Space Sci Rev (2014) 186:359–386
DOI 10.1007/s11214-014-0068-0

A Combined Analysis of the Observational Aspects of the Quasi-biennial Oscillation in Solar Magnetic Activity

G. Bazilevskaya · A.-M. Broomhall · Y. Elsworth · V.M. Nakariakov

Received: 31 March 2014 / Accepted: 26 June 2014 / Published online: 15 July 2014

Abstract Solar quasi-biennial oscillations (QBOs) with the time scale of 0.6–4 yrs appear to be a basic feature of the Sun's activity. Observational aspects of QBOs are reviewed on the basis of recent publications. Solar QBOs are shown to be ubiquitous and very variable. We demonstrate that many features of QBOs are common to different observations. These features include variable periodicity and intermittence with signs of stochastisity, a presence at all levels of the solar atmosphere and even in the convective zone, independent development in the northern and southern solar hemispheres, most pronounced amplitudes during the maximum phase of the 11-yr cycle and the transition of QBOs into interplanetary space. Temporal weakening of solar activity around the maximum of the 11-yr cycle (Gnevyshev Gap) can be considered an integral part of QBOs. The exact mechanism by which the solar QBO is produced is poorly understood. We describe some of the most plausible theoretical mechanisms and discuss observational features that support/contradict the theory. QBOs

---

G. Bazilevskaya
Lebedev Physical Institute, Russian Academy of Sciences, Leninsky prospect, 53, Moscow, 119991, Russia
e-mail: gbaz@rambler.ru

A.-M. Broomhall (✉)
Institute of Advanced Studies, University of Warwick, Coventry, CV4 7HS, UK
e-mail: a-m.broomhall@warwick.ac.uk

A.-M. Broomhall · V.M. Nakariakov
Centre for Fusion, Space, and Astrophysics, Department of Physics, University of Warwick, Coventry, CV4 7AL, UK

Y. Elsworth
School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

V.M. Nakariakov
School of Space Research, Kyung Hee University, Yongin, 446-701, Gyeonggi, Korea

V.M. Nakariakov
Central Astronomical Observatory at Pulkovo of RAS, St. Petersburg 196140, Russia

have an important meaning as a benchmark of solar activity, not only for investigation of the solar dynamo but also in terms of space weather.

Keywords Sun: activity · Sun: magnetic fields

1 Introduction

The mechanisms governing the solar cycle are still far from fully understood. Enormous information concerning this problem can be retrieved from the variability of solar phenomena, including the diversity of quasi-periodic processes. In addition, the influence of the Sun on the heliosphere and, in particular, on solar-terrestrial coupling is impacted by similar temporal variations and is, therefore, worthy of careful investigation. Of particular interest are oscillations with periods of the order of 2 yrs which appear to be connected with the internal fine structure of the solar magnetic field. The main feature of the quasi-periodic solar variations is their intermittency. The variations exist from time to time, and their period varies in the range of 0.6–4 yrs. In the literature, periodicities of 0.6–4 yrs are often referred to as quasi-biennial oscillations (QBOs). However, we note that periodicities in the range considered here have also been referred to as intermediate- or mid-term quasi-periodicities (for example Lou et al. 2003; Valdés-Galicia et al. 2005; Valdés-Galicia and Velasco 2008; Chowdhury et al. 2009b; Kudela et al. 2010).

The quasi-periodic processes in the Sun are considered to be a separate phenomenon from the well-established terrestrial quasi-biennial oscillation (e.g. Kane 2005a), which are far more uniform than the solar QBO. However, the exact relationship between the Sun's magnetic field and Earth's climate is poorly understood and so some form of resonance cannot be completely excluded.

An example of the QBO extraction is illustrated in Fig. 1. The upper panel gives the monthly values of the sunspot area for the whole disk from 1875 to 2012.[1] In the lower panel the 25-month smoothed series presents the long-term variability (red curve) while the residuals obtained by subtraction of the long term set from the monthly data present the short-term variability (blue curve). The oscillations, whose amplitudes are modulated by the 11-yr cycle, are clearly seen.

When considering a power spectral density (PSD) of common indices of solar activity, such as sunspot number or sunspot area, the interval of 0.6–4 yrs does not seem special compared to the power intrinsic to 11-yr cycle (Fig. 2a). However, removing the long-term variability reveals a PSD, as shown in Fig. 2b, with a highly disturbed multi-peaked structure. Figure 3, where the PSD is shown as a function of the period, demonstrates a local attenuation in the PSD just below $T = 1$ yr, then a general increase in the 1–1.5 yr range, and a rather uniform PSD distribution in the $T = 1.5$–2.5 yr region, that is an apparent separation of the two groups of variations. Historically, research on these two domains also often developed separately. However, as it will be shown below, many features of the two groups are similar.

Since the QBOs cannot be analyzed without preparatory filtration a variety of processing methods are used by different authors. They include discrete and fast Fourier transforms, spherical harmonic decomposition, wavelet transform analysis, periodogram analysis, passband filters (e.g., time-smoothing), maximum entropy method, and, recently, the Huang-Hilbert transform, which builds on empirical mode decomposition (EMD) analysis, to mention only a few. In general the results of the various procedures are consistent within the

---

[1] http://solarscience.msfc.nasa.gov/greenwch.shtml.

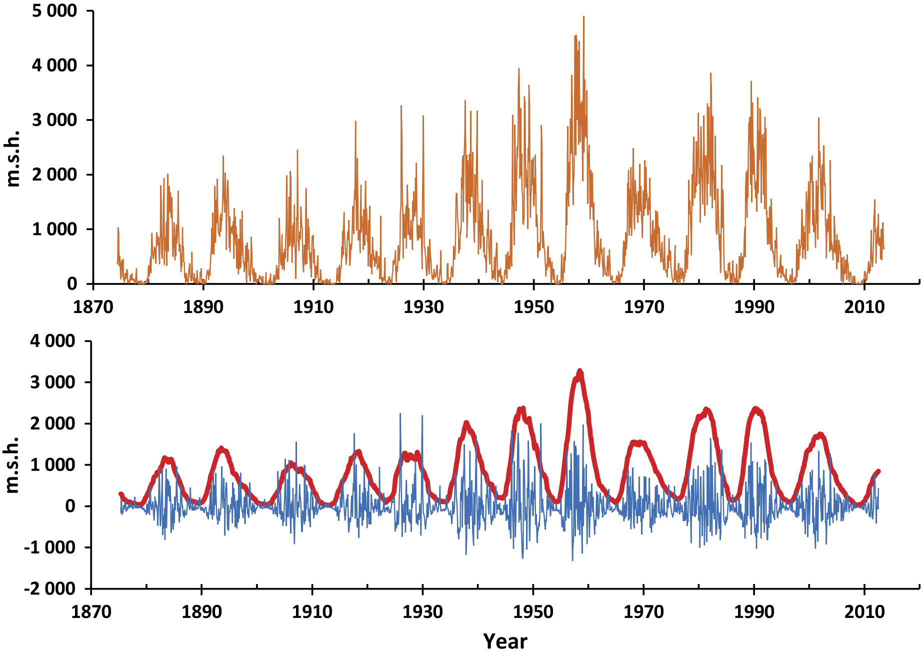

Fig. 1 *Upper panel*: monthly values of the sunspot area (http://solarscience.msfc.nasa.gov/greenwch.shtml) in millionths of a solar hemisphere. *Lower panel*: 25-month smoothed values of the sunspot area (*red curve*) and the short-term oscillations (*blue curve*) isolated by subtracting the smoothed data from the data shown in the *upper panel*

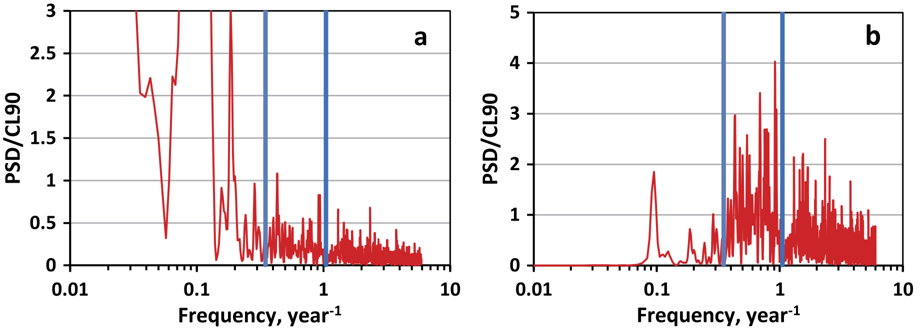

Fig. 2 (**a**): Power spectrum density of the monthly meanings of the sunspot area for the whole solar disk from 1875 to 2012. (**b**): The same as (**a**) but with an ∼11 yr variation withdrawn by subtraction of 25-month running averages from the monthly values of sunspot area. PSD is given in the units of 90 % confidence level for the highest peak, meaning that values greater than unity imply that there is less than a 10 % chance of such power in noise. *Vertical bars* denote approximately the frequency range of QBOs indicated by this data, however, we note that many authors consider periodicities outside these limits (see Table 1)

accuracy of the processing. Many authors exploring the variability of different solar, interplanetary and terrestrial indices, found common features in the QBO behavior. In this paper, these features are illustrated by original figures where QBOs are isolated by subtracting the 25-month smoothed monthly values from the 7-month smoothed values unless otherwise in-

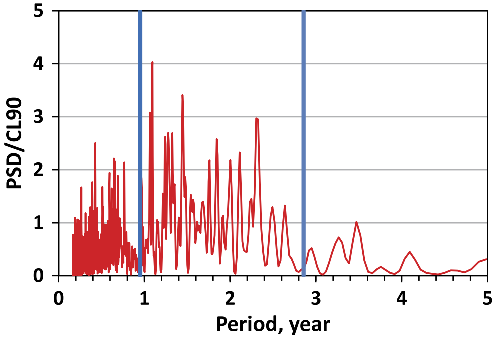

Fig. 3 Higher frequency range of the PSD spectrum from the Fig. 2b, but with PSD depicted vs. period value and linear scale on the abscissa axis. *Vertical bars* denote approximately the period range of QBOs indicated by this data

dicated. This procedure passes 1.5–1.7 yr signal without distortion (i.e. it has around a 100 % frequency response at 1.5–1.7 yr) and above a 50 % response between 1 and 3.3 yrs. The output results are, in general, consistent with results of other filtration. The results shown in this paper were found to be stable to different smoothing intervals: the amplitude of the QBO was observed to change by an insignificant amount.

An interest in quasi-biennial variations in solar activity was probably stimulated by the discovery in the 1960s of the so-called 26-month oscillations in the Earth's atmosphere (see Maeda 1967, and references therein). The atmospheric QBOs mainly have a terrestrial origin and although they are influenced by the 11-yr solar cycle (Baldwin et al. 2001; Petrick et al. 2012), seemingly not by the solar QBOs. Sakurai (1979) found a QBO in the solar neutrino flux as measured in the Homestake neutrino experiment (Bahcall and Davis 1976). Silverman and Shapiro (1983) discovered the "unexpected" 1.4 yr variations in the 1721–1943 data set of visual auroras. Akioka et al. (1987) reported on a 17-month periodicity in the number and area of sunspot groups. A rapid increase of investigations has followed.

