searching for plausible biophysical mechanisms. In the search for such mechanisms, methods for quantifying both the level of geomagnetic activity and the health of a test subject are needed, as well as a statistical methodology to analyse the associations.

2 Parameters and methods used

In this review, several different parameters are used as measures of geomagnetic activity and of human health, and are explained below. This section also describes the methodology used for the statistical analysis and defines some of the more technical 'space weather' terms used later.

2.1 Definition of geomagnetic indices

In order to study the associations between geomagnetic activity and human health, a measure of the level of geomagnetic activity is required. Geomagnetic observatories use magnetometers to provide a global network of magnetic field variations. The most widely used measures to quantify the size of a geomagnetic disturbance are defined below:

> ''The K index is a quasilogarithmic measure of the maximum disturbance in steps of 0–9 every 3 h (UTC). Normally its values lie between 1 and 3, 0 representing an unusually quiet period. K values of 4–9 mark magnetic storms. The K_p, or planetary 3 h range index, is defined to be the arithmetic mean of

> the K values of 13 selected world wide geomagnetic observatories. The A_k index is derived from the K index and characterises the magnitude of geomagnetic disturbances over 24 h intervals, measured for each local geomagnetic observatory. The A_p index is a planetary equivalent of the daily amplitude (A_k index), related to K_p, starting each day at 0 h UTC" (Gmitrov and Gmitrova 2004).

2.2 Methods to quantify human response to geomagnetic variations

As with the level of geomagnetic activity, a quantifiable measure of the health status or performance of a human subject is required.

The indirect indicators are essentially epidemiological data showing the temporal and spatial distribution of defined events or health disturbances, e.g. of temporal distribution of emergency calls and of hospital admissions, frequency of industrial and traffic accidents. They are normally investigated in retrospective studies, involving considerable numbers of test subjects over several years.

The direct indicators are physiological parameters, which can be objectively verified and which are acquired either in vivo, directly on the subject, e.g. heart rate and variability, blood pressure, microcirculation parameters, reaction time, or in vitro by laboratory diagnostics or tissue investigations. The fundamental problem is that most of the direct indicators also vary significantly with factors other than the geomagnetic activity.

The potential co-factors, e.g. tropospheric weather, season, demographic factor, working environment, nutrition, electromagnetic background noise, etc., must be considered in the interpretation of the indicators.

Two examples of direct indicator techniques developed to quantify the human response to changes in geomagnetic activity are described here.

2.2.1 Heart Rate Variability (HRV)

Heart Rate Variability (HRV) refers to the beat-to-beat alterations in heart rate (Kristal-Boneh et al. 1995). The heart rate variability method as a diagnostic tool was developed for remote monitoring of cosmonauts' health during orbital flight (Chernouss et al. 2001). It is widespread in world practice now, and was used as an effective tool for measurements of the Autonomic Nervous System (ANS) response to Geophysical Risk Factor (GRF) variations (Chernouss et al. 2001). The ANS relates to neurons that are not under conscious control, comprising two antagonistic components, the sympathetic and parasympathetic nervous systems. The autonomic nervous system coordinates key functions including the activity of the cardiac (heart) muscle, smooth muscles (e.g. of the gut), and glands. The ANS has two divisions:

1. The sympathetic nervous system that accelerates the heart rate, constricts blood vessels, and raises blood pressure.
2. The parasympathetic nervous system that slows the heart rate, increases intestinal and gland activity, and relaxes sphincter muscles (On-line medical dictionary http://www.cancerweb.ncl.ac.uk/cgi-bin/omd).

The spectral power of HRV in the frequency range 0.15–0.4 Hz (HF, "high frequency") corresponds to the parasympathetic activity of ANS, while the frequency range 0.04–0.15 Hz (LF, ‘‘low frequency’’) reflects the sympathetic influence (Chernouss et al. 2001). There are two types of people in regard to activity of ANS branches. In people who have a sympathetic response (SP) the LF power spectra prevails over the HF spectra. Conversely, for people with a parasympathetic response (PP) the HF power spectra dominate the LF (Chernouss et al. 2001). It should be noted, however, that the LF/HF ratio naturally undergoes extensive changes both as a function of age and on the scale of a day (circadian rhythm) (Otsuka et al. 1997).

2.2.2 Foetal cardiotocography

Cardiotocography is a non-invasive method for evaluating the state of a foetus. It is based on the ultrasonic analysis of the foetal pulse rate and the method is an important component in the clinical diagnosis of foetal state. It is possible to obtain an index defining the state of health of the foetus by analysing the pulse rate of the foetus and its relationship with uterine contractions over a sufficiently long period (usually 1 h). The integral ‘‘foetal state index’’, shown in Table 1, is calculated from the analysis of several components of the data such as variations of the basal rhythm, the maximum peak-to-peak pulse rate amplitude and increases and decreases in the pulse rate (Shumilov et al. 2003).

2.3 Statistical methods

When investigating a reported association between a measured geomagnetic index and a measure of the health of a test subject, the use of statistics is necessary to establish if there is a link between the two that goes beyond random chance. To decide whether or not the reported correlation coefficient (r) between a pair of results is statistically significant, Table V of Young (1962) was used to produce Fig. 1. If the correlation coefficient for the size of sample available lies below the line representing a probability (P) of 0.05 that the correlation arises by chance (equivalent to two standard deviations), we have considered it to be not statistically significant. Any value of r that lies above the 0.01 probability line corresponds to roughly three standard deviations and is therefore statistically highly significant.

Table V of Young (1962), reproduced as Table 2, contains values of the correlation coefficient, r, which has a certain probability, P, of being exceeded for N pairs of observations of variables, whose parent distributions are independent. For example, for a sample of 10 pairs of observations on unrelated variables ($N = 10$), the probability P is 0.10 that it will have $r \geq 0.549$, and the probability is 0.001 that $r \geq 0.872$.

Table 1 Index values corresponding to foetal state (Shumilov et al. 2003)

Foetal state	Integral foetal state index
Healthy	0.0–1.0
Traits of chronic illness	
Initial	1.1–2.0
Pronounced	2.1–3.0
Severe	3.1–4.0

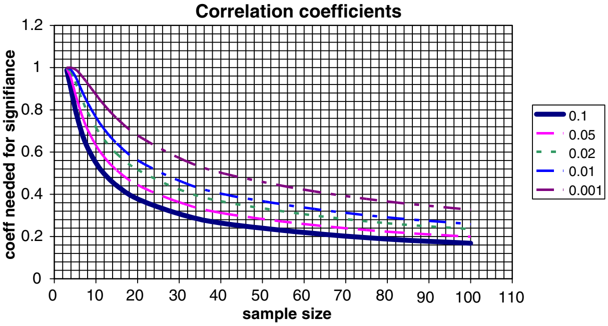

Fig. 1 Graph used to decide the statistical significance of a reported correlation, for a sample size of *N*, adapted from Young (1962)

2.4 Definitions of some 'space weather' terms

Using ground-based and space-borne observatories, we know that interplanetary space is very dynamic on all spatial and temporal scales. The dynamics of the near-Earth space environment are driven by the Sun and are referred to as space weather. The most relevant aspects of space weather are defined and briefly explained below. For a general treatment of space weather, see Crosby et al. (2006) and Kivelson and Russell (1995).

2.4.1 Coronal Mass Ejection (CME)

The corona is the outer-most layer of the Sun and can be thought of as the Sun's atmosphere. Comprised mainly of helium ions, this extremely rarefied gas extends beyond the orbit of the Earth. Although the temperature of the corona is about 2×10^6 K, its extremely low density (10^{15} m^{-3} dropping to 10^7 m^{-3} near the Earth)

Table 2 Table showing correlation coefficients required for statistical significance of different probabilities from Young (1962)

N	Probability				
	0.1	0.05	0.02	0.01	0.001
3	0.988	0.997	0.999	1.000	1.000
4	0.900	0.950	0.980	0.990	0.999
5	0.805	0.878	0.934	0.959	0.992
6	0.729	0.811	0.882	0.917	0.974
7	0.669	0.754	0.833	0.874	0.951
8	0.621	0.707	0.789	0.834	0.925
10	0.549	0.632	0.716	0.765	0.872
12	0.497	0.576	0.658	0.708	0.823
15	0.441	0.514	0.592	0.641	0.760
20	0.378	0.444	0.516	0.561	0.679
30	0.307	0.362	0.423	0.464	0.572
40	0.264	0.312	0.367	0.403	0.502
60	0.219	0.259	0.306	0.337	0.422
80	0.188	0.223	0.263	0.291	0.366
100	0.168	0.199	0.235	0.259	0.327

means that it contains only a minute amount of heat (Kivelson and Russell 1995). Coronal mass ejections (CMEs) are large-scale, violent ‘eruptions’ of relatively high-density plasma, which travel at high velocity outwards from the Sun. The mechanism of formation is not fully understood but is believed to involve a reconfiguration of magnetic field lines on the photosphere—the apparent surface of the Sun. CMEs are transmitted to Earth as disturbances in the solar wind, where the increased density and energy can cause problems for satellites, aircraft and ground-systems (Crosby et al. 2006).

2.4.2 Solar energetic particle event (SPE)

When Solar energetic particles (SEPs) are experienced, the event is called a SPE. These events can be caused by CMEs but are usually associated with solar flares—short-lived violent accelerations of plasma from the Sun’s ‘surface’ caused by the reconnection of magnetic field lines in the photosphere.

2.4.3 Magnetic storms

Magnetic storms occur when the coupling of the solar wind to the magnetosphere becomes strong and prolonged. Geomagnetic activity becomes intense and auroral currents are almost continuously disturbed. A storm often begins with a sudden increase in magnetic field that may last for a few hours, followed by a rapid and often disturbed decrease—the storm main phase. After this, magnetic field intensity begins a rapid recovery, transitioning to a stage of long, slow recovery. Storms typically last 1–5 days and have a magnitude of about 100 nT, although storms with magnitudes of over 500 nT (~1% Earth’s magnetic field at the pole) occur every few years (Kivelson and Russell 1995).

3 Results

3.1 Early work up to 1990

Since the mid 20th century, different individual investigations into the possibility that solar and geomagnetic activity affect human health have yielded contradictory results. A study into the relationship between the geomagnetic index, A_p, and mortality from coronary heart disease and stroke (a condition due to the lack of oxygen to the brain which may lead to reversible or irreversible paralysis) in the USA found no correlations (Feinleib et al. 1975). “The data did not support previous assertions by Soviet researchers of an association between solar activity and cardiovascular mortality”. Although many correlations have been claimed to exist between activity originating at the Sun and adverse human health, there is widespread scepticism as to the reality of such connections (Malin and Srivastava 1979).

Credited with founding modern “heliobiology”, Tchizhevsky (1976) presented evidence that the incidence of various illnesses, including myocardial infarction (MI) (death of an area of cardiac muscle tissue due to lack of oxygen) and mental illness, increases during periods of increased geomagnetic disturbance. Around this time, Lipa et al. (1976) used three different statistical methods to investigate the relationship between geomagnetic activity and death due to coronary heart disease and strokes. The study, which used 4 years of data from the USA during the 1960s, concluded that no such relationship exists.