The domain below 1 yr oscillations refers to the so called Rieger-type variations, which were discovered in the solar X-ray burst and flare occurrence that was observed by the SMM spacecraft in the early 1980s (Rieger et al. 1984). Specifically Rieger et al. observed a 154 d periodicity in the temporal distribution of flares. Usually, the <1 yr and >1 yr types of variations are considered in different works. Around 30 % of QBO papers published after 2000 were devoted to the Rieger-type oscillations, and 70 % to >1 yr variations. However, some researchers noticed their intrinsic resemblance (e.g. Boberg et al. 2002; Kudela et al. 2002, 2010; Singh and Gautam Badruddin 2012). Actually many features are similar, so here they are described without separation despite the fact that there is currently no agreement as to whether a physical connection between the Rieger-type variations and those with periods >1 yr exists (this is discussed further in Sects. 2.2 and 5).

2 The Ubiquity of the QBO

The QBO is visible in almost all measures of the Sun's magnetic field, from deep in the solar interior right out to the heliosphere, and there are numerous papers that consider the behavior of solar activity indices. Here we include merely a sample of these papers, the majority of which include substantial reference lists themselves. Table 1 presents a list of selected papers published since 2000 where the studied indices and periods of oscillations are given. From the Table the diversity of solar activity proxies and oscillation periods are apparent. The majority of works consider QBOs in the sunspot number and area as a common

Table 1 Selected papers related to QBO observations, published since 2000. SOL stand for various solar indices, IPL for solar wind and interplanetary magnetic field, GEO for geomagnetic indices, CR for galactic cosmic rays, and SEP for solar energetic particles

Author	Publication yr	Indices	Periods	Epoch of observation
Bazilevskaya et al.	2000	SOL	∼2 yr	cycles 21–22
Howe et al.	2000	SOL	1.3 yr	1995–1999
Mursula and Zieger	2000	GEO, IPL	1.3–1.7 yr	1932–1998, 1964–1998
Bazilevskaya et al.	2001	SEP	∼2 yr	1950–2000
Hill et al.	2001	CR	146–154 d	1998–1999
Lockwood	2001	SOL, GEO	1.3 yr	∼1980–1995
Obridko and Shelting	2001	SOL	∼2 yr	1915–1999
Rybák et al.	2001	SOL, CR	1.7–2.4 yr	1969–1998
Ivanov et al.	2002	SOL	∼2 yr	1920–1980
Boberg et al.	2002	SOL	$<$1 yr, $>$1 yr	cycles 21–24
Krainev et al.	2002	SOL, CR	∼2 yr	cycles 21–22
Krivova and Solanki	2002	SOL	154–158 d, 1.28 yr	1749–2001
Kudela et al.	2002	IPL, CR	150 d, 1.3 yr, 1.7 yr	cycles 20–22
Bai	2003	SOL	$<$1 yr	cycles 19–23
Benevolenskaya	2003	SOL	1–1.5 yr	cycles 21–23
Kato et al.	2003	CR	1.3–1.7 yr	cycles 21–22
Lou et al.	2003	SOL, CME	$<$1 yr	1999–2003
Mavromichalaki et al.	2003	SOL, CR	$<$1 yr	1981–1983
Mursula et al.	2003	IPL, GEO, CR	1.2–1.7 yr	cycles 9–22
Özgüç et al.	2003	SOL	150 d, 1.3 yr	1966–2001
Wang and Sheeley	2003	SOL	1–3 yr	1978–2002
Badalyan and Obridko	2004	SOL	1.5–3 yr	1943–2001
Ballester et al.	2004	SOL	160 d	cycles 21–23
Mursula and Vilppola	2004	IPL	1.3–1.7 yr	cycles 21–22
Shirai	2004	SOL	2.5 yr	1996–2001
Ataç et al.	2005	SOL	64 d, 125 d	cycle 23
Benevolenskaya	2005	SOL	1–1.5 yr	cycles 21–23
Cadavid et al.	2005	SOL, IPL, GEO	1–2.5 yr	1978–2003
Joshi and Joshi	2005	SOL	$<$1 yr	cycles 21–23
Kane	2005	SOL, CR	$<$1 yr, $>$1 yr	cycles 20–23
Knaack and Stenflo	2005	SOL	$<$1 yr, $>$1 yr	1966–2004
Moussas et al.	2005	SOL, GEO	$<$1 yr, $>$1 yr	
Richardson and Cane	2005	SOL, IPL, GEO, SEP	∼150 d	cycle 23
Bazilevskaya et al.	2006	SEP	∼2 yr	cycles 19–23
Chowdhury and Ray	2006	IPL, SEP	$<$1 yr, $>$1 yr	cycles 21–23
Forgács-Dajka and Borkovits	2007	SOL, IPL	1–4 yr	1975–2005
Obridko and Shelting	2007	SOL	1.3 yr	1915–1996
Badalyan et al.	2008	SOL	∼2 yr	1939–2001
Lara et al.	2008	SOL, CME	$<$1 yr	cycle 23
Ruzmaikin et al.	2008	SOL, IPL	1.3 yr	1976–2008

Table 1 (*Continued*)

Author	Publication yr	Indices	Periods	Epoch of observation
Valdés-Galicia and Velasco	2008	SOL, IPL, CR	1–2 yr	1940–2004
Vecchio and Carbone	2008	SOL	∼2 yr	1939–2006
Chowdhury et al.	2009	SEP	<1 yr, >1 yr	1986–2001
Chowdhury et al.	2009	SOL	<1 yr, >1 yr	cycles 22–23
Laurenza et al.	2009	SOL	<1 yr, >1 yr	1974–2001
Vecchio and Carbone	2009	SOL	1.5–4 yr	1939–2005
Fletcher et al.	2010	SOL	∼2 yr	cycles 22–23
Kudela et al.	2010	SOL, IPL, GEO, CR	26–32 d, 150 d, 1.7 yr	1958–2008
Vecchio et al.	2010	SOL, SEP, CR	∼2 yr	1974–2001
Zaqarashvili et al.	2010	SOL	155–160 d	cycle 21
Badalyan and Obridko	2011	SOL	∼2 yr	1874–2009
Okhlopkov	2011	SOL, IPL, CR	∼1-2 yr	1965–2007
Katsavrias et al.	2012	IPL, GEO	20 d,-4 yr	1966–2010
Laurenza et al.	2012	IPL, CR	∼2 yr	1964–2004
Simoniello et al.	2012	SOL	∼2 yr	cycle 23
Singh and Gautam Badruddin	2012	IPL, CR	9–260 d, 1.3 yr	cycle 23
Vecchio et al.	2012	CR	∼2 yr, ∼6 yr	1953–2004
Vecchio et al.	2012	SOL	<1 yr, >1 yr	1976–2003
Chowdhury et al.	2013	SOL	<1 yr, 1.4 yr, 2.1 yr	cycles 23–24
Choudhary et al.	2014	SOL	<1 yr, >1 yr	2004–2008
Cho et al.	2014	SOL, IPL, GEO	1.3 yr	1970–2007
Choudhary et al.	2014	SOL	155 d	1996–2011
Gyenge et al.	2014	SOL	1.3 yr	cycles 21–23

index alongside other solar proxies. The multi-peaked highly-variable structure of sunspot area values, which are especially pronounced around the maximum phases of the 11-yr cycle, is clearly seen in Fig. 1. This behaviour appears to be a common feature of activity at different levels of the Sun (see Sect. 3).

2.1 Different Solar Activity Proxies in Which the QBO is Observed

2.1.1 Measures of the Solar Interior

Shirai (2004), Vecchio et al. (2010), D'Alessi et al. (2013) resumed an interest in possible QBOs in the solar neutrino flux. Vecchio et al. (2010) used empirical mode decomposition techniques to show that the QBO observed in the solar neutrino flux is strongly correlated with the QBO present in galactic cosmic ray data, believed to be caused by the Sun's magnetic field. This implies that the solar magnetic field plays a crucial role in the modulation of the neutrino flux. This raises certain questions over the origin of the interaction between the Sun's magnetic field and solar neutrinos. For example, Vecchio et al. (2010) speculate that such a modulation in the neutrino flux could occur through coupling between the neutrinos magnetic moment and the Sun's magnetic field or because of a modulation in the neutrino

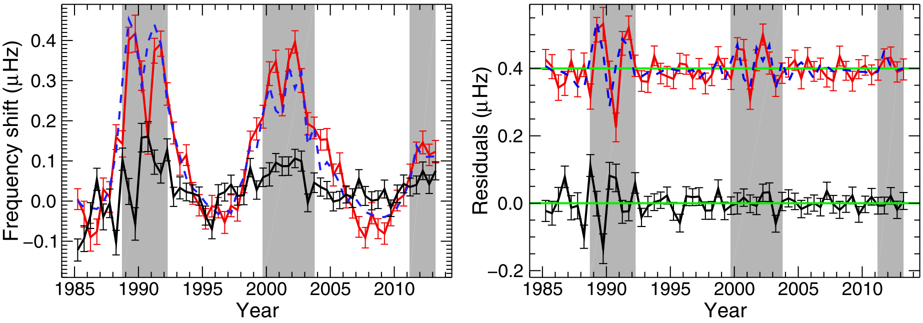

Fig. 4 *Left*: average frequency shifts of "Sun-as-a-star" modes with frequencies between 1.90 and 2.70 mHz (low-frequency range, *black*) and 2.70 and 3.55 mHz (high-frequency range, *red*). The frequency shifts were obtained from 182.5 d non-overlapping Birmingham Solar Oscillations Network (BiSON) data. This length of time series was used as it represents a compromise between having enough resolution to detect the QBO but still obtaining a good enough signal-to-noise ratio in the power spectra to obtain the p-mode frequencies. For comparison a scaled version of sunspot area has been plotted (*blue dashed line*). The daily sunspot area data were rebinned to 182.5 d to match the helioseismic observations and then linearly scaled and offset to match the high-frequency range shifts. *Right*: residuals left after dominant 11-yr signal has been removed by subtracting the frequency shifts once they have been smoothed over 2.5 yr. The colours are the same as in the *right-hand panel*. The high-frequency-range residuals have been artificially offset by 0.4 μHz for clarity (the zero lines for the residuals are indicated by the *green dot-dashed line*). The *grey shading* indicates times of high surface activity, by which we mean the sunspot area is above halfway between the minimum and maximum values. This was determined separately for each cycle

production rate. If the latter is true not only may this provide evidence for the presence of a magnetic field in the radiative zone but this may also be a hint that the magnetic field deep in the solar radiative region may exhibit quasi-biennial oscillations. D'Alessi et al. (2013) postulate that the neutrino flux QBO may be due to variations in the production rate caused by the magnetic modulation of gravity (g) waves, which are, in theory, trapped in the radiative zone. Such a modulation would change the density profile of the radiative zone, thereby altering the neutrino production rate. To date no definitive detection of individual g modes has been made (see Appourchaux et al. 2010, for a review) and so to date this theory cannot be tested. Gravity waves may also provide a link between the production rate of the solar magnetic field and neutrinos simultaneously (see Sect. 5 for further discussion).