> “In summary, our study does not support the findings of Gnevyshev and Novikova (1972), nor their proposal for a new branch of science—heliobiology. It is possible that the correlations they find are either not statistically significant or not due to a causal relationship between geomagnetic disturbances and coronary heart disease and stroke. If their correlations are indeed indicative of a causal relationship, it will be necessary to determine whether it is sensitive to geographical location, to phase of the solar cycle or to some other parameter which might distinguish the samples we have analysed from those of the Soviet scientists” (Lipa et al. 1976).

Malin and Srivastava (1979) carried out a similar 5-year study in India, and presented data for which the correlation between the number of cardiac emergency admissions to two hospitals and geomagnetic disturbance is particularly high. They went on to suggest reasons why Lipa et al. (1976) observed no correlation. Malin and Srivastava (1979) pointed out that the level of artificial magnetic fields in India is significantly lower than in the USA due to its less developed electrical power distribution infrastructure, etc.; this may obscure the effect of varying natural electromagnetic fields on humans in the USA. They also suggested that death induced by geomagnetic disturbance via MI (destruction of an area of heart muscle resulting from a blocked coronary artery) or stroke may occur at a later date than the event that caused it. The authors suggested that the date and time of admission to hospital gave a more accurate “time-stamp” for any geomagnetic event causing health problems. The “events” rather than “outcomes” should therefore be used as criteria, since the latter are dependent on the quality of available diagnostics and care.

In the same year, Knox et al. (1979) attempted to confirm the results presented by Malin and Srivastava (1979), by analysing medical data from the West Midlands region of the U.K. for the period 1969–1970. The data consisted of the number of daily admissions for Acute Myocardial Infarctions (AMI) and the same geomagnetic K_p index as used in the Indian study. As with the investigation by Lipa et al. (1976), statistical analysis yielded no significant correlations. Knox et al. (1979) suggested that different social customs in India could introduce different periodic fluctuations in the medical data when compared with the “western” 7-day social cycle. A difference in the length of the social cycle could potentially cause social variations in the medical data to combine with natural periodic variations in the geomagnetic field, possibly resulting in a stronger association between MI and geomagnetic activity.

As the U.K. has a level of technological development and power distribution infrastructure similar to that in the USA, the suggestion by Malin and Srivastava (1979) that the relatively high level of ambient anthropogenic magnetic field “swamps” the natural electromagnetic field fluctuations seems to be relevant in this study also.

According to Halberg et al. (1999), one of the first studies to convince many of those sceptical about associations between geomagnetic disturbances and human health effects was performed by Breus et al. (1989). The data set studied consisted of over 6.3 million diagnoses made in response to ambulance call-outs in Moscow during three years of high solar activity (1979–1981). Using a variety of approaches, including cross-spectral analysis and superposed epochs, an effect of magnetic storms could be validated for 85,819 cases of MIs (Halberg et al. 1999). The analysis of such a large amount of data provided much needed support for the proponents of heliobiology as a valid scientific discipline.

3.2 Studies since 1990 relating geomagnetic activity and cardiovascular effects

Previous to 1990, heliobiological studies were sparse, but in the last 15 years or so there has been a marked increase in the number of such studies. The majority of these more recent studies have focused on the association between geomagnetic activity and the functional state of the human cardiovascular system, which explains why the present section is particularly long.

Because the Earth's magnetic field strength at the surface is approximately twice as strong at the magnetic poles as at the magnetic equator, and because geomagnetic activity is greatest in the auroral zones (near 67° geomagnetic latitude), it may be expected that heliobiological studies performed at higher magnetic latitudes would show more pronounced correlations than at lower latitudes. The population of these areas is increasing due to population growth and the need to utilise the natural resources situated therein. In the 1990s, studies have focused on regions at high geomagnetic latitudes. As a reviewer has pointed out, site specificity is an important issue that may involve more than a simple dependence on latitude. The time structure of a given variable, such as sudden cardiac death statistics, may differ from one geographic/geomagnetic location to another. Other studies showing latitude dependence relate to HRV (Otsuka et al. 2001) and melatonin (Wetterberg et al. 1999).

Recent studies have confirmed that the effect of geomagnetic disturbance on people is greater under the auroral belt. Using the HRV method, these have identified a group of people who are particularly sensitive to changes in geomagnetic activity, referred to as Aurora Disturbance Sensitive People (ADSP) (Chernouss et al. 2001). To explain the existence of a subset of the population more sensitive to natural magnetic disturbance, Chernouss et al. (2001) suggested that those people indigenous to the circumpolar region have developed mechanisms to cope with the enhanced magnetic disturbances, whilst people who have migrated to the area in recent years have not yet fully adapted to the change in their geophysical environment.

Chernouss et al. (2001) further divided the ADSP into people who respond sympathetically with magnetic disturbance, and those who respond parasympathetically. The two groups are distinguished by their response to changes in K-index; the stress index of SP people seems to increase with increasing K-index, whilst the stress index of PP people seems to decrease slightly as the K-index increases. These authors suggest that this demonstrates that SP individuals have a higher adaptive ability to stress than PP people.

The effects of geomagnetic variations at high latitudes are least studied in infants. Shumilov et al. (2003) made more than 2,500 measurements of women at least 33 weeks pregnant, between 1994 and 2000 in the Murmansk region of Russia. Using foetal cardiotocography, the authors calculated monthly foetal state index distribution histograms. It is clear that the data lack a pronounced seasonal variation although the maximal values of foetal index are not uniformly distributed. The authors claim that the only months that include foetal state indices of greater than 3.5 (severe chronic illness) are January, March, April and November and that this is consistent with the seasonal variation in infant mortality rate data. However, the format in which the English translation of the paper was published shows the months with a foetal state index of greater than 3.5 to be January, February, March, May, June and September. The corresponding author informed us that the labels on the histograms had been published in the wrong positions. However, after making the author's recommended corrections (see Fig. 2), the months with foetal state index of greater than 3.5 are January, March, May, June, September and November. This confusing discrepancy between the results and the authors' analysis reduces our confidence that the other assertions made by the authors are reliable.

However, they do report some interesting results, e.g. that the correlation of the foetal state index with the distribution of the number of magnetic storms is maximal, and highly significant for the 15th percentile (15%) of the data ($r = 0.71$, $N > 2{,}500$, $P < 0.01$). The authors claim that this shows that heliogeophysical factors affect 10–15 % of all people. Although the authors do not propose a mechanism to explain how geomagnetic activity could affect foetal state, they claim that there are practical uses for these findings, primarily relating to the obstetric treatment of pregnant women. These results show that the foetal state derived from cardiotocography can be influenced by external geophysical factors and is not necessarily due to problems during pregnancy. The authors conclude that obstetricians should be cautious when choosing a course of action as the indices may improve over a short period of time as the geomagnetic environment changes.

For some time, there have been unconfirmed claims that heart attacks occur more frequently at high northern latitudes whenever the "northern lights" occur. Messner et al. (2002) investigated whether there was any relation between the aurora borealis (measured as geomagnetic activity) and the number of AMI in the northern area of Sweden, between 1985 and 1998. The AMI cases were collected from the northern Sweden MONICA (multinational MONItoring of trends and determinants of CArdiovascular disease) AMI registry. The WHO (World Health Organisation) MONICA project, an international collaboration of researchers from 21 countries, studied more than 30 populations, mainly in Europe, from the mid 1980s to the mid 1990s. It is the largest community based study on heart disease ever undertaken (WHO website). The geomagnetic information was collected from continuous measurements made at the Swedish Institute of Space Physics at Kiruna. In the analyses, the authors studied the relation between individual AMI cases and ambient geomagnetic activity, as well as the relation between the mean daily K index and the daily number of AMI cases. The authors found no statistically significant relation between the number of fatal or non-fatal AMI cases, the number of sudden deaths or the number of patients with chest pain, and geomagnetic activity. They concluded that the data do not support a relation between geomagnetic activity and AMI. Cornélissen et al. (2002) studied mortality from MI during 29 years in Minnesota, USA, and found an approximate 10.5-year cycle, similar to that of solar activity, but no strong association with the K_p index of geomagnetic activity.

There have been several other claimed effects of geomagnetic variation on the activity of the heart reported in the literature, e.g. Stoupel et al. (1994) aimed to determine whether differences exist in the frequency of paroxysmal atrial fibrillation (intermittent, rapid involuntary contractions of the heart muscle) and stroke

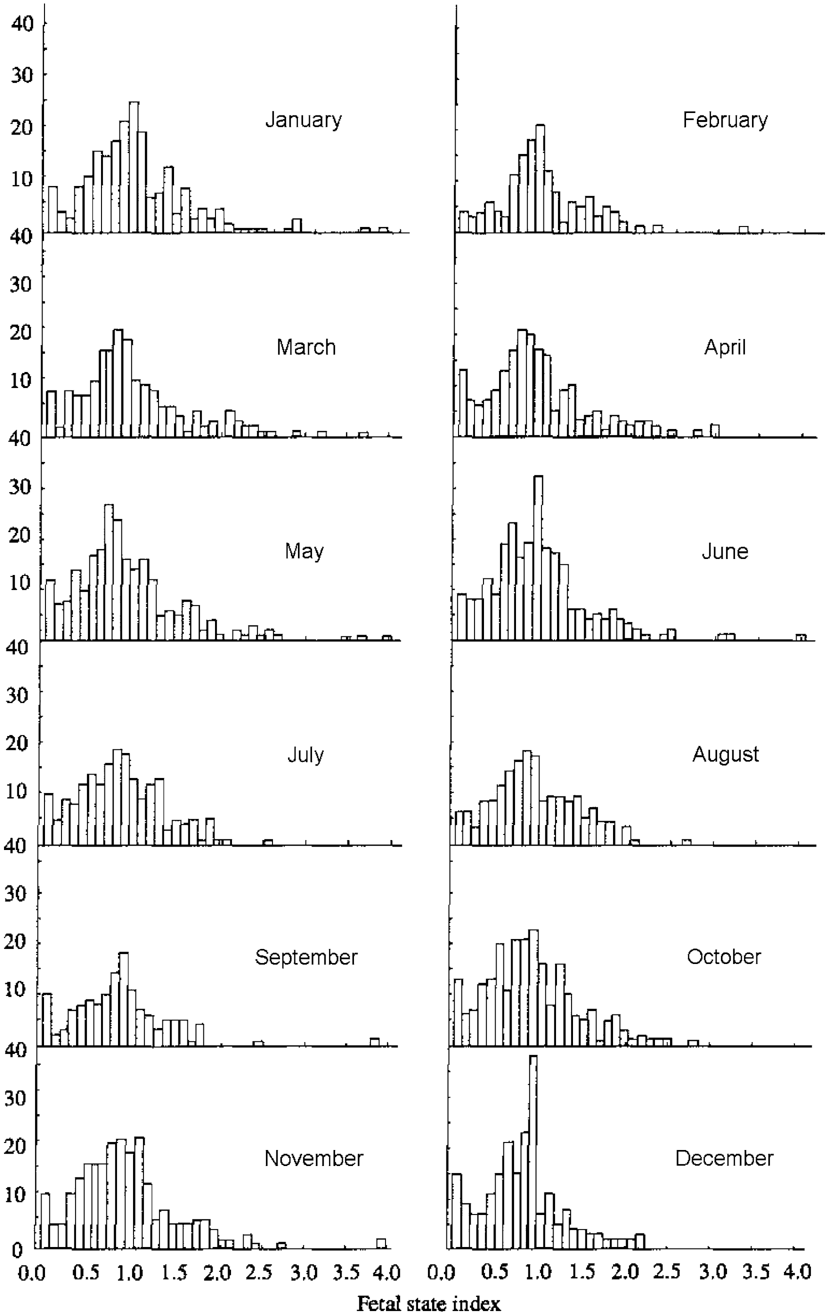

Fig. 2 Histogram showing the number of cases plotted against foetal state index during the year, modified from Shumilov et al. (2003)

on days of different geomagnetic activity levels. Geomagnetic activity was divided into four levels ranging from level I (quiet conditions) to level IV (stormy conditions). Measurements were made according to the six highest hourly geomagnetic parameters over a period of 24 h. The study period covered 1,185 consecutive days, from January 1990 to March 1993. The data consisted of all patients treated in the admission department of a major university hospital in Petah Tiqva, Israel, for stroke (977 patients) or paroxysmal atrial fibrillation (653 patients). Groups were also divided by sex and age (above/equal to or below 65 years of age) for comparison.

The main results were:

1. A highly significant negative correlation was found between daily paroxysmal atrial fibrillation and geomagnetic activity level ($r = -0.976$, $P = 0.02$)
2. The absolute number of daily admissions for paroxysmal atrial fibrillation was higher on geomagnetic activity I days than level IV days ($P < 0.004$)
3. Stroke admissions showed the same highly significant negative correlation with increasing geomagnetic activity, but only in males of 65 years or less ($r = -0.99$, $P = 0.0008$).

The authors conclude that these data show increased heart electrical instability during periods of lowest geomagnetic activity. Using Fig. 1 the results are found to be statistically significant.

In a study performed in Moscow, Russia, Gurfinkel et al. (1995) investigated the effect of geomagnetic disturbances on blood flow in patients with Ischemic heart disease (IHD)—inadequate blood flow leading to a lack of oxygen in the cardiac tissue. The authors studied capillary blood flow in the cuticle above the nail for 80 patients (47 male, 33 female) on a daily basis for up to 3 weeks. Capillary indices were examined for perivascular edema (large amounts of fluid in the intercellular tissue around a blood vessel), red blood cell aggregation and blood flow velocity. These data were compared with A and K geomagnetic indices and also with atmospheric pressure. Changes in capillary flow in 71.5% of patients with AMI were associated with magnetic storms. The authors observed the appearance of perivascular edema, red blood cell aggregation and reduced capillary blood flow. Similar changes were detected in 64.8% of patients with angina pectoris—“heavy” chest pain due to lack of oxygen in the heart muscle. The number of patients with IHD affected by geomagnetic disturbances exceeded the number of patients affected by a change in atmospheric pressure by a factor of 2.5. This study seems to report real changes in the physiology of patients with IHD in response to geomagnetic activity.

Ghione et al. (1998) sought to answer the question of whether or not geomagnetic disturbances affect arterial blood pressure. They compared mean daytime, nighttime and 24-h blood pressure and heart rate measurements from 447 consecutive untreated out-patients at the CNR Institute of Clinical Physiology, Pisa, Italy, with the K-sum index measured at the nearest geomagnetic observatory in L’Aquila, approximately 287 km south east of Pisa. This and the following studies were performed at low magnetic latitudes. Significant to highly significant positive correlations were observed for K-sum with systolic (the maximum arterial pressure during contraction of the left ventricle of the heart) and diastolic (the pressure during the period between contractions) blood pressures, but not with heart rate. However, the correlation of K-sum and systolic blood pressure (SBP) was not observed during nighttime. As a referee has pointed out, sometimes the association is with the variability in a given variable rather than its value at a given time or its average over a given interval. When this is the case, a negative correlation during the nighttime may become a positive correlation during the daytime. Multiple correlations, which took into account other factors such as date and age of the subject, confirmed a significant effect of K-sum on blood pressure. Compared with quiet days, geomagnetically disturbed days always showed significantly higher values for all blood pressure parameters except systolic nighttime pressure. The authors conclude that the results seem to reflect a real relation between geomagnetic disturbances and blood pressure. They add that the results are unlikely to be due to unrelated secular trends.

Gavryuseva et al. (2002) investigated the relationship between measurements of human conductivity and blood pressure in connection with solar and geomagnetic activity in Naples, Italy. The conductivity measurements were taken between a point on one hand and a point on the other, with a total of 20 measurements for both hands. They also took into account meteorological conditions, and discovered that there is a strong correlation ($r = 0.73$) of conductivity with atmospheric temperature. Here, we suggest that the increase in conductivity arises from the increased moisture on the skin, as the test subject sweats more when the temperature is higher. The authors also report a weaker negative correlation of conductivity with humidity ($r = -0.53$), which they attribute to the fact that humidity is negatively correlated with air temperature. The authors do not appear to attribute a Confidence Interval (CI) to these results so it is difficult to say whether the correlations are statistically significant or not. As there are roughly 240 independent pairs of data points, using Fig. 1 the correlation coefficient required for statistical significance at the 95% CI is well below 0.2. The correlation coefficients are reasonably large in this case so the correlations are statistically significant. This result seems to be counter-intuitive; sweat evaporates less readily when humidity is higher, meaning that there is more sweat on the skin. There may be another effect from the reduced evaporation and therefore reduced cooling—the body temperature may be slightly higher, which promotes sweating. Either way, we would rather expect that the conductivity would increase as the humidity increases. This is an example of co-factors that have an influence on the results.

Gavryuseva et al. (2002) studied the relationship between phenomena on the solar surface, geomagnetic perturbations and biophysical characteristics of a group of 30 people in Naples, Italy. During the 8 months of measurements, an enormous increase in solar activity caused a very strong magnetic storm to occur on 31 March 2001. On 2 April, the resulting major SPE was observed. The correlation between the conductivity and geomagnetic index A_p was equal to 0.53 with a 2-day delay during the period between 10 March and 20 April 2001. The correlation coefficient between CMEs and conductivity during March and April was equal to 0.46, with a delay of 2 days. There is also a correlation in March and April between the conductivity and mean solar magnetic field with a delay of 5 days ($r = 0.47$). Again, the authors do not quote a CI, but using Fig. 1 we can see that these correlations are statistically significant.

Another reported phenomenon is the correlation of blood pressure with sunspot area for a group of 30 people in Naples, Italy. Gavryuseva et al. (2002) report a correlation coefficient of 0.50 for systolic and 0.21 for diastolic blood pressures (DBPs), at a "very high significance level", for 100-day long data sets. The correlation increases with delay, although the correlation coefficient peaks at a different delay time for systolic and DBPs—3 days and 1 day, respectively (Fig. 3). If there were a real effect on blood pressure from sunspot area, we might expect the correlation with both systolic and DBPs to peak on the same day. However, because the variations in blood pressure do not always include both systolic and diastolic values, we cannot make a strong statement here. The apparent correlation could be an artefact of the 5-day running mean used in the calculation, which smoothes the data considerably.

The blood pressure data set is roughly 120 days long; using a 5-day running mean, this reduces the number of data points (N) to 116, as 2 days at either end of the data set are not used. Using Fig. 1, the 95% CI corresponds to a correlation coefficient of just less than 0.2, making all of the data points in Fig. 3 significant, the SBP considerably more so than the diastolic pressure. However, the 5-day running mean causes each blood pressure value to depend in part on those around it, i.e. it becomes a dependent variable. This reduces the number of degrees of freedom to 24 (120/5) and therefore reduces the significance of the correlations found.

The change in the strength of the correlation between sunspot area and mean daily blood pressure with delay should give clues about the mechanism linking the two variables. If the correlation is strongest with no or little delay, it is more likely that the association is via a photic mechanism. Another possibility is that the increased solar activity associated with sunspots causes solar wind variations that alter the geomagnetic environment when they reach the Earth. Because the solar wind takes 2–3 days to reach the Earth, then, if the mechanism of interaction is non-photic, we would expect a delay of at least 2–3 days between an event on the Sun and its subsequent effect on human blood pressure. Interestingly, the maximum correlation between sunspot area and SBP occurs with a delay of 3 days. The change in correlation of DBP with delay is inconsistent with this theory.

Watanabe et al. (2001) reported correlations of geomagnetic activity with systolic and DBPs at Daini hospital in Tokyo. The authors observed an inverse relationship between Wolf Number and the variability in SBP and, to lesser extent, DBP. The Wolf number (WN), or relative sunspot number, is an index of the entire visible disk of the Sun, which is determined each day without reference to previous days. The relative sunspot number is defined as

$$R = k(f + 10g)$$

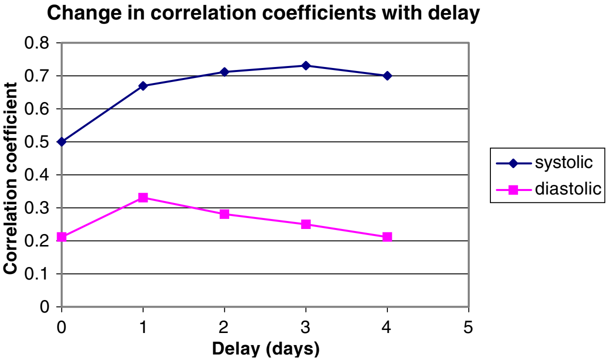

Fig. 3 Variation in the correlation coefficients of systolic and DBPs with time since geomagnetic disturbance (produced from data presented in Gavryuseva et al. 2002)

where *g* is the number of groups of sunspots and *f* is the total number of distinct spots. The scaling factor *k* depends on the sensitivity of the observing equipment and is usually less than unity (Hargreaves 1992). The data used in this study were from one individual who self-measured his blood pressure and heart rate at intervals of 15–30 min from August 1987 to July 1998, and beyond. The subject was 35 at the start of the 11-year data set, and was clinically healthy. A direct association between heart rate and WN was found to be solar cycle stage-dependent, whilst an inverse relationship was consistently found between WN and heart rate variability (Watanabe et al. 2001). This seems to suggest that high levels of solar activity, and therefore high levels of geomagnetic disturbance, cause HRV to decrease. Cornélissen et al. (2002) also report that magnetic storms cause HRV to decrease; Chernouss et al. (2001) confirm this result but state that the response varies significantly between different individuals.

Cornélissen et al. (2002) claim that the incidence of mortality due to MI increases in Minnesota, USA, by 5% during years of maximal solar activity compared with years of minimum activity. This corresponds to an extra 220 deaths per year (in a population of about 5 million) during periods of high solar activity. Also reported are a positive correlation of heart rate (HR) and a negative correlation of HRV with solar activity, measured via the sunspot number. Interestingly, the correlation of HR with sunspot number is significant only for the ascending part of the solar cycle. We suggest that the increase in heart rate and decrease in HRV could be a result of ageing of the test subject(s). However, the heart rate normally decreases with age, and there are many other variables which affect heart rate. The claim would be more convincing if there was also an association during the descending part of the cycle.