Further evidence for the presence of QBOs in the solar interior can be found through helioseismology, which uses the Sun's natural acoustic oscillations (p modes) to study the solar interior (Christensen-Dalsgaard 2002). It is well known that the properties of p modes vary throughout the 11-yr solar activity cycle, with, for example, the frequencies of the oscillations being at their largest at solar maximum (e.g. Woodard and Noyes 1985; Pallé et al. 1989; Elsworth et al. 1990; Libbrecht and Woodard 1990; Chaplin et al. 2007; Jiménez-Reyes et al. 2007). The left-hand panel of Fig. 4 shows the frequency shifts of global p modes. The 11-yr cycle is seen clearly in the p-mode frequencies and shorter-term variations, with a period of approximately 2 yrs, are visible on top of the general 11-yr trend (Broomhall et al. 2009, 2011, 2012; Fletcher et al. 2010; Simoniello et al. 2012a,b, 2013).

In order to extract signals in the vicinity of the QBO we subtracted a smooth trend from the average total shifts by applying a boxcar filter of width 2.5 yrs. This removed the dominant 11-yr signal of the solar cycle. Note that, although the width of this boxcar is only slightly larger than the periodicity we are examining here, wider filters produce similar results. The resulting residuals, which can be seen in the right-hand panel of Fig. 4, show a periodicity on a timescale of about 2 yrs. The QBO has been observed in a number of different helioseismic data sets (Fletcher et al. 2010; Broomhall et al. 2011; Simoniello et al. 2012a). Furthermore the quasi-biennial signals present in the different helioseismic data are well correlated (Broomhall et al. 2011), implying they are not instrument artifacts. The correlation between the helioseismic residuals and those obtained from the sunspot area data is $R = 0.93$, which is significant at less than a 1 % level (we note that the Spearman correlation coefficient is also significant at less than a 1 % level).

For the 11-yr cycle a strong frequency dependence in the magnitude of the change in mode frequency is observed. This indicates that the variation in mode frequency must be the result of changes in the acoustic properties of the region just beneath the visible surface of the Sun (e.g. Libbrecht and Woodard 1990). There are some indications that the QBO shows a weaker frequency dependence than the 11-yr signal, implying that the changes responsible for the QBO are positioned deeper within the solar interior than those responsible for the 11-yr signal (Broomhall et al. 2012; Simoniello et al. 2012a). However, it is very difficult to disentangle the frequency dependence of the QBO from the dominant presence of the 11-yr cycle making any such inferences somewhat tenuous.

Howe et al. (2000) observed variations in the rotation profile of the Sun at a radius of $0.72 R_{\odot}$, most predominately at low latitudes, with a period of 1.3 yr. However, other authors did not observe the same signal (e.g. Antia and Basu 2000). A more recent analysis (Howe et al. 2011) demonstrated that the signal was intermittent and has not been observed since 2001. However, Howe et al. found that when present the 1.3 yr signal was highly correlated in data recorded by two independent observation programs, implying that it is solar in origin. Jiménez-Reyes et al. (2003) observed a 1.3 yr modulation in the p-mode energy supply rate. Broomhall et al. (2011) observed an excess of power at $\sim$1.3 yr in periodograms of the low-l p-mode frequency shifts. This excess of power was found to be significant at more than a 2 per cent level and was observed in data from independent observational programs, implying that is it solar in origin.

2.1.2 *Measures of the Photosphere, Chromosphere and Corona*

Perhaps the most obvious manifestation of photospheric solar activity is sunspots. It is widely accepted that the QBO can be observed in sunspot number and sunspot area (see Figs. 1, 2, and 3). Wang and Sheeley (2003) also found periodicities in sunspot area in the range 0.2 to 2.6 yrs, with no single periodicity dominating. Furthermore, Wang and Sheeley reported periodicities in the range 1 to 3 yrs in photospheric measures of the equatorial dipole component.

1–2 yr patterns were discovered in the behavior of the solar magnetic field (Hoeksema 1991; Benevolenskaya 1995), while, in the last decade, periodicities of around 1.3, 1.7 and 2–4 yrs were observed in the temporal evolution of the large-scale solar photospheric magnetic field (e.g. Boberg et al. 2002; Cadavid et al. 2005; Kane 2005b; Knaack and Stenflo 2005; Knaack et al. 2005; Laurenza et al. 2009; Vecchio et al. 2012a, etc). Furthermore, consistent results were obtained by analyzing the magnetic fields inferred from the H-alpha filament observations since 1915 (Obridko and Shelting 2001, 2007; Ivanov et al. 2002). Danilovic et al. (2005) observed quasi-biennial periodicities in the equivalent width and central depth data of the Mn 539.4 nm solar spectral line, which is photospheric in origin. Kane (2005b) found evidence for numerous QBO and Reiger-type periodicities in a number proxies of the solar magnetic field (see Sect. 2.1.3), including the sunspot number and the CaII plage area and CaII K index, which originate in the chromosphere. Özgüç et al. (2003) studied the flare index observed between 1966 and 2001 and found periodicitites of 150 d and 1.3 yr and Ataç et al. (2005) found periodicites of 64 d and 125 d in the flare index observed during cycle 23.

Badalyan and Obridko (2004) found the 1.3 yr periodicity in the correlation of the green-line intensity and magnetic field in the lower corona, while Vecchio and Carbone (2009) revealed QBOs in the green coronal line emission whose period varied with time in the range of 1.5–4 yrs.

2.1.3 Comparisons Between Proxies

Many authors considered several solar indices jointly to detect QBOs in their behavior: for example Kane (2005b, sunspot number, CaII area and K index, Lyman α, 10.7 cm flux, coronal green line, open fluxes, interplanetary magnetic field, and cosmic rays), Valdés-Galicia and Velasco (2008, coronal hole area, radio emission in the 10.7 cm band, and sunspots), Choudhary et al. (2014, sunspot area, solar flares, and coronal mass ejections). Moreover, it has been shown (Mursula and Vilppola 2004; Knaack and Stenflo 2005; Knaack et al. 2005) that oscillations with period of around 1.3 yr are a single process which manifests itself at all levels from the tachocline and photosphere (e.g., areas and numbers of sunspots, large-scale magnetic fields) up to the Earth's magnetosphere (geomagnetic activity) and the far heliosphere (cosmic rays).

The QBOs in various solar indices (sunspot number and area, 10.7 cm radio emission, mean solar magnetic field, coronal green line, H-alpha flare number) isolated with a pass-band filter behave rather similarly. The QBOs in the sunspot area alongside the 10.7 cm radio emission[2] are plotted in the upper panel of Fig. 5 where excellent agreement is apparent: the correlation coefficient $R = 0.884$. The lower panel manifests the QBOs in the sunspot area alongside the 530.3 nm coronal line emission.[3] Here, correlation is worse ($R = 0.495$), but still the QBOs are reasonably coherent. It is worth noting that the data depicted in Fig. 5 resembles that of the QBOs in the radial solar magnetic field at the heliolatitude of 25° from Vecchio et al. (2012a) as shown in the upper panel of their Fig. 7.

2.1.4 The QBO Transition into the Interplanetary Space

Papers devoted to QBOs in interplanetary parameters are mostly directed towards finding a cause-and-effect relationship between solar and interplanetary/terrestrial phenomena. Therefore they usually consider interplanetary parameters such as heliospheric magnetic field strength, solar wind speed, geomagnetic indices and galactic cosmic ray modulation in correspondence to solar parameters such as sunspot number or area, solar magnetic field, flare index, and coronal activity (e.g. Bazilevskaya et al. 2000; Rybák et al. 2001; Krainev et al. 2002; Mursula et al. 2003; Wang and Sheeley 2003; Moussas et al. 2005; Richardson and Cane 2005; Forgács-Dajka and Borkovits 2007; Katsavrias et al. 2012; Singh and Gautam Badruddin 2012; Laurenza et al. 2012). Vecchio et al. (2012b) used the EMD analysis to uncover a wide range oscillations in the galactic cosmic ray intensity. They showed that the QBOs are actually responsible for the Gnevyshev Gap phenomenon (see Sect. 4) and the step-like decreases typical for the galactic cosmic ray modulation.

Bazilevskaya et al. (2001, 2006) explored the occurrence of solar-energetic-particle (SEP) events observed between 1955–2004, using ground-based and spacecraft observations. SEPs are high energy particles (ranging from a few 10s of keV to GeV) that are accelerated away from the Sun by solar flares or coronal mass ejections (CMEs). Bazilevskaya

---

[2] http://www.ngdc.noaa.gov/stp/solar/flux.html.

[3] ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_CORONA/INDEX/Lomnicky/.

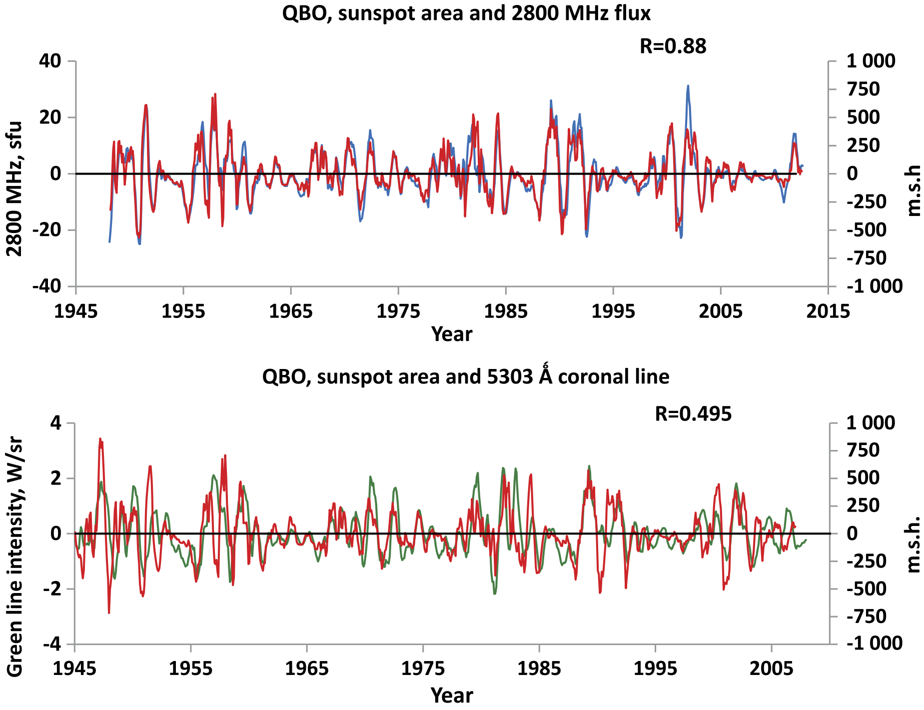

Fig. 5 The QBOs as isolated from the sunspot area (*red curve*) compared with the 2800 MHz (10.7 cm) radio emission (*upper panel*, *blue curve*) and with the 530.3 nm *coronal line* (*lower panel*, *green curve*)

et al. (2001, 2006) concluded that the QBOs in the total number of SEP events are fairly similar to the QBOs in other solar indices, especially in the strong X-ray bursts. Bazilevskaya et al. (2001, 2006) also considered the occurrence of the powerful ground level enhancements (GLEs): a GLE is recorded when SEPs are accelerated to high enough energies to enhance the count rate of ground-based neutron monitors, which requires energies above several GeV to avoid being absorbed by Earth's atmosphere. Bazilevskaya et al. (2001, 2006) found that GLEs sometimes occurred during zero and even negative phases of the solar QBOs. Evidence of QBOs in the occurrence rates of coronal mass ejections, SEP events and geomagnetic storms with sudden commencements during solar cycle 23 were found by Richardson and Cane (2005). Laurenza et al. (2009) studied the QBOs in the interplanetary proton fluxes registered onboard the IMP 8 spacecraft between 1974–2001 and found periodicities of 3.8 and 1.7–2 yrs.

It is interesting that QBOs can be observed rather far from the Sun but still within the heliosphere. Kato et al. (2003) found 1.7- and 1.3-yr oscillations in the galactic cosmic ray intensity variation in the outer heliosphere during the 1980s (solar cycle 21) and the 1990s (solar cycle 22) in agreement with similar variations observed at neutron monitors.

The observational features of the QBOs seen in interplanetary space are similar to solar QBOs: They are characterized by intermittence in periodicity and an amplitude that varies with time and is largest around times of solar activity maxima. Furthermore, there are often epochs where no QBOs at all are detected (they are temporally intermittent). However, there is rather poor correspondence between the time series of the solar and interplanetary QBOs (Rybák et al. 2001; Cho et al. 2014). Transition from the solar to interplanetary QBOs refers

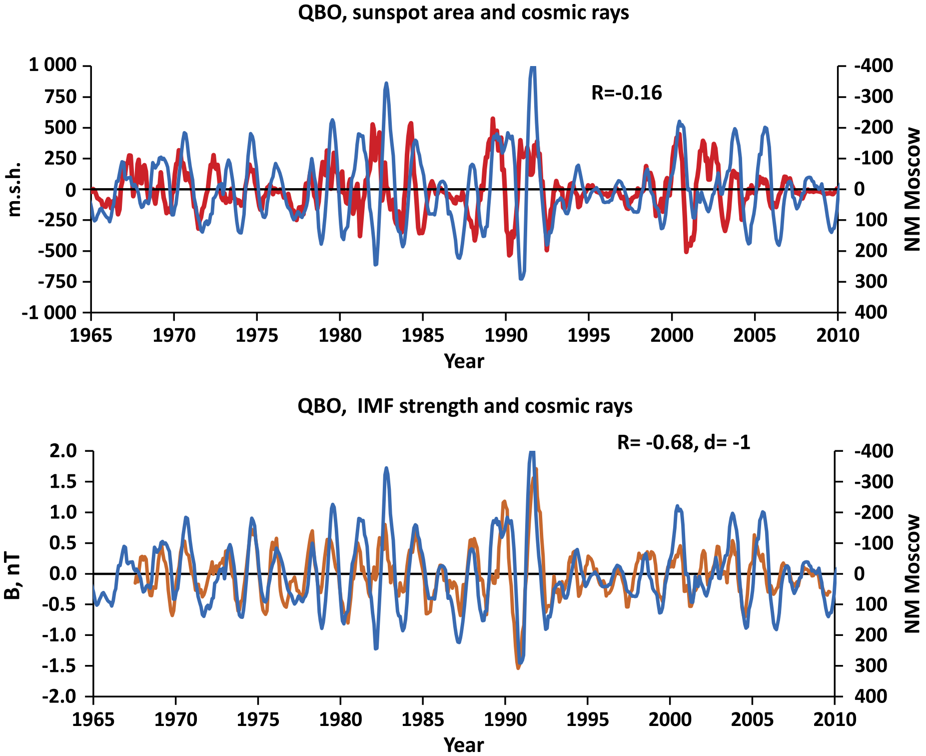

Fig. 6 *Upper panel*: QBOs in the sunspot area (*red curve*) and galactic cosmic ray intensity (*blue curve*, Moscow neutron monitor). *Lower panel*: QBOs in the interplanetary magnetic field strength (*orange curve*) and galactic cosmic ray intensity (*blue curve*). Note the reverse scaling on the *right vertical* (cosmic ray) axis

to the fundamental problem of interactions of stars with convective outer layers and their respective stellar spheres (see review by Zurbuchen 2007). Although much of the magnetic energy is stored in closed magnetic structures on the Sun part of the solar magnetic field is pulled into the heliosphere owing to the high coronal temperature. This portion of the solar magnetic field is commonly referred to as open magnetic flux. The solar QBOs can be transmitted into interplanetary space through the open magnetic flux (Lockwood 2001). As it is shown by Wang et al. (2002) the strength of the radial heliospheric field (HMF) is proportional to the total open flux. The QBOs in the galactic cosmic ray intensity are not coherent with the QBOs in the sunspot area and other solar indices, while they correspond well with the QBOs in the heliospheric magnetic field strength[4] as is shown in Fig. 6. The correlation coefficient between the curves depicted in the upper panel of Fig. 6 is $R = -0.16$, and in the lower panel of Fig. 6 is $R = -0.68$ with galactic cosmic rays delayed relative to heliospheric magnetic field by 1 month. A correlation coefficient of $R = -0.65$ and a delay of 2 months is observed if the radial component of HMF is considered. The Moscow neutron monitor data[5] are presented in Fig. 6, but the result is similar for other stations of galactic cosmic ray monitoring. The QBOs in geomagnetic activity do not correlate with

---

[4] ftp://spdf.gsfc.nasa.gov/pub/data/.

[5] helios.izmiran.rssi.ru/cosray/.

the solar QBOs but are coherent with the QBOs in the product of solar wind velocity, V, and the heliospheric magnetic field strength, B. The geomagnetic Dst index characterizes geomagnetic storms. The correlation coefficient between the QBOs in the geomagnetic Dst index[6] and in sunspot area during 1967–2009 is $R = -0.2$, while a correlation coefficient of $R = -0.82$ is observed between QBOs in Dst and VB. The apparent lack of correlation between solar and heliospheric QBOs is an obvious challenge for theorists.

2.2 Reiger-Type Oscillations

The Rieger-type ($T < 1$ yr) oscillations are also observable in many solar indices, such as sunspot number and area, photospheric magnetic field, optic and X-ray flares (e.g. Boberg et al. 2002; Krivova and Solanki 2002; Ballester et al. 2004; Chowdhury and Ray 2006; Chowdhury et al. 2009a). In the galactic cosmic ray intensity the oscillations with $T \sim 150$ d have been reported by Mavromichalaki et al. (2003), Kudela et al. (2010), Laurenza et al. (2012). Rieger-type QBOs in the CME rate were found by Lou et al. (2003), Lara et al. (2008). While Chowdhury and Ray (2006), Chowdhury et al. (2009a) found a variety of QBOs including the Rieger-type periodicities in the solar electron fluxes observed by IMP 8. Hill et al. (2001), using Voyager 1 data at 73AU, have shown that the quasi-periodic variations in anomalous cosmic rays are in phase, with the QBOs in O and He observations having periods of approximately 151 d, while protons exhibit a period of approximately 146 d. However, we note that these periodicities are within 1σ of each other ($\sigma = 12$ d for O and 15 d for He and protons).

Reiger-type oscillations are often revealed as a well-defined periodicity, e.g., 154 d (Rieger et al. 1984), 34, 51, 85, 129, 135 d (Bai 2003). However, sometimes they are reported as a range of days, such as 64–125 d, 150–160 d (Zaqarashvili et al. 2010a) or even as a signal with multiple periodicities (Lou 2000; Joshi and Joshi 2005; Chowdhury et al. 2009b). Some authors consider <1 yr and >1 yr jointly, however, suggest a different origin: Boberg et al. (2002) propose that the 1–2 yr periodicity observed in solar mean magnetic field measurements are related to the internal rotation rate of the Sun, while the 80–200 d periodicities are connected to the evolution of large active regions. Vecchio et al. (2012a) explain the QBO as an integral part of the Sun's dynamo but associate the shorter Reiger-type periodicities with the outbreak of bipolar regions on the solar surface. Often a more generic link is proposed, for example, Krivova and Solanki (2002) propose that the 154–158 d Reiger periodicity is a harmonic of the 1.3 yr QBO. More details on the possible causes of both QBOs and Reiger-type periodicities are discussed in Sect. 5 and a comprehensive overview of the Rieger-type periodicities is given by Bai (2003).

3 Main Features of the QBO

3.1 Multipeaked and Variable Periodicity

Many studies have shown that when proxies of the Sun's magnetic field are plotted as a function of time multiple peaks are observed around solar maximum (as can be seen in Figs. 1 and 4 of this paper). This is somewhat analogous to the features in the spectra of 3-min sunspot oscillations, where multiple peaks are also observed (e.g. Reznikova et al.

---

[6] http://wdc.kugi.kyoto-u.ac.jp/dstae/index.html.

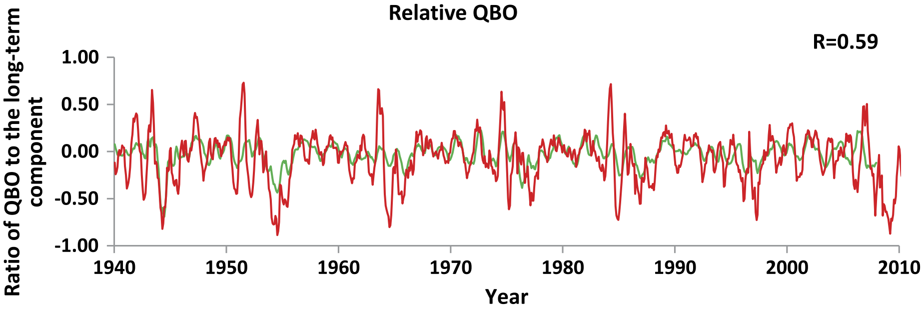

Fig. 7 Relative QBO of sunspot area (*red*) and 530.3 nm *green coronal emission line* (*green*). The relative QBOs were obtained by determining the ratio of the QBO time series, which are plotted together in the *bottom panel* of Figure 5 to the 25-month smoothed value of solar activity indices (which are plotted for sunspot area in Figure 1)

2012). Furthermore, studies of the QBO frequently uncover multiple periods in the data, many of which appear to vary with time. For example, a multi-peaked structure in the solar, interplanetary and galactic cosmic ray time sets was observed by Kudela et al. (2002), Mavromichalaki et al. (2003), Wang and Sheeley (2003), Kudela et al. (2010). Some papers isolate and study definite period values (most often attention is attracted by the $T = 1.3$ yr period), however inspection of a bulk of works instead reveals sets of distinct pulses while time series with a definite period occupy only limited epochs. Mursula et al. (2003) uncovered an alternation in the dominant periods of the QBO observed in geomagnetic activity during the last 15 solar cycles. These results were corroborated by Katsavrias et al. (2012), who analysed solar wind and interplanetary magnetic field parameters. Several authors have stressed that the QBO appeared as “a stochastic superposition of different oscillators” (Vecchio and Carbone 2009), “highly intermittent in time” (Ataç et al. 2005), having “elusive and enigmatic character” (Zaqarashvili et al. 2010a). The signature of stochasticity can be seen in Figs. 2b and 3 where no distinct period is observed.