Cornélissen et al. (2002) also report a 7.6% increase in incidence of MI after a reversal of the direction of the North-South component (Bz) of the interplanetary magnetic field (IMF). On the following day a 5.9% decrease is observed (Cornélissen et al. 2002). A North-to-South Bz “flip” is known to trigger auroras and magnetospheric storms (Arnoldy 1971), with a typical delay of 2 or 3 h. During such a reversal of the IMF, the total current in the magnetosphere increases by a factor of 10, whilst the potential difference across the geomagnetic tail and across the polar cap increases from typically 10 to 100 kV.

Cornélissen et al. (2002) conclude that there is additional risk of MI at solar maximum compared with solar minimum, which implies an additional risk for high levels of geomagnetic activity. Other studies report an additional risk whenever the level of geomagnetic activity deviates from its “nominal” level. For example, Shumilov et al. (2003) report that not only high levels but also extremely low levels of geomagnetic activity have an adverse affect on foetal state in Murmansk, at ~65°N magnetic latitude.

Shumilov et al. (submitted) conclude that many cases of unexpected deaths, cardiovascular diseases and psychotic disorders in a high-latitude mining community were observed during periods of extremely low geomagnetic activity. The statistical study used hospital and mine records from the town of Barentsburg on Svalbard (78°N) between 1985 and 2001. About 55% of the 297 traumas (injuries or wounds) and 43% of the 267 sudden illnesses (cardiovascular diseases, nervous and psychiatric disorders) were observed during, or just after, the local maximum of geomagnetic disturbance. 20% of traumas and 30% of sudden illnesses were observed during days with a local minimum of magnetic activity (Shumilov et al. submitted). These data seem to support the hypothesis that any large deviation—either up or down—from the mean level of geomagnetic activity can induce health problems. Other studies suggesting harmful effects related to magnetic quiet can be found in Cremer-Bartels et al. (1984). If high and low levels of geomagnetic activity both adversely affect human health, the overall correlation of a health indicator with geomagnetic activity would be close to zero. This may explain why many studies have been inconclusive and, in some cases, contradictory.

Stoupel et al. (1995) examined the relationship between changes in solar and geomagnetic activity parameters, and changes in the total number of in-hospital and MI related deaths. Solar activity was compared with the total number of deaths (15,601) and deaths from MI (1573) at Tel Aviv university hospital, Israel over a period of 180 months (1974–1989). Total hospital deaths and MI-related deaths were significantly correlated with solar activity parameters (r = +0.35, $P < 0.001$).

3.3 Studies concerning mental illness and suicide since 1990

Other types of adverse health effects that have been investigated are mental illness and depression, which can sometimes lead to suicide. Suicides are not evenly distributed over time and most studies have found that suicide rates peak during spring and summer (Yip et al. 1998; Alatamura et al. 1999). A more recent study in Oulu, northern Finland, reported a bimodal distribution of suicides throughout the year, peaking in spring and autumn (Partonen et al. 2004), as shown in Fig. 4. About 96% of the 1726 suicides during a continuous 153-month period were analysed and, although the seasonal effect was significant, the authors point out that the effect was modest compared with sex and age as risk factors. The data contained no information on alcohol consumption or mental health, which would have been useful. The authors claim that geomagnetic storms had no effect on the risk of suicide, but it is interesting to note that the times of year of maximum statistical risk of suicide coincide with the times of maximum geomagnetic disturbance—spring and autumn. This is caused by the seasonal change in the geometry of the Earth's magnetic field relative to the direction of the IMF entrained within the solar wind (Kivelson and Russell 1995). Halberg et al. (2005) show that suicides in Minnesota also exhibit a similar bi-modal distribution.

Kay (1994) investigated the hypothesis that geomagnetic storms account in part for the seasonal variation in the incidence of depression, by acting as a precipitant of depressive illness in susceptible individuals. The data showed a statistically signifi-

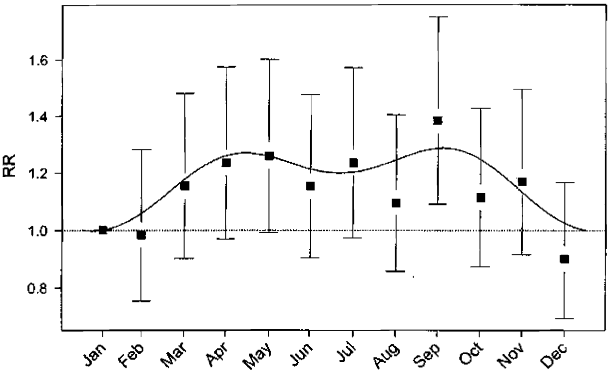

Fig. 4 Relative risk of suicide in northern Finland throughout the year from Partonen et al. (2004)

cant 36% increase in male hospital admissions at Westbank Clinic in Falkirk, UK, with a diagnosis of depressed phase, manic-depressive illness in the second week following a solar storm, compared with geomagnetically quiet periods. Despite this, there was no correlation between the magnitude of geomagnetic disturbance and the number of male admissions with psychotic depression. The author claims that this is consistent with a threshold event, which only affects a certain percentage of the population, i.e. predisposed individuals. A smaller, but not statistically significant, increase in female psychotic and non-psychotic depression admissions following geomagnetic storms was also observed. The difference in correlation levels between manic depression and psychotic depression is indicative of a difference in the pathogenesis of the two conditions.

The study performed by Stoupel et al. (1995) discussed in the previous section also investigated the relationship between suicide and geomagnetic activity parameters. All suicides registered in the state of Israel ($N = 2{,}359$) for a 108-month period between 1980 and 1989 were analysed and compared with the total number of deaths (15,601) and deaths from MI (1,573) in a large university hospital over a period of 180 months (1974–1989). The monthly suicide rate was significantly correlated with geomagnetic activity ($r = -0.22$, $P = 0.03$).

Gender differences were prominent in the data, which is presumably due to the well-established difference in the risk of suicide between the sexes—males are more likely to complete a suicide attempt than females. The monthly suicide distribution over 108 months was negatively correlated with both the distribution of deaths due to MI ($r = -0.33$, $P = 0.0005$) and total hospital mortality ($r = -0.22$, $P = 0.024$).

This negative correlation of monthly suicides with deaths due to MI and total hospital mortality is confusing and unexplained. One explanation may be that those individuals that are at higher risk of death by MI or other causes are also at higher risk of committing suicide. This would mean that, if these individuals died of MI or other causes, they could obviously not become part of the "suicide statistic". Again, there are many co-factors (e.g. social interactions, habits, etc.) that need to be considered in such studies.

3.4 Other associations reported since 1990

A correlation coefficient of 0.90 was found between the monthly number of Sudden Infant Death Syndrome (SIDS) cases for the years 1960 and 1961 in Ontario, Canada, and the increase in the number of days per month with an average geomagnetic activity of 11–20 nT and 31–40 nT (O'Connor and Persinger 1997). Interestingly, a negative correlation was found between the monthly number of SIDS cases and an increase in the number of days with an average geomagnetic activity level of 21–30 nT. The authors claim that this non-linear effect may explain the failure by other researchers to detect an association between the numbers of deaths and indicators of geomagnetic activity when searching for a linear association. Alternatively, this phenomenon could indicate that the geomagnetic activity interval of 21–30 nT is a "normal" sized disturbance for Ontario, and that deviations in disturbance magnitude either side of this interval adversely affect those who are susceptible. This reinforces the idea that deviations of geomagnetic activity from the "normal" levels for that geomagnetic latitude can cause health problems in humans at the Earth's surface.

Other studies have reported that geomagnetic disturbances affect circadian and other biological rhythms (for a review, see Breus et al. 2002). The synchronisation of biological rhythms is broadly viewed as a result of photic solar effects, although evidence for non-photic solar effects is slowly being recognised (Breus et al. 2002). The roughly 7-day (circaseptan) period of neonatal blood pressure correlates with that of the local geomagnetic disturbance index K, and circaseptans which are seen early in human life may provide information about the possible sites of life's origins from an integrative as well as evolutionary perspective. The concept of the alteration of human circadian and other biological rhythms by geomagnetic disturbance plays an important part in some of the mechanisms proposed to explain the observed correlations.

Many studies into the effect of geomagnetic disturbances on biological systems have been performed using animals, although their relevance to human health is questionable due to the differences in physiology between various animals and between animals and humans. Chibisov et al. (1995) investigated six physiological parameters of the cardio-vascular system of rabbits for the duration of two geomagnetic storms. Changes in "cardiomyocyte ultra structure" (arrangement of the cells of the heart muscle) ostensibly induced by changes in geomagnetic activity were studied. The circadian structure of each of the six physiological parameters was lost at the initial and main phases of the storm. As the storm grew, so did the asynchronicity, and an abrupt decrease in cardiac activity was observed during the main phase of the storm. Chibisov et al. (2001) reported that the most pronounced alterations of cardiomyocyte ultra structure were observed during the major phase of the storm. The main storm phase was followed by degradation and death of heart muscle cells. However, whilst the magnitude of geomagnetic disturbance was still in the recovery phase, the six cardiac parameters became substantially synchronised by circadian rhythm structure.

Gmitrov and Gmitrova (2004) present the results of a study of Baroreflex Sensitivity (BRS) performed on rabbits in Japan. Baroreflex is a negative feedback system, which buffers short-term changes in blood pressure. Increased pressure stretches blood vessels, which activate pressoreceptors (baroreceptors) in the vessel walls. The baroreflex mechanism can compensate rapidly for both increases and decreases in blood pressure. The authors claim that BRS is significantly and positively correlated with HRV ($r = 0.35$ for $N = 87$, $P = 0.001$), but that the correlation between BRS and blood pressure is statistically insignificant ($r = 0.21$, $N = 86$, $P = 0.055$). Using Fig. 1, we would say that the first result is definitely significant and the second result is on the boundary of being significant.

These authors also claim that, using multiple linear regression analysis, BRS is negatively correlated with K-index (t-statistic $= -2.15$ for $N = 87$, $P < 0.035$) but is positively correlated with the A_k index ($t = 3.07$ for $N = 87$, $P < 0.003$). We are suspicious of these results because not only is the first BRS result on the borderline of statistical significance, but also we would expect the correlation with the two geomagnetic indices to have the same sign, i.e. both would be either positive or negative, as they are independent measures of the same geomagnetic disturbances. It is questionable whether a documented causal mechanism linking geomagnetic activity to the BRS in rabbits could be assumed to occur in humans.

4 Mechanisms

4.1 Overview

Cleary's (1993) comprehensive review states that the development of biophysical interaction mechanisms to explain the biological effects of ELF (Extremely Low Frequency, 3 Hz–3 kHz) non-ionising electromagnetic fields (EMFs) have been impeded by three major obstacles:

1) Effects occur under conditions where the apparent coupling of non-ionising electromagnetic field energy to the biological system is significantly less than that required by classical physical- or physiochemical-interaction mechanisms;
2) Effects occur over a limited range of frequencies or modulations (predominantly in the ELF range), referred to as frequency or modulation windows;
3) Instead of classical dose-response relationships, effects occur in multiple dose or intensity ranges, referred to as intensity windows.

These factors have meant that the search for viable mechanisms has yielded few conclusive results. This section discusses some of the possible mechanisms that could help to explain the results presented in Section 2.

A possible mechanism to explain the results reported by Partonen et al. (2004) involves the alteration of melatonin levels in the body due to geomagnetic disturbances (Kay 1994; Tarquini et al. 1998; Burch et al. 1999; Weydahl et al. 2001). Burch et al. (1999) propose that geomagnetic disturbances are causally associated with the reduced nocturnal excretion of a major melatonin metabolite (6-OHMS), the substance formed when melatonin is metabolised (broken down) in the liver. Tarquini et al. (1998) claim that this inferred reduction in melatonin concentrations could exacerbate Seasonal Affective Disorders (SAD) in predisposed individuals. Our interpretation is that this could explain the association of geomagnetic disturbances with increased incidence of depression (Kay 1994) and, in extreme cases, an increase in the rate of suicides (Partonen et al. 2004). About 60–70% of patients with acute depression experience suicidal ideas and there is a high incidence of suicide (10–15%) in depressive patients (Moller 2003).

For the proposition made by Shumilov et al. (submitted) that "humans require a certain level of geomagnetic disturbance to maintain optimum health" to be true, the mechanism by which humans detect geomagnetic activity must be dependent on disturbance magnitude and/or frequency. One idea to explain this is the proposal that contained within geomagnetic activity is a "zeitgeber" ("time-giver", i.e. "synchronizer") that humans use to synchronize their biological rhythms. Other well-documented zeitgebers, such as sunlight in the morning, operate on hormone systems such as the melatonin-serotonin balance.

In an attempt to identify the causal mechanism behind the many reported associations between geomagnetic activity and adverse human health, much research has focused on natural environmental signals.

In the 1950s, Schumann hypothesised that electromagnetic signals could resonate in the cavity between the Earth's surface and the ionosphere (Schumann 1952). The so-called Schumann Resonance (SR) signals are electromagnetic resonances of the global Earth-ionosphere (quasi) spherical-shell cavity (Barr et al. 2000). These resonances are excited by global lightning activity and are measured in the lower ELF band between 5 and 60 Hz, as shown in Fig. 5. Schumann showed that the resonance frequencies are given by an equation of the form

$$f_n = 7.49(n(n+1))^{1/2}$$

This formula predicts a fundamental mode frequency (n = 1) of f_1 = 10.6 Hz with overtones (or harmonics) at 18.4, 26.0, 33.5 and 41.1 Hz (Barr et al. 2000). The first definite experimental confirmation of Schumann's prediction was the ELF noise spectral analysis of Balser and Wagner (1960); these spectra actually have maxima near 7.8, 14.2, 19.6, 25.9 and 32 Hz corresponding to the first 5 modes in Schumann's formula. The ~40% reduction in all of the resonant frequencies is due to damping.

Hainsworth (1983) noted that the average frequency at which there is minimum power circulating in the Earth-ionosphere cavity is the same frequency as the dominant human brain-wave rhythm—10.5 Hz. Cannon and Rycroft (1982) and more recently Schlegel and Füllekrug (1999) reported the effects on Schumann resonances produced by ionospheric disturbances induced by solar activity. Solar Proton Events (SPEs) have been found to decrease the frequency of the Schumann Resonance modes. Roldugin et al. (2001) found that, during the peak of four SPEs, the frequency of the first Schumann mode decreased by about 0.15 Hz, as measured in the Kola Peninsula of Russia. Roldugin et al. (2001) also reported an increase in the frequency and a resonance bandwidth decrease of about 0.2 Hz of the first Schumann mode as a result of a very intense solar X-ray burst. Any change in the Schumann resonance signals due to ionospheric disturbances will be superposed on the diurnal (i.e. circadian) variations due to solar heating and ionisation on the day-side.

As visual and auditory stimulation produce biological effects, Hainsworth (1983) argues that electromagnetic signals at frequencies in the brain wave spectrum can be expected to produce biological effects too. He also argues that the association with the human alpha-rhythm near 10 Hz with the frequency of a minimum energy in the

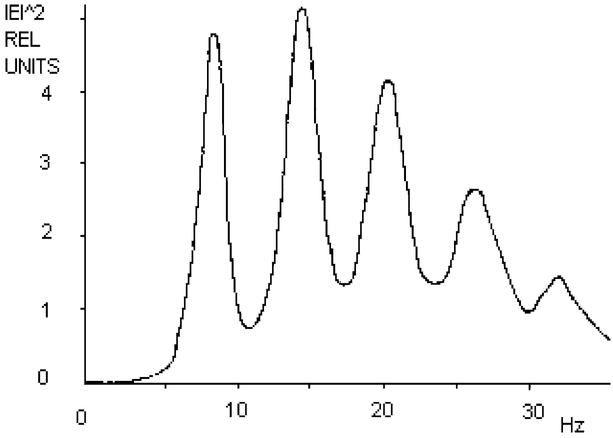

Fig. 5 Schumann resonance energy peaks (adapted from Polk 1983)

Schumann resonance spectrum and, therefore, of minimum natural interference is unlikely to be coincidence.

It has been shown that the intensity of the SR signals is affected by air temperature. Williams (1992) demonstrated a positive correlation between the monthly means of the tropical surface-air-temperature anomaly and the magnetic field amplitude for the fundamental Schumann resonance mode. A 2 K change in temperature was shown to produce a 20-fold change in lightning activity (Barr et al. 2000).

Williams (1992) also reported that El Nino/La Nina conditions produce corresponding increases and decreases in SR signal intensity, which may have implications for future global climate change. Rycroft et al. (2000) discuss the topic of the global atmospheric electric circuit and climate change in greater depth.

4.2 Detailed discussion

Cherry (2002) presents a theory which argues that the Schumann resonance signals constitute a plausible mechanism for the human health effects of solar and geomagnetic activity. He claims that, because brain waves and SR share the same frequency range, resonant absorption of the SR signals by the human brain is possible. Further, Cherry (2002) claims that extensive research shows that this is highly likely, although he did not offer a specific mechanism by which it could happen. In our view, this omission is the weakest link in Cherry's theory, and although many parts of the hypothesis make logical sense, it cannot be accepted until the central biophysical mechanism of interaction between the SR signal and the human brain is identified and verified.

Hainsworth (1983) suggests that other factors that could affect the apparent connection between geophysical parameters and biological effects are links with geographical considerations. For instance, wind eddies carrying ionised air can produce oscillatory signals in the range 3–6 Hz. These could be associated with thunderstorm activity or with winds such as the Fohn wind in Austria, and could have localised biological effects.

According to Cherry (2002), in order for a "receiver" resonantly to absorb a weak signal, it must be able to "tune-in" to it. A phase-locked loop circuit produces a feedback signal in proportion to the phase difference between the entrained signal and the reference signal. Cherry (2002) claims that this evidence shows that it is possible for the brain to detect, tune into, and respond to the SR signal. Although Cherry (2002) claims that ELF environmental electromagnetic fields have been shown to alter significantly cellular calcium ion fluxes and "brain-waves", he does not explain the details of this alteration. This effect needs clarification before Cherry's (2002) hypothesis can be considered further.

König (1974 postulated that the human ELF brain waves (10.5 Hz) evolved to use the SR signals as zeitgebers—perhaps to synchronize biological (circadian) rhythms with daily cycles (Cherry 2002). Circadian rhythms are of endogenous origin and are used to regulate many homeostatic systems in the human body. Homeostasis refers to the tendency towards stability in the internal environment of an organism and is achieved by a system of control mechanisms activated by negative feedback. Wever (1986) reported that under temporal isolation, i.e., after the exclusion of all known environmental time cues, human circadian rhythms persist, but with a period close to 25 h rather than 24 h.

4.2.1 The role of melatonin

Melatonin (*N*-acetyl 5-methoxytryptamine) was characterised roughly 50 years ago and is now known to be the major secretory product of the pineal gland in all mammals, including man (Reiter 2003). Melatonin acts at the level of the suprachiasmatic nucleus (SCN) to modulate its activity and influence circadian rhythms (Reiter 2003). The SCN is an ovoid densely packed collection of small cells and is part of the hypothalamus, lying close to the point of crossing of the optic nerve fibres. It has been identified as the central circadian "pacemaker" (Reiter 2003) and has an intrinsic period that deviates slightly from 24 h. It must therefore be entrained (i.e. synchronised) with the 24-h day on a daily basis, the light-dark cycle being the most important environmental stimulus involved in these daily adjustments (phase shifts) of the human circadian system (Warman et al. 2003b). Properly timed melatonin administration also shifts circadian rhythms, facilitates re-entrainment to a novel light-dark cycle, and alters the metabolic activity of the SCN. The chronobiotic effects of melatonin explain its benefit in reducing the severity and/or duration of jet lag and in promoting restful sleep (Reiter 2003). It should be pointed out that the SCN's exclusivity as a pacemaker has been questioned by Cornélissen et al. (1994) who showed that some rhythms persist after bilateral SCN lesioning.

Melatonin has also been linked in various biological species to the regulation of immune function, retinal physiology, and altered tumour growth and, most recently, it has been found to be a free radical scavenger and antioxidant (Reiter 2003). Therefore, a reduction of melatonin levels in the body could precipitate various health problems. Unlike classical endocrine organs, the pineal gland in general, and melatonin synthesis in particular, are not markedly influenced by hormones from other glands or cells. Rather, the major regulator of melatonin production is the prevailing light-dark environment. Only during darkness at night does the pineal gland produce melatonin in abundance (Reiter 2003).

The amount of melatonin produced in the pineal gland is genetically determined. Among individuals of the same age, the nighttime increases in blood melatonin concentrations vary widely. Thus, while some individuals exhibit what is considered to be a robust nocturnal increase in blood nocturnal melatonin concentrations, in others the amplitude of the peak may be severely attenuated (Reiter 2003). This could explain why the response to variations in geomagnetic activity, particularly nocturnal melatonin suppression, differs between individuals. Age influences the amount of melatonin secreted; in elderly humans, the amplitude of the nocturnal melatonin increase can be significantly reduced (Reiter 2003).

In the study performed by O'Connor and Persinger (1997) discussed in the previous section, the authors hypothesised that sudden decreases in nocturnal melatonin by a specific range of geomagnetic activity would precipitate SIDS.

Experimental manipulation of Earth-strength magnetic fields as well as exposure to magnetic fields (MFs) associated with the 50/60 Hz electric power distribution system have been shown to suppress melatonin production in some, but not all, studies (Warman et al. 2003a; Phillips and Deutschlander 1997; Reiter 1994). Light exposure may be critical for MF-induced melatonin suppression and it also modifies the ability of certain species to derive compass information from the Earth's magnetic field (Phillips and Deutschlander 1997).