3.2 Temporal Modulation of the Amplitude of the QBO with 11 yr Cycle

Most of the above mentioned researchers (e.g. Bazilevskaya et al. 2000; Benevolenskaya 2003; Ballester et al. 2004; Kane 2005b; Fletcher et al. 2010; Zaqarashvili et al. 2010b; Singh and Gautam Badruddin 2012; Vecchio et al. 2012a, and many others) noticed that QBOs are modulated by the 11-yr cycle, being strongest around maxima of solar activity. This pattern can also be clearly seen in Figs. 1, 4, 5, and 6. It is therefore interesting to consider the existence of QBOs during solar minima. There is evidence that the QBO is still present in the helioseismic p-mode frequency shifts away from solar maxima (see Fig. 4 and Broomhall et al. 2009, 2011, 2012; Fletcher et al. 2010; Jain et al. 2011), implying that the QBO is still present in the solar interior even at times where activity is at a minimum. Figure 7 demonstrates the relative QBO, which is determined in the following manner. First we must define the QBO time series for a given proxy, which is obtained by subtracting a smoothed component, that primarily shows the 11 yr cycle, from data averaged over a shorter length of time. For example, here we have subtracted the 25-month smoothed values from the 7-month smoothed values (see Figs. 1, 5, and 6). The relative QBO is then the ratio of the QBO timeseries to the 25-month smoothed time series (which is plotted for sunspot area in Fig. 1) i.e. a ratio of the QBO to the smoothed component of the 11-yr cycle (Bazilevskaya et al. 2000). It can be seen that the QBOs are present during epochs of low solar activity. Furthermore the relative QBOs have the highest amplitudes just in the minima of solar activity. A correlation between the relative QBOs of the 530.3 nm line and the sunspot area is even higher ($R = 0.59$) than between absolute QBOs, which were produced by subtracting the 25-month smoothed values from the 7-month smoothed values and are presented in Fig. 6 ($R = 0.49$).

Of special interest are possible changes in the QBOs over relatively long periods of time and the dependence of QBO features on the characteristics of the 11-yr cycle. The long-term changes in the geomagnetic aa-index QBO power were stated by Mursula et al. (2003) and Mursula and Vilppola (2004): periods where the QBOs were strong were found in the mid-19th century and since 1930, while QBOs were weak during low solar activity from the 1860s to the 1920s; the geomagnetic 1.3–1.4 yr pulsations were found to be more pronounced in the even cycles (18, 20 and 22) while the 1.5 and 1.7 yr QBOs, in the odd cycles. Similar conclusions about dependence on alternate cycles were drawn by Kudela et al. (2002) in an analysis of galactic cosmic ray intensity and by Knaack and Stenflo (2005) in an analysis of the magnetic QBOs.

3.3 Temporal Variation in the Periodicity of the QBOs and a Possible Connection with the 11-yr Cycle

In the previous section we discussed the temporal variation of the amplitude of the QBO and its relation to the 11-yr solar cycle. We now move on to consider the frequency/period modulation of the QBO. For example, Bai (2003) explored the solar flare occurrence rate and found a periodicity of 51 d for cycles 19, 85 and 129 d for cycle 20, 153 d for cycle 21, and 34 and 129 d for cycle 23. No statistically significant periodicities were found for cycle 22.

Khramova et al. (2002), argued that the QBO characteristics depend on the power and length of a particular 11-yr cycle. Okhlopkov (2011) studied QBOs (20–24 months) in galactic cosmic rays, solar mean magnetic field, interplanetary parameters and geomagnetic Ap index during solar activity cycles 20–23. He showed that the average QBO period was 20.2–20.8 months in the odd cycles and 22–23.5 months in the even cycles. This was in agreement with the results of Kudela et al. (2002). However, Obridko and Shelting (2007) did not find a distinct correlation between the QBOs (1.3 yrs) in solar magnetic field and the parity of the cycle number. Nor did they find any correlation with the height of the solar maxima.

3.4 Spatial Distribution of QBO

While the QBOs in different layers of the solar atmosphere are rather synchronous the QBOs in the northern and southern hemispheres do not correlate with each other. The correlation coefficient between the QBOs observed in sunspot area of the north and south hemispheres calculated on the base of 1875–2012 is $R = 0.001$, while $R = 0.53$ for the monthly meaned data and $R = 0.87$ for the 25-month smoothed means.

The north-south (NS) asymmetry in QBOs has been extensively studied (Badalyan and Obridko 2004, 2011; Knaack et al. 2004; Ataç et al. 2005; Forgács-Dajka and Borkovits 2007; Badalyan et al. 2008; Zharkov et al. 2008). It appeared that QBOs in the asymmetry of various solar activity indices are even more pronounced and better synchronized than QBOs in the indices themselves. In addition, the QBO power and absolute value of asymmetry are negatively correlated (Badalyan et al. 2008; Badalyan and Obridko 2011). Badalyan and Obridko (2011) studyed the NS asymmetry and suggested that to a great extent solar activity may be generated independently in the two hemispheres. Furthermore these findings argue that the NS asymmetry is a fundamental characteristic of solar activity.

Cadavid et al. (2005), using longitudinally averaged fields from NSO/KPNO synoptic Carrington rotation maps, noticed that the spatial distribution of QBO periods throughout the solar surface was not uniform: oscillation periods of the order of 1.0–1.5 yrs were more typical of the polar and high-latitude fields and periods of 1.3 and 1.7 yrs characterized the mid- and low-latitudes. Though the further analysis of Ruzmaikin et al. (2008) supported the latitudinal distribution of the pattern, the authors stressed its variable frequency and intermittent appearance. This is consistent with the results of Howe et al. (2000) who not only observed a 1.3yr periodicity in helioseismic data at low latitudes but also observed the 1.3 yr periodicity to disappear in 2001.

A comprehensive analysis of the spatial-temporal dynamics of the solar magnetic field in the period of August 1976–September 2003 was made by Vecchio et al. (2012a), using an EMD technique. The QBOs were found to be uniformly distributed over all latitudes with high amplitudes during the maximum and descending phase of each solar cycle. Antisymmetric behavior of the radial, meridional and east-west components of the solar magnetic field with respect to the equator was pointed out. The QBOs revealed in the radial and meridional components of the photospheric magnetic field were shown to be fundamental timescales and were associated with the poleward magnetic flux migration from low latitudes around the maximum and descending phase of the solar cycle (see also Benevolenskaya 2003, 2005). The signs of an equatorward drift, at an $\sim$2 yr rate were found in the radial and east-west components, suggesting a link to a dynamo operation. The Rieger-type oscillations demonstrated the butterfly diagram, reflecting the emergence of active regions on the solar surface at these timescales.

3.5 Summary of the QBO Observable Features

The QBOs appear to be the most prevalent quasi periodicity shorter than the 11-yr cycle in solar activity phenomena. Their amplitudes are higher during periods of high solar activity, however they do not disappear in the solar minima. The QBOs are highly irregular resembling a set of intermittent pulses/waves with signatures of stochasticity. The oscillations in the northern and southern solar hemispheres develop independently. The oscillations in various indices of solar activity related to different levels of the solar atmosphere are rather coherent. However, the solar QBOs are translated into the heliosphere through the open magnetic flux and therefore the QBOs in the solar and interplanetary parameters are not synchronous.

4 Gnevyshev Gap

4.1 Gnevyshev Gap as an Appearance of the QBO

During the last decade, many authors (e.g. Bazilevskaya et al. 2000, 2006; Astafyeva and Bazilevskaya 2000; Benevolenskaya 2003, 2005; Storini et al. 2003; Storini and Laurenza 2003; Sello 2003; Wang 2004; Knaack and Stenflo 2005; Knaack et al. 2005; Ataç et al. 2005; Kane 2006; Hathaway 2010; Vecchio et al. 2010, 2012a,b; Laurenza et al. 2012), have argued that one of the main features of the QBO is a temporal weakening of solar activity observed in the maximum phase of an 11-yr solar cycle (the so-called Gnevyshev Gap). However, since the Gnevyshev gap was first examined in the 1960s, this phenomenon has been studied separately from the QBOs and even now it is not absolutely clear if it can be totally reduced to the QBOs.

It was M.N. Gnevyshev, a Pulkovo astronomer, who first drew attention to this phenomenon by demonstrating the effect using observational data on the coronal green line during the 19th solar activity cycle (Gnevyshev 1967, 1977). Gnevyshev considered coronal activity at various heliolatitudes and concluded that there were actually two activity waves: a first one with a maximum at the end of the rising phase and a second one at the start of the declining phase of a solar cycle. Gnevyshev found similar behavior in many parameters of solar activity (sunspots, flares, UV, radio, corpuscular emissions, and geophysical data). Summarized over heliolatitudes the maximum of the 11-yr solar cycle looked like a double-peak structure.

The name "Gnevyshev Gap" was used for the first time by Schove (1979), who traced the double-peak structures in the aurorae occurrence. However, it was only after a comprehensive work by Feminella and Storini (1997), that the reinvented term was accepted by the scientific community and became conventional. Feminella and Storini (1997) have examined the Gnevyshev Gap (GG) extensively using the recent data on spots, flares, radio, and X-ray fluxes. They confirmed Gnevyshev's findings that the structured activity maxima were detected in all solar atmospheric levels and were more distinct in strong and/or long-lasting events. However, they stressed that the temporal structures are different in the north and south hemispheres and more than two peaks of activity occurred rather often. In addition they found that GGs were even more clearly seen when the variability of solar indices, such as the standard deviation, was examined.

Heliospheric GG effects deserve to be given special importance because of their clear appearance just around the maximum phase of solar activity that could be fruitfully used for the space weather investigation and even forecast. A coherent picture of the GG appearance in the space weather was given by Storini et al. (2003) with a great number of references.

A characteristic time scale of the GG is about 2 yrs, and it can be, at least formally, considered as the appearance of QBOs. Figure 8 demonstrates, as an example, the relation between the GG and QBOs in the sunspot area index taken separately from the northern and southern solar hemispheres. The upper panels show the monthly averaged values of the sunspot area. There are several local minima around the maximum phase of the solar cycle which are emphasized by the 7-month smoothing. The most prominent ones are marked by vertical bars in the middle panel and are actually the GGs. The 25-month smoothed data are also plotted in this panel, which accentuate the 11-yr component. The procedure of subtraction of the 25-month averages from the 7-month reveals the QBOs (similarly to Fig. 5), where in the bottom panel of Fig. 8 the GGs are again pointed out by the vertical bars. It is seen that the GGs are actually a consequence of the QBOs modulated by the 11-yr cycle.

4.2 Common Features of the QBO and GG

Main features of the GG are actually similar to those of the QBOs. Wide spreading of GG in the solar and interplanetary phenomena has been shown already by Gnevyshev (1967, 1977), Feminella and Storini (1997) and references therein. The latter authors demonstrated the independent appearance of GGs in the two solar hemispheres, which was corroborated by Bazilevskaya et al. (2000), Kane (2002), Sello (2003), Norton and Gallagher (2010).