Burch et al. (1999) reported the results from a study in Colorado, USA, which suggested that increased geomagnetic activity was associated with decreased nocturnal melatonin production. They reported decreased excretion of the urinary melatonin metabolite, 6-hydroxymelatonin sulphate (6-OHMS), among the study population of 142 male workers with electric power generation, distribution or administrative duties. The quantity of this product in the urine is greater at night than during the day, reflecting the pineal melatonin synthesis and secretion cycle (Reiter 2003). Daily geomagnetic activity (from March 1995 to March 1996) was assessed using 3-h K indices from the U.S. Geological Survey (Boulder, Colorado) approximately 40 miles from the study location. K indices were converted to equivalent amplitudes (A_k), adjusted to local time and averaged over the 24- or 36-h period preceding each sample collection. If a 3-h index was missing, that day was excluded. Global geomagnetic activity was assessed using the average (aa) index averaged over the same periods and complete geomagnetic activity data were available for 132 of the 142 men.

Thresholds for biological effects associated with K indices have been observed at approximately 30 nT and above (Burch et al. 1999). When threshold values of the aa index equal to 15, 20, 25, 35, 40 and 45 nT were evaluated to assess cut point bias, mean 6-OHMS values were consistently lower on days when geomagnetic activity exceeded 20 nT. The correlation becomes statistically significant (at the two standard deviation level) for aa index values of between 25 and 35 nT in size (~0.1% Earth's static magnetic field strength at the equator). This corresponds to a 20% average decrease in the mass of overnight 6-OHMS excretion in the test subjects. On days when the aa index was 40 and 45 nT, the mass of 6-OHMS excreted overnight was reduced by 28% and 38%, respectively. Burch et al. (1999) conclude that these data show that reduced melatonin secretion is a plausible biological mechanism underlying some of the reported adverse health effects and that further research is required to identify the precise geophysical parameters that alter pineal gland function. Again, however, no attempt was made to identify the human geomagnetic "receiver". Kirschvink et al. (2001) have investigated the idea of magnetoreception based on magnetite.

Several studies have suggested that the visual system is involved when melatonin concentrations are suppressed due to magnetic disturbances. Olcese et al. (1985) studied the effect of magnetic fields on acutely blinded and intact male rats. They found that only in intact animals did the magnetic stimulus significantly reduce pineal activity and melatonin content. No effects were detected in blinded animals. The authors conclude that these data point to a retinal magneto-sensitivity, which may serve to modulate pineal gland function. Reiter (2003) states that "the classical photoreceptor cells, i.e. the rods and cones, seem not to be involved in light perception that modulates pineal melatonin production. Rather, there are specialised neurons which contain a unique photopigment in the retina that respond to light". The details of these specialised neurons are currently unknown.

Johnson (1999) reviewed circadian rhythm phase-response to external factors and stated that light pulses can cause phase delays when administered in the early subjective night and phase advances when administered in the late night/early morning. However, the retinal photoreceptor(s) responsible for transmitting the light information from the eyes to the human endogenous clock have not been identified (Warman et al. 2003b).

Warman et al. (2003b) performed a study to test the hypothesis that "the photopic visual system provides the primary input for the phase shifting effects of light on the human circadian system". The authors argued that if the "circadian" strength of the light stimulus can be quantified in photopic lux, then it would be expected that a low intensity short wavelength light pulse would be significantly less effective than that of a high intensity white light pulse and have as little effect as a dim white light pulse of the same intensity. If, however, the phase shifting effects of light exhibit short wavelength sensitivity, then it would be expected that a low lux short wavelength light pulse would be as effective as a high lux white light pulse and significantly more effective than a dim white light pulse.

Eleven healthy male subjects aged 18–40 years (28 ± 5, mean ± SD) participated in 15 phase shifting sessions at the University of Surrey, UK. Subjects were not taking any medication or drugs known to affect melatonin production and were screened for drugs of abuse. Each study lasted 4 days and the timing and content of the three daily meals were standardised. Warman et al. (2003b) found that the data demonstrated that a very low intensity short wavelength light pulse (8 lux) is able to phase advance the human circadian system to a similar magnitude as a bright white pulse (12,000 lux) containing 185-fold more photons. They argue that this finding suggests that the human circadian system is particularly sensitive to the phase advancing effects of short wavelength light and that the visual photopic system is not primarily involved. Warman et al. (2003b) conclude that their findings support the recent human studies investigating the spectral sensitivity of light-induced melatonin suppression. This finding could help to explain why there seems to be no effect of alternating electromagnetic fields of specific power distribution frequencies (50 Hz) on melatonin levels but that geomagnetic variations do seem to have an effect. The effect of anthropogenic electric and magnetic fields on human health is discussed further in Section 5.

According to Weydahl et al. (2001) factors other than light may affect variations in melatonin, including geomagnetic disturbances. Weydahl et al. (2001) tested this hypothesis in Alta, Norway (70°N), where the aurora borealis is often observed and where the Sun remains below the horizon for several weeks of the year. To examine whether changes in geomagnetic activity influence the secretion of melatonin, saliva was collected from 25 healthy subjects several times during the day and night at different times of year. After correlation analysis, the data suggested that changes in geomagnetic activity had to be of a certain magnitude to affect the circadian amplitude of melatonin. When the changes in geomagnetic activity were larger than 80 nT in a 3-h period, concentrations of salivary melatonin were significantly decreased. These results support the hypothesis that geomagnetic variations affect melatonin levels in the body although they do not help to identify the mechanism.

In summary, if geomagnetic activity does suppress nighttime melatonin levels, it could explain many of the reported adverse health effects. The details of how geomagnetic activity could alter melatonin levels remain unclear, although the retina has been suggested as a possible magneto-sensitive “receiver”. It seems that magnetic disturbances above a certain threshold, sensed via the retina, somehow “confuse” the system intended to synchronise the human circadian and other rhythms (including melatonin–serotonin balance) with the daily cycle.

4.2.2 Other possibilities

There has been some investigation into the role of calcium ions as a potential link between geomagnetic variations and human health issues. Blackman et al. (1990)

suggested that the evidence indicates that electric and magnetic fields can alter normal calcium ion homeostasis (maintenance of equilibrium) and lead to changes in the response of biological response of cells. Suggestions regarding the health implications of alterations in cellular calcium ion homeostasis are wide ranging and include reduced nocturnal production of melatonin in the pineal gland (Walleczek 1992), which is interesting in the context of the previous discussion about the role of melatonin. Although the knowledge about calcium ion alteration by external electric and magnetic fields is limited, it is generally believed that the cell membrane and Ca^{2+} regulated activity is involved in bioactive ELF field coupling to living systems (Walleczek 1992).

Cleary (1993) discussed the various ways—cyclotron resonance or parametric resonance—that ELF electric and magnetic fields could be absorbed by biological systems.

4.2.2.1 Cyclotron resonance

> “The cyclotron resonance frequencies of some physiologically important ions e.g. Ca^{2+} are in the ELF range. For a 50 μT static field, the Ca^{2+} frequency is 38.4 Hz. The general validity of this as a plausible biophysical mechanism has been questioned on the basis of ion hydration and collision damping” (Cleary 1993).

In a biological fluid at atmospheric pressure, the density is so large that an ion makes very many collisions with neutral particles in a time equal to the reciprocal of the cyclotron resonance frequency. Therefore, this cyclotron resonance would not occur.

4.2.2.2 Parametric resonance

> “An alternative biophysical-interaction was proposed by Lednev (1991), to explain the effects of ELF non-ionising electromagnetic fields on ions in biological systems. In this model, an ion such as Ca^{2+}, weakly bound within a protein molecule such as calmodulin, is described as a charged oscillator, vibrating at the frequency of thermal motion. Alteration in the state of Ca^{2+} binding within the calmodulin molecule could affect many enzymes that are regulated by calmodulin, thus leading to various physiological alterations”.

Cleary (1993) gives an overview of other possible biophysical mechanisms of interaction between magnetic and electric fields and the human body; these involve ion-molecular orbital precession, nuclear-magnetic resonance (NMR) and magnetic-field effects on free radicals.

4.2.2.3 Ion-molecular orbital precession

> “Zhadin and Fesenko (1990) proposed a biophysical mechanism for ELF non-ionising electromagnetic fields coupling to a molecularly bound ion ... by an extrinsic electric field. However, a protein-bond ion such as Ca^{2+} in a geomagnetic field would require relatively long duration exposure to an extrinsic ELF MF of relatively high flux density (i.e. 0.1mT) to induce bond distortion.

> The involvement of such bond distortions in reported biological effects of ELF non-ionising electromagnetic fields is uncertain'' (Cleary 1993).

The required magnetic flux density is twice the maximum geomagnetic field strength and 3 orders of magnitude higher than a typical geomagnetic disturbance. This makes it difficult to accept as an interaction mechanism for natural geomagnetic fluctuations.

4.2.2.4 NMR

> ''Charged nuclei with spin have an intrinsic magnetic moment, M, which can couple energetically with static and alternating magnetic fields. This is the principle which NMR imaging and spectroscopy use. At geomagnetic flux densities, characteristic NMR precession frequencies are in the ELF range for many nuclei found in living systems. The flux densities of alternating magnetic fields capable of inducing significant physiological effects due to NMR coupling have not been determined. Since many highly abundant isotopes (e.g. ^{16}O, ^{56}Fe, ^{12}C, etc.) found in living systems have zero nuclear spins, the physiological relevance of NMR-energy coupling, via weak ELF magnetic fields is questionable'' (Cleary 1993).

The field strengths at which NMR imagers operate are several Teslas in magnitude, typically 3 T. This is around five orders of magnitude greater than the Earth's magnetic field strength at the equator (30,000 nT), which again makes this unlikely as a plausible interaction mechanism for natural electromagnetic variations.

4.2.2.5 Magnetic-field effects on free radicals

> ''Free radicals are generated continuously in living systems as the result of biochemical reactions (e.g. oxidative metabolic processes), as well as due to the absorption of electromagnetic radiation such as sources of visible light in the retina. Increased tissue free radical concentration, due to metabolic dysfunction or extrinsic physical factors, has been associated with a variety of pathophysiological changes including carcinogenesis.
>
> Static magnetic fields on the order of 1 mT are known to affect free-radical chemical reactions in vitro (McLauchlan 1989). This suggests the possibility that ELF magnetic field effects on living systems may involve field-induced changes in free radicals.
>
> Free radical lifetimes (and hence concentrations) depend upon the rate of conversion of triplet-state to singlet-state electrons, which, in turn, depends, in part, upon the energies of the singlet and triplet state. Extrinsic or intrinsic (nuclear) magnetic fields increase or decrease triplet-state energies, depending on the orientation of triplet spin relative to the magnetic field, to form either $T-1$ or $T+1$ triplet states.
>
> Combined static and alternating ELF magnetic fields could hypothetically affect free-radical reactions in living systems, in situations where the intrinsic static magnetic-flux density was poised near the critical level. If the magnitude of the alternating ELF magnetic field was equal to the difference between the intrinsic and critical level, and if the period of the field was sufficiently long to

> permit the triplet-to-singlet transition, the alternating magnetic field could modulate biochemical processes" (Cleary 1993).

Figure 6 shows a schematic diagram, which illustrates the principle of free-radical production in the presence of an external magnetic field, similar to the process described by Cleary (1993). The bold arrows represent the relative direction of spin of each molecule.

Cleary (1993) summarises that, although a variety of biophysical-interaction mechanisms have been proposed to explain the effects of weak ELF magnetic and/or electric fields on living systems, no mechanism proposed to date appears to account fully for the experimental observations, suggesting the possibility of multiple biophysical-interaction mechanisms or the need to consider additional mechanisms. According to Cleary (1993), "it appears somewhat unlikely that a single mutually exclusive mechanism will emerge to explain all of the observed effects of low-intensity ELF electric fields or magnetic fields".

Sienkiewicz et al. (1993) also reviewed the biological effects of electromagnetic fields. Exposure to changing magnetic fields causes the induction of electric fields and currents in biological tissues, and may result in a variety of biological responses. "A threshold current density between 10 Hz and 1 kHz of 10 mA m^{-2} can be conservatively estimated for weak electric-field effects on central-nervous system activity" (Sienkiewicz et al. 1993).

Sienkiewicz et al. (1993) report that, although few studies have involved human volunteers, one of the most consistent responses seems to be minor reduction in heart rate, observed immediately during or after exposure to a combined electric and magnetic field. Resting heart rate was found to be slightly reduced by about 3–5 beats per minute during or immediately after exposure for 2–6 h to a 60-Hz field of 9 kV m^{-1} and 20 μT (Cook et al. 1992). Sienkiewicz et al. (1993) conclude, however, that the small magnitude and transitory nature of this effect does not suggest a health risk.

Regarding cancer related studies, Sienkiewicz et al. (1993) conclude that there is no convincing evidence that electromagnetic fields cause genetic damage; therefore they are extremely unlikely to have any effect on the initiation of cancer. However,

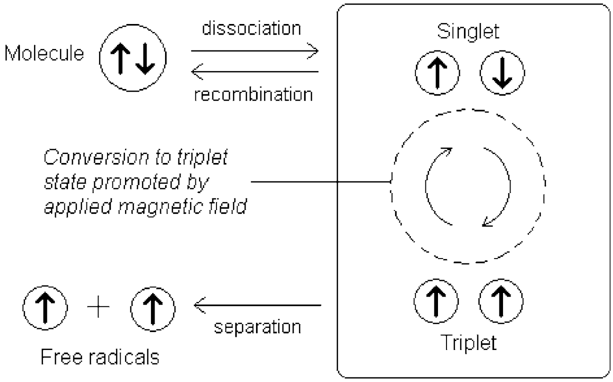

Fig. 6 Schematic diagram showing a possible free radical formation mechanism involving an external alternating magnetic field (modified from a slide presented by Prof. Michael Crumpton at The Royal Society Bernal lecture, 6 May 2004, "Are low-frequency environmental electromagnetic fields a health hazard?")

they add that the evidence remains confused, with no clearly reproducible effects apparent and that more research is required. Ulmer (2002) offers a putative mechanism for the interaction of ions in the body with external magnetic fields.

It is possible to postulate about the effects of each potential mechanism. For instance, Sobel et al. (1995) suggest that a mechanism involving alteration of calcium homeostasis, such as cyclotron resonance or parametric resonance could inappropriately activate immune system cells, initiating events that could result in neuronal degeneration. This could lead to conditions such as Alzheimer's disease and, in fact, Sobel et al. (1995) identify occupational electromagnetic fields as a possible risk factor for Alzheimer's. However, until clinical studies validate any of the mechanisms discussed above, they remain hypothetical.

5 Anthropogenic electric and magnetic fields

Although the focus of this work is on the human health effects of natural electric and magnetic fields, it is worth noting that much research has focused on anthropogenic electric and magnetic fields which has been carried out independently of research on geomagnetic activity effects. The majority of this research is concerned with health effects arising from the proximity of 50/60 Hz power distribution lines, and the possible health effects of prolonged mobile phone use has also been studied.

One of the hypotheses investigated is that exposure to magnetic fields generated by high voltage installations can increase cancer incidence in children. A pooled analysis of two Scandinavian studies supported the hypothesis of an association between magnetic fields and childhood leukaemia (Feychting et al. 1995). In this study, two case–controlled studies were pooled, a Swedish study based on children living within 300 m of power transmission lines, and a Danish study based on the entire Danish population. National cancer registries were used to identify cases of leukaemia, lymphoma or central nervous system tumour and controls were selected from the study populations at random. For childhood leukaemia, an elevated relative risk of 2.0 (95% CI 1.0–4.1) was found for magnetic fields of $\geq 0.2\ \mu$T, and a relative risk of 5.1 (95% CI 2.1–12.6) for magnetic field levels of $\geq 0.5\ \mu$T. A 0.2 μT (200 nT) electromagnetic field is about the same magnitude as the variation in the static geomagnetic field during a large magnetic storm. The results from Feychting et al. (1995) seem to support the idea that the human health effect of geomagnetic disturbances of the magnitude caused by geomagnetic storms can be detected in national cancer registries. However, the field caused by the power distribution lines is constantly alternating at a steady frequency, whilst geomagnetic disturbances are intermittent and a disturbance of 200 nT is relatively rare (Kivelson and Russell 1995).

Reiter (1994) stated that one of the most uniform changes associated with the exposure of animals to either pulsed static geomagnetic fields or to sinusoidal ELF magnetic fields has been a reduction in the night-time levels of melatonin. Reiter (1994) went on to say that, if artificial electromagnetic field exposure increases the incidence of cancer in humans, a plausible mechanism could involve a reduction in melatonin, which is the consequence of such exposures.

However, studies into the effects of power frequency magnetic fields on human melatonin levels have yielded contradictory results. Wood et al. (1998) exposed 30 adult male subjects to a 20 μT magnetic field (50 Hz) at certain times in relation to the predicted time of onset of melatonin. When exposure preceded the onset of melatonin rise, a significant delay in onset time relative to a sham-exposure of approximately 30 min was observed. Wood et al. (1998) also reported marginally significant reductions in maximum melatonin level. They observed these effects in only about 20% of the test subject population. This split in the population between those who respond to 50/60 Hz magnetic fields and those who do not is reminiscent of the findings of Chernouss et al. (2001) discussed earlier, who revealed that it is a subset of the population which is sensitive to auroral disturbances.

Warman et al. (2003a) investigated the effect of exposure to circularly polarised high magnitude, power frequency magnetic fields on 19 male subjects aged 18–35 years. The authors stated that, although melatonin suppression and circadian rhythm phase-shift due to light exposure at night is accepted and well understood, data supporting the effect of magnetic fields on melatonin level are very limited and often poorly controlled. They added that, unlike light exposure, the potential neuroanatomical pathways for melatonin suppression due to magnetic field exposure remain obscure. Warman et al. (2003a) reported that their study into the effects of 200–300 μT magnetic fields (50 Hz) showed no effect on melatonin suppression or circadian rhythm phase-shift.

Commenting on the earlier study, Warman et al. (2003a) suggested that the work of Wood et al. (1998) provides some of the most controlled data concerning the potential effect of 50 Hz magnetic fields on the human melatonin profile to date. However, they attribute the disparity between their results and those of Wood et al. (1998) to the fact that the latter did not provide controls for postural or lighting effects, and different subjects appear to have received exposures of different lengths (1.5–4 h). Wood et al. (1998) hypothesised that, if magnetic fields were acting on melatonin in a similar way to light, then the timing of magnetic field exposure relative to the phase of the circadian clock may be important to observe an effect. Warman et al. (2003a) point out that limited support for this is found in the data collected by Wood et al. (1998).

Brainard et al. (1999) reviewed literature concerning the relationship between electromagnetic field and light exposures and melatonin and breast cancer risk. The review was performed in the context of the hypothesis that increased incidence of breast cancer in industrialised countries is related to the increased use of electricity (Stevens and Davis 1996). This hypothesis specifically proposes that increased exposure to light at night and electromagnetic fields reduce melatonin production. To evaluate the hypothesis, Brainard et al. (1999) reviewed the epidemiological data on associations between electricity and breast cancer, and assessed the data on the effects of electromagnetic field exposure on melatonin physiology in both laboratory animals and humans. The authors concluded that it is currently unclear if electromagnetic field and light exposure are significant risk factors for breast cancer. They pointed out that, due to the ubiquitous nature of electromagnetic fields and artificial light exposure along with the high incidence of breast cancer, even a small risk would have a large impact on public health.

Melatonin suppression has also been documented in studies of mobile phone use. Burch et al. (2002) investigated the relationship between mobile telephone use and excretion of the melatonin metabolite 6-OHMS in two populations of male electric utility workers (Study 1, $N = 149$; Study 2, $N = 77$). Participants collected urine samples and recorded cellular telephone use over 3 consecutive workdays and personal 60-Hz magnetic field and ambient light exposures were characterised on the same days. No change in 6-OHMS excretion was observed among those with a daily cellular telephone use of greater than 25 min in Study 1 (5 worker-days). Study 2 workers with more than 25 min of cellular telephone use per day (13 worker-days) had a lower mean nocturnal 6-OHMS concentration ($P = 0.05$) and overnight 6-OHMS excretion ($P = 0.03$) compared with those without cellular telephone use. A non-significant linear trend of decreasing mean nocturnal 6-OHMS concentrations ($P = 0.02$) and overnight 6-OHMS excretion ($P = 0.08$) across categories of increasing cellular telephone use was observed. According to the criteria of our study, this first statistic is significant but the second statistic is not, as it is below the 95% CI. A combined effect of cellular telephone use and occupational 60 Hz MF exposures in reducing 6-OHMS excretion was also observed in Study 2.

The authors concluded that exposure-related reductions in 6-OHMS excretion were observed in Study 2, where daily cellular telephone usage of greater than 25 min was more prevalent. The authors also cautioned that prolonged use of cellular telephones may lead to reduced melatonin production, and that elevated 60-Hz MF exposures may exacerbate the effect.

6 Conclusions and discussion

This work has summarised some of the major work carried out in the field of heliobiology over the last 30 years. During the 1970s there were many inconclusive studies concerning heliobiology—some even refuted the need for such an area of research (Feinleib et al. 1975). Presented below and also in Table 3 are the main results that we have found in the literature concerning this research topic.

6.1 Definite conclusions

There are several specific themes that recur in the literature. It is very likely that the five conclusions given below are true.

6.1.1 Geomagnetic disturbances have a greater effect on humans at higher geomagnetic latitudes

Chernouss et al. (2001) have shown that, in the northern auroral region, people are particularly sensitive to changes of geomagnetic activity.

6.1.2 Unusually high values of geomagnetic activity have an effect on human cardiovascular health

Cornélissen et al. (2002) found an excess 220 deaths per year, from a population of about 5 million, due to MI during spans of high solar activity, as compared to years with low solar activity. Gurfinkel et al. (1995) observed changes in the blood flow in 70% of patients with AMI and 65% of patients with angina pectoris associated with elevated levels of geomagnetic activity. Ghione et al. (1998) reported a positive relation between geomagnetic activity and blood pressure. SBP was correlated to a higher level than diastolic pressure. The maximum correlation was obtained for a delay of 3 days (to the nearest whole day), which corresponds to the time required for solar wind from an active region on the Sun to reach the Earth.