The solar wind and interplanetary magnetic field data demonstrated GGs which were reflected by geomagnetic disturbances and the related modulation of galactic cosmic ray fluxes (Ahluwalia 2000; Krainev et al. 2002; Richardson et al. 2002; Storini and Laurenza 2003; Ahluwalia and Kamide 2005; Amenomori et al. 2006; Kane 2006; Belov 2009). Like

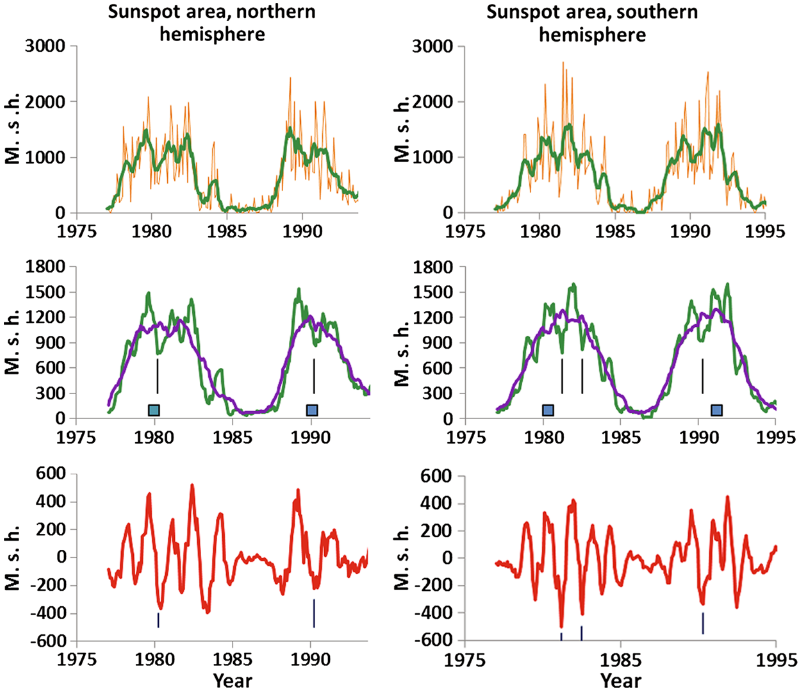

Fig. 8 *Upper panel*: monthly values of the sunspot area in the northern and southern solar hemispheres (*light brown*) and the 7-month smoothed values (*dark green*). *Middle panel*: 7-month and 25-month smoothed values; *vertical bars* indicate the GG occurrence; *squares* are times of solar polar magnetic field reversals (http://wso.stanford.edu). *Bottom panel*: QBOs resulted by subtraction of the 25-month smoothed data from the 7-month smoothed ones; *vertical bars* indicate the GG occurrence. Adopted with minor changes from Bazilevskaya et al. (2000)

the QBOs, the GGs in the solar indices do not always match with the interplanetary GGs (Kane 2005c, 2006).

Solar energetic particle (SEP) events are extremely difficult to analyze because their observable features accumulate numerous signatures of solar and interplanetary factors. The GG effects can shed additional light on the reason for SEP occurrence such as the relative role of solar flares and CMEs. The topic was discussed by many authors (e.g. Nagashima et al. 1991; Storini et al. 2005; Bazilevskaya et al. 2006; Miroshnichenko 2008). Rodríguez-Pacheco et al. (2012) observed the GG effect in fluxes of the energetic particles aboard Ulysses at high heliolatitudes.

Similar to the QBOs, GGs are rather intermittent. A double-peaked, three-peaked and sometimes single-peaked shape of the solar maxima may occur (Feminella and Storini 1997; Kane 2005c). Considering the sunspot area during 12 solar cycles Norton and Gallagher (2010) found GGs in 10 solar cycles in the northern solar hemisphere and in 8 cycles in the southern hemisphere. Wang (2004) assumed a connection between GGs and stochastic fluctuations.

4.3 Peculiar Features of the GG Phenomenon

A number of GG characteristics are either not inherent to QBOs or alternatively are not investigated by QBO researchers. Following Gnevyshev (1967, 1977) and Feminella and

Storini (1997) some authors found more distinct GGs in stronger or longer-lasting solar phenomena. Recently Kilcik et al. (2011) corroborated this result for solar cycles 22 and 23. Kilcik and Ozguc (2014) examined cycles 1–23 and suggested that a possible reason for a double maximum in solar cycles is the different behavior of large and small sunspot groups connected with two different dynamo mechanisms. Different properties of the first and second Gnevyshev peaks were reported also by Kane (2002) and Ahluwalia and Kamide (2005). The latter work emphasizes the difference in the interplanetary conditions during the first and the second Gnevyshev peaks. Lukianova and Mursula (2011) used the GG peaks as benchmarks of solar activity and showed that the reduction of sunspot magnetic fields started quite abruptly in 2001/2002, just during the secondary peak after the GG.

Since the GGs occur in the maximum phase of the 11-yr cycle they could be related to the solar polar magnetic field reversal, as was suggested by Nagashima et al. (1991). Although the majority of researchers support this idea careful consideration does not confirm a direct causal link (Kane 2006; Murakozy and Ludmany 2008). The middle panel of Fig. 8 demonstrates that no strict time coincidence is observed between the GGs and the magnetic polarity inversion periods. To date this issue has been insufficiently studied.

There are approaches to the GG understanding not involving the QBOs. Sykora (1980) and Antalova and Gnevyshev (1983) proposed that the GG effect can be explained in terms of solar activity pulses. This was further developed by Zolotova and Ponyavin (2012) who constructed simple models to reproduce the well-known butterfly diagrams, and various empirical laws to describe the distribution of sunspots, and demonstrated that activity pulses can satisfactorily reproduce the multi-peak structure of the solar cycle. Georgieva and Kirov (2007, 2011), Georgieva (2011) explain the two peaks of the GG by the development of two parts of the poloidal field, one being advected by the meridional circulation all the way to the poles and another one being diffused directly to the tachocline at midlatitudes. Both parts of the poloidal field generate the toroidal fields at the base of the convective zone. This suggestion needs further accumulation of observational data and model development.

Presently, the GG phenomenon is not fully understood. Further investigation should explain the GG peculiarities and its relation to the QBOs.

5 Physical Mechanisms that May be Responsible for the Observed QBOs

The QBO nature is not yet fully understood and a complete discussion of possible scenarios is beyond the scope of this paper. We now give details of a few of the most likely mechanisms that have been discussed in the literature. The majority of authors believe that QBOs are intrinsic to the solar dynamo mechanism (e.g. Benevolenskaya 1998; Howe et al. 2000; Krivova and Solanki 2002; Mursula et al. 2003; Mursula and Vilppola 2004; Cadavid et al. 2005; Knaack and Stenflo 2005; Forgács-Dajka and Borkovits 2007; Obridko and Shelting 2007; Ruzmaikin et al. 2008; Valdés-Galicia and Velasco 2008; Vecchio and Carbone 2009; Vecchio et al. 2010, 2012b; Zaqarashvili et al. 2010b; Katsavrias et al. 2012; Laurenza et al. 2012; Singh and Gautam Badruddin 2012; D'Alessi et al. 2013; Popova and Yukhina 2013; Cho et al. 2014, and others). An extended discussion on the QBO nature is given by Knaack and Stenflo (2005) and references therein.

In any discussion on the drivers of the QBO it should be remembered that the Sun is not the only star to exhibit more than one activity cycle. It is well known that many stars exhibit two distinct activity cycles, where the shorter cycle has a smaller amplitude and is regarded as secondary (e.g. Baliunas et al. 1995; Saar and Brandenburg 1999; Böhm-Vitense 2007; Oláh et al. 2009; Metcalfe et al. 2013). Böhm-Vitense (2007) suggest an explanation in terms of two dynamo actions, one fed by the near-surface differential rotation and another seated at the interface at the base of the convection zone.

A similar explanation has been proposed to explain the QBO in the Sun: two dynamos, one at the base of the convection zone and another seated near the bottom of the layer extending 5 % below the solar surface (∼35000 km). This region shows strong rotational shear, like the shear observed across the deeper-seated tachocline where the omega effect of the main dynamo is believed to operate (Corbard and Thompson 2002; Antia et al. 2008). The presence of two different types of dynamo operating at different depths was proposed by Benevolenskaya (1998) to explain the QBO observed in the surface magnetic field. However, this structure is also able to explain features observed in the helioseismic data, which are sensitive to the Sun's internal magnetic field: when the 11-yr cycle is in a strong phase, buoyant magnetic flux sent upward from the base of the envelope by the main dynamo could help to nudge flux processed by this second dynamo into layers that are shallow enough to imprint a detectible acoustic signature on the modes and be visible in surface measures of solar activity. When the main cycle is in a weak phase, the flux from the second dynamo would not receive an extra nudge, and would not be buoyant enough to be detected in surface proxies. However, the QBO magnetic field would still be able to influence the acoustic oscillations, although to a lesser extent. This would explain why the amplitude of the QBO signal is largest around times of solar maximum. Furthermore, there is a suggestion that the QBO is present in the p-mode frequencies away from solar maximum (Fig. 4 and Broomhall et al. 2009, 2011, 2012; Fletcher et al. 2010; Jain et al. 2011). This is understandable since p-mode frequencies respond to conditions beneath the surface where the short-term dynamo would be positioned away from solar maximum. If one could detect the QBO in both p modes and surface activity proxies away from solar maximum, one might, therefore, expect a phase shift between the helioseismic QBO and the surface QBO.

Wang and Sheeley (2003) simulated the Sun's equatorial dipole field strength and total open flux using a flux transport model and assuming that active regions emerge at randomly distributed longitudes. The size of the peaks in the time series simulated by Wang and Sheeley (2003) were primarily dependent on the longitudes of the emergence of active regions, while the periodicity was determined by the decay timescale of the equatorial dipole, which here they took to be about 1 yr based on measures of the meridional flow speed (Wang et al. 2002). Their simulations produce peaks similar to those associated with the QBO and suggest that the highest peak associated with the QBO is as likely to occur during the declining phase of the 11yr cycle as at the maximum in solar activity, which is in agreement with the helioseismic observations (see, for example, Fig. 4). The simulated data also show many other features observed in the real observations such as multipeaked maxima, and periodicities in the range 1–3 yrs, with no dominant periodicity in that range. Wang and Sheeley also note that if the meridional flow rate varies from cycle to cycle in the manner observed by Wang et al. (2002) the periodicities will also vary, again replicating a QBO feature of the real data. However, Knaack and Stenflo (2005) argued that they found certain regularities in the QBO features during odd and even solar cycles which would be unlikely if these periodicities were a random occurrence.

An alternative explanation is in terms of the instability of magnetic Rossby waves in the solar tachocline (e.g. Lou 2000; Knaack and Stenflo 2005; Chowdhury et al. 2009b; Zaqarashvili et al. 2010b, 2011). The period of the instability is dependent on the parameters used to describe the differential rotation and the strength of the magnetic field, which both vary through the solar cycle. Therefore the instability of magnetic Rossby waves can explain many of the observable features of the QBO, including intermittency and variable periodicity. Zaqarashvili et al. (2010b) claim that magnetic Rossby waves can also explain the N-S asymmetry. The same process can be used to explain Reiger-type periodicities: When the magnetic field is relatively weak ($<10^4$ G) the instabilities produce Reiger-type periodicites (Zaqarashvili et al. 2010a), while QBO periodicities are produced when the magnetic field is strong (10^5 G). We note that helioseismic estimates of the strength of the magnetic field at the base of the convection zone are of the order of 10^5 G (Chou and Serebryanskiy 2005; Serebryanskiy and Chou 2005; Baldner et al. 2009).

Another explanation with the potential to explain some of the observed results is spatiotemporal fragmentation. Covas et al. (2000a) produce a two-dimensional axisymmetric mean field dynamo model to show that for certain values of the magnetic Reynolds number spatiotemporal fragmentation occurs near the base of the convection zone that produces oscillations in the differential rotation. The mean field dynamo model used by Covas et al. extends the work of Covas et al. (2000b), who showed that this sort of dynamo model is able to produce torsional oscillation flows similar to those observed in helioseismology. Covas et al. believe that such processes may explain the results of Howe et al. (2000), who observed a 1.3 yr periodicity in the solar rotation profile at the base of the convection zone. Covas et al. also find that for high enough magnetic Reynolds numbers the temporal variations become non-periodic which may explain the intermittent behaviour of the observed 1.3 yr periodicity in the rotation profile (Howe et al. 2011). Spatiotemporal fragmentation would be able to produce the 1.3 yr periodicity because three 11 yr period halvings produces approximately 1.3 yr. We therefore note here that the observed 1.3 yr periodicity may simply be the 8th harmonic of the sunspot cycle (Krivova and Solanki 2002). Furthermore, Kane (2005b), who examined a wide range of solar activity indices, found that "every observed value fits some harmonic or other, and no harmonic is left out".

Ichimoto et al. (1985) suggested that the 155 d periodicity may be related to the timescale for storage and/or escape of magnetic fields in the convection zone. Ballester et al. (2002) suggest the link between Reiger-type periodicities observed in the number of high-energy flares and the photospheric magnetic flux may occur because when new sunspots emerge within already established sunspot groups the conditions for the production of high-energy flares are achieved. Since active regions may persist for up to 30 rotations Chowdhury et al. (2013) suggest that quasi-biennial periodicities may be related to the lifetime of complex active regions. However, the exact cause of the periodicities within the emergence of sunspots remains uncertain.

Simoniello et al. (2013) find that helioseismic results are consistent with the QBO being generated by the beating between dipole and quadropole magnetic configurations of a dynamo (Moss 1999, 2004; Fluri and Berdyugina 2004). It is possible that a nonaxisymmetric (quadropole-like) dynamo could exist alongside the dipole-like dynamo (Moss et al. 1995; Moss and Brooke 2000). It has been proposed that such a quadropole-like dynamo may explain the behaviour whereby active longitudes can suddenly shift by 180° (Tuominen et al. 2002; Berdyugina and Usoskin 2003; Moss 2004). The periodicity at which the active longitudes switch is expected to be the same as the axisymmetric dynamo (Berdyugina et al. 2002). Simoniello et al. (2013) find that major spot activity switches between active longitudes every 1.8–1.9 yr. Furthermore this formalism predicts that the amplitude of the secondary (quadropole) cycle is expected to be smaller than the primary (dipole) cycle, as is observed.

Finally we consider the analogies between the solar and terrestrial QBO. It is widely believed that the QBO observed in Earth's atmosphere is driven by the transport of angular momentum via the interaction between gravity waves, convection and shear (e.g. Baldwin et al. 2001, and references therein). Kumar et al. (1999) demonstrated that a similar transport of angular momentum by gravity-Alfvén waves beneath the base of the convection zone could produce a strong shear layer capable of generating a toroidal magnetic field. Thompson (2001) postulates that this behaviour could explain the helioseismic results observed by Howe et al. (2000). We recall that D'Alessi et al. (2013) suggested that gravity waves might be crucial to the QBO observed in the neutrino flux rate (see Sect. 2.1.1). Furthermore, this is not the first time gravity modes have been suggested to explain short-term variability in the Sun's magnetic field: Wolff (1983) suggested that the influence of gravity modes on the rotation profile of the solar interior may be responsible for Reiger-type periodicities.

The conclusions of different authors are contradictory (see Sect. 3.3). Some light may be shed by detailed study of the GG structures during each solar maximum. However, to date no single candidate stands out as the favoured explanation.

6 Conclusion

The quasi-biennial oscillations of solar origin have already been investigated over several decades. They are ubiquitous, but have some stochastic features, such as intermittency, and variable time-scales. Recent studies reveal a fundamental nature of the QBOs, their intrinsic connection to the dynamo mechanism. The solar QBOs are transferred into the interplanetary space and reflected in the solar wind, galactic cosmic ray modulation and geophysical disturbances. The QBOs are most prominent around the maxima of the 11-yr cycles, this being a reason for temporal lulls in solar activity, or the so called Gnevyshev gaps. Thus, the QBOs are important not only for fundamental physics, but also for the space weather problems. We have tried to demonstrate that our understanding of the nature of the QBO is now rapidly growing and promises new insights into the entity of solar activity.

Acknowledgements The paper was stimulated by the workshop "The solar activity cycle: physical causes and consequences". It is a pleasure to thank André Balogh, Hugh Hudson, Kristof Petrovay, Rudolf von Steiger and the International Space Science Institute for financial support, excellent organization and hospitality. We thank SIDC-team, World Data Center for the Sunspot Index, Royal Observatory of Belgium, Royal Observatory (Greenwich), Wilcox Solar Observatory, NOAA NGDC, GSFC, IZMIRAN Cosmic Ray group, WDC for Geomagnetism (Kyoto) providing their data in open access. We thank the Birmingham Solar Oscillations Network for making their data available to us. G.B. acknowledges support from the Russian Academy of Sciences. A.M.B thanks the Institute of Advanced Study, University of Warwick for their support. Y.E. acknowledges support from the UK Science and Technology Facilities Council (STFC). A.M.B. and Y.E. acknowledge the Leverhulme trust for funding "Probing the Sun: inside and out" project upon which this research is partly based. V.N.: This work was supported by the European Research Council under the SeismoSun Research Project No. 321141 and the BK21 plus program through the National Research Foundation funded by the Ministry of Education of Korea.

References

H.S. Ahluwalia, Ap time variations and interplanetary magnetic field intensity. J. Geophys. Res. **105**, 27481–27488 (2000). doi:10.1029/2000JA900124

H.S. Ahluwalia, Y. Kamide, Gnevyshev gap, Forbush decreases, ICMEs and solar wind electric field: relationships. Adv. Space Res. **35**, 2119–2123 (2005). doi:10.1016/j.asr.2004.11.030

M. Akioka, J. Kubota, K. Ichimoto, I. Tohmura, M. Suzuki, The 17-month periodicity of sunspot activity. Sol. Phys. **112**, 313–316 (1987). doi:10.1007/BF00148785

M. Amenomori, S. Ayabe, S.W. Cui, Danzengluobu, L.K. Ding, X.H. Ding, C.F. Feng, Z.Y. Feng, X.Y. Gao, Q.X. Geng, H.W. Guo, H.H. He, M. He, K. Hibino, N. Hotta, H. Hu, H.B. Hu, J. Huang, Q. Huang, M. Izumi, H.Y. Jia, F. Kajino, K. Kasahara, Y. Katayose, C. Kato, K. Kawata, Labaciren, G.M. Le, J.Y. Li, H. Lu, S.L. Lu, X.R. Meng, K. Mizutani, J. Mu, K. Munakata, A. Nagai, H. Nanjo, M. Nishizawa, M. Ohnishi, I. Ohta, H. Onuma, T. Ouchi, S. Ozawa, J.R. Ren, T. Saito, M. Sakata, T. Sasaki, M. Shibata, A. Shiomi, T. Shirai, H. Sugimoto, M. Takita, Y.H. Tan, N. Tateyama, S. Torii, H. Tsuchiya, S. Udo, T.

Utsugi, B.S. Wang, H. Wang, X. Wang, Y.G. Wang, H.R. Wu, L. Xue, Y. Yamamoto, C.T. Yan, X.C. Yang, S. Yasue, Z.H. Ye, G.C. Yu, A.F. Yuan, T. Yuda, H.M. Zhang, J.L. Zhang, N.J. Zhang, X.Y. Zhang, Y. Zhang, Zhaxisangzhu, X.X. Zhou (Tibet AS γ Collaboration), Variation of sun shadow in the solar cycle 23 observed with the Tibet air shower array. Adv. Space Res. **38**, 936–941 (2006). doi:10.1016/j.asr.2006.04.023

A. Antalova, M.N. Gnevyshev, Latitudinal distribution of sunspot areas during the period 1874–1976. Contrib. Astron. Obs. Skaln. Pleso **11**, 63–93 (1983)

H.M. Antia, S. Basu, Temporal variations of the rotation rate in the solar interior. Astrophys. J. **541**, 442–448 (2000). doi:10.1086/309421

H.M. Antia, S. Basu, S.M. Chitre, Solar rotation rate and its gradients during cycle 23. Astrophys. J. **681**, 680–692 (2008). doi:10.1086/588523

T. Appourchaux, K. Belkacem, A.-M. Broomhall, W.J. Chaplin, D.O. Gough, G. Houdek, J. Provost, F. Baudin, P. Boumier, Y. Elsworth, R.A. García, B.N. Andersen, W. Finsterle, C. Fröhlich, A. Gabriel, G. Grec, A. Jiménez, A. Kosovichev, T. Sekii, T. Toutain, S. Turck-Chièze, The quest for the solar g modes. Astron. Astrophys. Rev. **18**, 197–277 (2010). doi:10.1007/s00159-009-0027-z

N. Astafyeva, G. Bazilevskaya, Long-term changes of cosmic ray intensity: spectral behaviour and 27-day variations. Phys. Chem. Earth, Part C, Sol.-Terr. Planet. Sci. **25**, 129–132 (2000). doi:10.1016/S1464-1917(99)00053-7

T. Ataç, A. Özgüç, J. Rybák, Overview of the flare index during the maximum phase of the solar cycle 23. Adv. Space Res. **35**, 400–405 (2005). doi:10.1016/j.asr.2005.01.040

O.G. Badalyan, V.N. Obridko, Solar magnetic fields and the intensity of the green coronal line. Astron. Rep. **48**, 678–687 (2004). doi:10.1134/1.1787070

O.G. Badalyan, V.N. Obridko, North-South asymmetry of the sunspot indices and its quasi-biennial oscillations. New Astron. **16**, 357–365 (2011). doi:10.1016/j.newast.2011.01.005

O.G. Badalyan, V.N. Obridko, J. Sýkora, Quasi-biennial oscillations in the North—South asymmetry of solar activity. Sol. Phys. **247**, 379–397 (2008). doi:10.1007/s11207-008-9120-0

J.N. Bahcall, R. Davis Jr., Solar neutrinos: a scientific puzzle. Science **191**, 264–267 (1976). doi:10.1126/science.191.4224.264

T. Bai, Periodicities in solar flare occurrence: analysis of cycles 19–23. Astrophys. J. **591**, 406–415 (2003). doi:10.1086/375295