Table 3 Table summarising the main conclusions of this literature survey

		Evidence
Confident conclusions		
1	Geomagnetic disturbances have a greater effect on humans at higher geomagnetic latitudes	Chernouss et al. (2001)
2	Unusually high values of GMA have an effect on human cardiovascular health	Cornélissen et al. (2002), Ghione et al. (1998), Gurfinkel et al. (1995), Stoupel et al. (1995)
3	Unusually low values of GMA have an effect on human cardiovascular health	O'Connor and Persinger (1997), Shumilov et al. (submitted, 2003)
4	Only 10–15% of people are significantly affected by GMA (in areas studied)	Chernouss et al. (2001), Shumilov et al. (2003)
5	HRV is negatively correlated with GMA	Cornélissen et al. (2002), Stoupel et al. (1994), Watanabe et al. (2001)
Less confident conclusions		
1	Evidence of positive association between GMA and mental illness	Kay (1994)
2	Evidence of link between GMA and suicide rates	Partonen et al. (2004), Stoupel et al. (1995)
3	Direct action of natural ELF electric and magnetic fields unlikely	Cleary (1993), Sienkiewicz (1993)
4	Evidence of importance of melatonin in mechanism	Burch et al. (1999), Weydahl et al. (2001)
5	Schumann resonance is a candidate for part of mechanism	Cherry (2002), Hainsworth (1983)
6	Human magneto-sensitivity may involve the retina	Olcese et al. (1985)

GMA—geomagnetic activity

HRV—heart rate variability

ELF—extremely low frequency

Messner et al. (2002) concluded that there is no significant relationship between geomagnetic activity and AMI or chest pain in Sweden between 1985 and 1998. However, Stoupel et al. (1995) found that hospital and AMI-related deaths in Israel were correlated with solar activity parameters between 1974 and 1989. These two results are confusing, especially because Israel is at lower geomagnetic latitude than Sweden. Results showing no correlation like those reported by Messner et al. (2002) are in the minority.

6.1.3 Unusually low values of geomagnetic activity seem to have an effect on human health

Shumilov et al. (submitted, 2003) indicate that high and extremely low levels of geomagnetic activity cause adverse health effects. O'Connor and Persinger (1997) reported a strong non-linear correlation between SIDS and geomagnetic activity in Ontario, Canada. They reported that there was an increase in numbers of cases of SIDS for geomagnetic disturbance levels of 11–20 and 31–40 nT. Interestingly, there was a negative correlation for disturbances of 21–30 nT. This seems to support the idea that deviations from a particular level of geomagnetic activity, either up or down, cause health problems.

6.1.4 Only a fraction of the population is significantly affected by geomagnetic variations

A subset of the population is more sensitive to auroral disturbances than the remainder; Shumilov et al. (2003) estimate this fraction to be 10–15% of the total population. Chernouss et al. (2001) further divide this group into those who respond sympathetically to geomagnetic activity, and those who respond parasympathetically. This difference is related to a difference in the response of the ANS; the sympathetic responders have a higher adaptive ability to changes in the geophysical environment.

6.1.5 HRV is negatively correlated with geomagnetic activity

Many studies report a negative correlation between HRV and the level of geomagnetic activity (Stoupel et al. 1994; Watanabe et al. 2001; Cornélissen et al. 2002). This supports the idea that enhanced geomagnetic activity is involved with a zeitgeber, whose function is to synchronize the internal rhythms, possibly via the Schumann resonance signals. The reduction in HRV could be related to the ANS response to changes in geomagnetic activity, which can be either sympathetic or parasympathetic in a particular individual.

6.2 Less certain conclusions

6.2.1 There may be a positive association between geomagnetic activity and mental illness

Kay (1994) reported a 36% increase in the number of depressed phase manic-depressive illness admissions in the second week following a geomagnetic storm when compared with geomagnetically quiet conditions. There was no increase in the admission numbers of male patients with psychotic depression. There was also a non-significant increase in the numbers of female depression patients. Presently, there are too few data to make a certain conclusion.

6.2.2 *There may be an association between geomagnetic activity and suicide rates*

Stoupel et al. (1995) reported that the monthly suicide rate in Israel was negatively correlated with geomagnetic activity between 1980 and 1989. Partonen et al. (2004) concluded that there was no effect of geomagnetic activity on suicide rates in northern Finland between 1987 and 1999. Despite this, there is a bimodal distribution of suicides over the year, with maxima in April and September, which corresponds to the seasonal maxima in geomagnetic activity. There are presently too few data to make a definite conclusion either way. If depression and mental illness are found to be positively correlated with geomagnetic activity, we would expect suicide rates also to be positively correlated due to the association of suicide with depression (Moller 2003).

6.2.3 *Direct action of natural ELF electric and magnetic fields seems unlikely*

Cleary (1993) and Sienkiewicz (1993) both state that it is unlikely that natural ELF electric and magnetic fields can directly cause health problems in humans. The field strengths involved are too small and biological fluids too dense at atmospheric pressure for phenomena such as cyclotron resonance to occur. "It appears somewhat unlikely that a single mutually exclusive mechanism will emerge to explain all of the observed effects of low-intensity ELF electric fields or magnetic fields" (Cleary 1993).

6.2.4 *Melatonin seems to play an important role in one or more mechanisms linking environmental conditions to human health*

Melatonin is a hormone produced in quantity only during darkness at night. It has been linked to the regulation of immune function, retinal physiology, and altered tumour growth, and is a free radical scavenger and antioxidant (Reiter 2003). The suppression of melatonin production by posture and high levels of light during night is well established; more controversial is the claim that variations in geomagnetic activity also suppress melatonin levels.

Several studies support the idea that geomagnetic disturbances alter the melatonin levels in the human body. Weydahl et al. (2001) reported that geomagnetic activity above a certain level (80 nT) reduced salivary melatonin in a study conducted in Alta, Norway (70°N). Burch et al. (1999) report a threshold geomagnetic disturbance of 30 nT in order to have a biological effect in Colorado, USA. The authors showed that the excretion of melatonin metabolite (6-OHMS) in a group of electrical workers was lower on days with higher levels of geomagnetic activity. The reduction in mass of overnight 6-OHMS excretion was 20%, 28% and 38% for geomagnetic disturbances of 30, 40 and 45 nT, respectively.

6.2.5 The Schumann resonance hypothesis explains some of the observed phenomena but is currently incomplete

Schumann resonance radio signals have been investigated as a possible candidate for the mechanism linking geomagnetic activity and adverse human health. Hainsworth (1983) argues that it is not a coincidence that the human brain alpha-rhythm has the same frequency as that at which there is minimum energy in the Earth-ionosphere cavity. In the context of evolution, it makes sense that the human brain evolved to use a frequency "channel" with a minimum of external "noise". For this to be true, the human brain would, at least at some period in the evolutionary past, have had to be sensitive to these Schumann signals. Assuming that the Schumann resonance signals have been at the same frequencies over evolutionary time, it could be expected that the human central nervous system has evolved to cope with them and perhaps even use them to synchronise internal biorhythms. When the frequencies of the signals are altered during a geomagnetic disturbance, it is possible that this coping mechanism breaks down, inducing stress symptoms, which could exacerbate existing health problems such as heart disease and mental illness.

The assumption that the Schumann signals have been constant during evolutionary time would be invalid if the distribution of tropical thunderstorms or the characteristics of the ionosphere had changed significantly during that time. The characteristics of the Earth-ionosphere cavity determine the frequencies of the Schumann signals whilst the number and extent of thunderstorms affects the SR intensity. We do not see any reason to believe that the physical properties of the ionosphere have changed much since humans have evolved, but the Earth's climate has changed considerably in the last 200,000 years.

Williams (1992) demonstrated a positive correlation between the monthly means of the tropical surface-air-temperature anomaly and the amplitude of the fundamental Schumann resonance mode. A 2 K change in temperature was hypothesised to produce a 20-fold change in lightning activity (Barr et al. 2000). During the last ice age, when global temperatures were significantly lower than today, the rate of production of thunderstorms must have been significantly lower than at present. This would have presumably led to a lower intensity of the Schumann resonance (SR) signals. However, the period between the end of the last ice age and modern day may have been enough time for humans to adapt to the "new" Schumann resonance intensities.

It is proposed that the absorption of these SR signals by the human brain can modulate the amount of melatonin produced and secreted by the pineal gland (Cherry 2002). The search for a mechanism by which this could happen is essential. As yet no conclusive results have been obtained, and so the hypothesis is incomplete.

6.2.6 Human magnetic sensitivity may involve the retina

Olcese et al. (1985) found that only rats with intact retinas were sensitive to magnetic fields and suggested that this retinal magneto-sensitivity could serve to modulate pineal gland function and therefore melatonin levels. However, Warman et al. (2003b) state that the retinal photoreceptors responsible for this sensitivity are yet to be established. The authors go on to argue that although the human circadian system is particularly sensitive to the phase advancing effects of short wavelength light and that spectral sensitivity of light induced melatonin suppression, the visual photopic system is not primarily involved.

6.3 Other conclusions

Although it was not within the scope of this paper to make conclusions about the effect of anthropogenic electric and magnetic fields on human health, it is worth noting the main points. Feychting et al. (1995) suggested a 2-fold risk increase in the incidence of childhood leukaemia for prolonged exposure to 50/60 Hz alternating fields equal or greater than 0.2 μT in magnitude. The authors report a 5-fold increase in the risk for prolonged exposure to similar fields equal or greater than 0.5 μT.

The study conducted by Wood et al. (1998) reported that 20 % of the test population was affected by a 20 μT magnetic field alternating at 50 Hz. This supports conclusion 5.1.4, that a subset of the population is more sensitive to environmental magnetic fields. In the affected individuals, a 30-min delay in the nighttime melatonin rise was observed as well as a reduction in the maximum level of melatonin. More recently, Warman et al. (2003a) reported that 50/60 Hz magnetic fields do not shift circadian rhythms. Warman et al. (2003a) also stated that acute exposure to 50 Hz fields of 200–300 μT does not suppress melatonin in young men.

Burch et al. (2002) suggested that the prolonged use of mobile phones, greater than 35 min per day, might lead to a decrease in melatonin concentration. They add that the effect may be amplified by exposure to 60 Hz alternating electromagnetic fields.

6.4 Future work

In order for more definite conclusions to be made in the field of heliobiology, more data need to be collected and analysed. A coordinated multi-nation analysis of national medical databases to search systematically for correlations with variations of geomagnetic and solar activity would provide a “new wave” of data that would either support or refute the current inconclusive results. Such an epidemiological search should include information on physiological and mental disorders and other parameters related to human health status.

Regarding mechanisms, more systematic work needs to be done to identify the site of human magneto-sensitivity. Several magnetoreceptors have been proposed, including the blood and the retina. In order for the Schumann resonance hypothesis presented by Cherry (2002) to be accepted, the mechanism for the “tuning into” and the resonant absorption of the Schumann signals by the human body needs to be identified and characterised.

7 Websites

Online medical dictionary—http://www.cancerweb.ncl.ac.uk/cgi-bin/omd
WHO website—http://www.who.int

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