C.S. Baldner, T.P. Larson, S. Basu, Solar-cycle related changes at the base of the convection zone, in *Solar-Stellar Dynamos as Revealed by Helio- and Asteroseismology: GONG 2008/SOHO 21*, ed. by M. Dikpati, T. Arentoft, I. González Hernández, C. Lindsey, F. Hill. Astronomical Society of the Pacific Conference Series, vol. 416, (2009), p. 477

M.P. Baldwin, L.J. Gray, T.J. Dunkerton, K. Hamilton, P.H. Haynes, W.J. Randel, J.R. Holton, M.J. Alexander, I. Hirota, T. Horinouchi, D.B.A. Jones, J.S. Kinnersley, C. Marquardt, K. Sato, M. Takahashi, The quasi-biennial oscillation. Rev. Geophys. **39**, 179–229 (2001). doi:10.1029/1999RG000073

S.L. Baliunas, R.A. Donahue, W.H. Soon, J.H. Horne, J. Frazer, L. Woodard-Eklund, M. Bradford, L.M. Rao, O.C. Wilson, Q. Zhang, W. Bennett, J. Briggs, S.M. Carroll, D.K. Duncan, D. Figueroa, H.H. Lanning, T. Misch, J. Mueller, R.W. Noyes, D. Poppe, A.C. Porter, C.R. Robinson, J. Russell, J.C. Shelton, T. Soyumer, A.H. Vaughan, J.H. Whitney, Chromospheric variations in main-sequence stars. Astrophys. J. **438**, 269–287 (1995). doi:10.1086/175072

J.L. Ballester, R. Oliver, M. Carbonell, The near 160 day periodicity in the photospheric magnetic flux. Astrophys. J. **566**, 505–511 (2002). doi:10.1086/338075

J.L. Ballester, R. Oliver, M. Carbonell, Return of the near 160 day periodicity in the photospheric magnetic flux during solar cycle 23. Astrophys. J. Lett. **615**, 173–176 (2004). doi:10.1086/426430

G.A. Bazilevskaya, M.B. Krainev, V.S. Makhmutov, E.O. Flückiger, A.I. Sladkova, M. Storini, Structure of the maximum phase of solar cycles 21 and 22. Sol. Phys. **197**, 157–174 (2000). doi:10.1023/A:1026515520311

G.A. Bazilevskaya, E.O. Fluckiger, M.B. Krainev, V.S. Makhmutov, A.I. Sladkova, M. Storini, Distribution of solar energetic particle events over an 11-year solar cycle. Int. Cosm. Ray Conf. **8**, 3413 (2001)

G.A. Bazilevskaya, V.S. Makhmutov, A.I. Sladkova, Gnevyshev gap effects in solar energetic particle activity. Adv. Space Res. **38**, 484–488 (2006). doi:10.1016/j.asr.2004.11.011

A.V. Belov, Forbush effects and their connection with solar, interplanetary and geomagnetic phenomena (2009). doi:10.1017/S1743921309029676

E.E. Benevolenskaya, Double magnetic cycle of solar activity. Sol. Phys. **161**, 1–8 (1995). doi:10.1007/BF00732080

E.E. Benevolenskaya, A model of the double magnetic cycle of the sun. Astrophys. J. Lett. **509**, 49–52 (1998). doi:10.1086/311755

E.E. Benevolenskaya, Impulses of activity and the solar cycle. Sol. Phys. **216**, 325–341 (2003). doi:10.1023/A:1026105100181

E.E. Benevolenskaya, The formation and evolution of complexes of activity, activity nests and the large-scale connectivity in the solar corona, in *Large-Scale Structures and Their Role in Solar Activity*, ed. by K. Sankarasubramanian, M. Penn, A. Pevtsov. Astronomical Society of the Pacific Conference Series, vol. 346, (2005), p. 129

S.V. Berdyugina, I.G. Usoskin, Active longitudes in sunspot activity: century scale persistence. Astron. Astrophys. **405**, 1121–1128 (2003). doi:10.1051/0004-6361:20030748

S.V. Berdyugina, J. Pelt, I. Tuominen, Magnetic activity in the young solar analog LQ Hydrae. I. Active longitudes and cycles. Astron. Astrophys. **394**, 505–515 (2002). doi:10.1051/0004-6361:20021179

F. Boberg, H. Lundstedt, J.T. Hoeksema, P.H. Scherrer, W. Liu, Solar mean magnetic field variability: a wavelet approach to Wilcox solar observatory and SOHO/Michelson Doppler imager observations. J. Geophys. Res. **107**, 1318 (2002). doi:10.1029/2001JA009195

E. Böhm-Vitense, Chromospheric activity in G and K main-sequence stars, and what it tells us about stellar dynamos. Astrophys. J. **657**, 486–493 (2007). doi:10.1086/510482

A. Broomhall, W.J. Chaplin, Y. Elsworth, S.T. Fletcher, R. New, Is the current lack of solar activity only skin deep? Astrophys. J. Lett. **700**, 162–165 (2009). doi:10.1088/0004-637X/700/2/L162

A.-M. Broomhall, S.T. Fletcher, D. Salabert, S. Basu, W.J. Chaplin, Y. Elsworth, R.A. García, A. Jiménez, R. New, Are short-term variations in solar oscillation frequencies the signature of a second solar dynamo? J. Phys. Conf. Ser. **271**(1), 012025 (2011). doi:10.1088/1742-6596/271/1/012025

A.-M. Broomhall, W.J. Chaplin, Y. Elsworth, R. Simoniello, Quasi-biennial variations in helioseismic frequencies: can the source of the variation be localized? Mon. Not. R. Astron. Soc. **420**, 1405–1414 (2012). doi:10.1111/j.1365-2966.2011.20123.x

A.C. Cadavid, J.K. Lawrence, D.P. McDonald, A. Ruzmaikin, Independent global modes of solar magnetic field fluctuations. Sol. Phys. **226**, 359–376 (2005). doi:10.1007/s11207-005-8187-0

W.J. Chaplin, Y. Elsworth, B.A. Miller, G.A. Verner, R. New, Solar p-mode frequencies over three solar cycles. Astrophys. J. **659**, 1749–1760 (2007). doi:10.1086/512543

I.-H. Cho, J. Hwang, Y.-D. Park, Revisiting solar and heliospheric 1.3-Year signals during 1970–2007. Sol. Phys. **289**, 707–719 (2014). doi:10.1007/s11207-013-0365-x

D.-Y. Chou, A. Serebryanskiy, In search of the solar cycle variations of p-mode frequencies generated by perturbations in the solar interior. Astrophys. J. **624**, 420–427 (2005). doi:10.1086/428925

D.P. Choudhary, J.K. Lawrence, M. Norris, A.C. Cadavid, Different periodicities in the sunspot area and the occurrence of solar flares and coronal mass ejections in solar cycle 23–24. Sol. Phys. **289**, 649–656 (2014). doi:10.1007/s11207-013-0392-7

P. Chowdhury, P.C. Ray, Periodicities of solar electron flare occurrence: analysis of cycles 21–23. Mon. Not. R. Astron. Soc. **373**, 1577–1589 (2006). doi:10.1111/j.1365-2966.2006.11120.x

P. Chowdhury, M. Khan, P. Ray, Intermediate-term periodicities in relativistic solar electron fluences during solar cycles 22 and 23. Adv. Space Res. **43**, 297–307 (2009a). doi:10.1016/j.asr.2008.06.008

P. Chowdhury, M. Khan, P.C. Ray, Intermediate-term periodicities in sunspot areas during solar cycles 22 and 23. Mon. Not. R. Astron. Soc. **392**, 1159–1180 (2009b). doi:10.1111/j.1365-2966.2008.14117.x

P. Chowdhury, D.P. Choudhary, S. Gosain, A study of the hemispheric asymmetry of sunspot area during solar cycles 23 and 24. Astrophys. J. **768**, 188 (2013). doi:10.1088/0004-637X/768/2/188

J. Christensen-Dalsgaard, Helioseismology, Rev. Mod. Phys. **74**, 1073–1129 (2002). doi:10.1103/RevModPhys.74.1073

T. Corbard, M.J. Thompson, The subsurface radial gradient of solar angular velocity from MDI f-mode observations. Sol. Phys. **205**, 211–229 (2002). doi:10.1023/A:1014224523374

E. Covas, R. Tavakol, D. Moss, Spatiotemporal fragmentation as a mechanism for different dynamical modes of behaviour in the solar convection zone. Astron. Astrophys. **363**, 13–16 (2000a)

E. Covas, R. Tavakol, D. Moss, A. Tworkowski, Torsional oscillations in the solar convection zone. Astron. Astrophys. **360**, 21–24 (2000b)

L. D'Alessi, A. Vecchio, V. Carbone, M. Laurenza, M. Storini, Quasi-biennial modulation of the solar neutrino flux: a "Telescope" for the solar interior. J. Mod. Phys. **4**, 49–56 (2013). doi:10.4236/jmp.2013.44A008

S. Danilovic, I. Vince, N. Vitas, P. Jovanovic, Time series analysis of long term full disk observations of the Mn i 539.4 nm solar line. Serb. Astron. J. **170**, 79–88 (2005). doi:10.2298/SAJ0570079D

Y. Elsworth, R. Howe, G.R. Isaak, C.P. McLeod, R. New, Variation of low-order acoustic solar oscillations over the solar cycle. Nature **345**, 322–324 (1990). doi:10.1038/345322a0

F. Feminella, M. Storini, Large-scale dynamical phenomena during solar activity cycles. Astron. Astrophys. **322**, 311–319 (1997)

S.T. Fletcher, A.-M. Broomhall, D. Salabert, S. Basu, W.J. Chaplin, Y. Elsworth, R.A. Garcia, R. New, A seismic signature of a second dynamo? Astrophys. J. Lett. **718**, 19–22 (2010). doi:10.1088/2041-8205/718/1/L19

D.M. Fluri, S.V. Berdyugina, Flip-flops as observational signatures of different dynamo modes in cool stars. Sol. Phys. **224**, 153–160 (2004). doi:10.1007/s11207-005-4147-y

E. Forgács-Dajka, T. Borkovits, Searching for mid-term variations in different aspects of solar activity—looking for probable common origins and studying temporal variations of magnetic polarities. Mon. Not. R. Astron. Soc. **374**, 282–291 (2007). doi:10.1111/j.1365-2966.2006.11167.x

K. Georgieva, Why the sunspot cycle is double peaked. ISRN Astron. Astrophys. **2011** (2011). doi:10.5402/2011/437838

K. Georgieva, B. Kirov, Long-term variations in solar meridional circulation from geomagnetic data: implications for solar dynamo theory. (2007). arXiv:physics/0703187

K. Georgieva, B. Kirov, Solar dynamo and geomagnetic activity. J. Atmos. Sol.-Terr. Phys. **73**, 207–222 (2011). doi:10.1016/j.jastp.2010.03.003

M.N. Gnevyshev, On the 11-years cycle of solar activity. Sol. Phys. **1**, 107–120 (1967). doi:10.1007/BF00150306

M.N. Gnevyshev, Essential features of the 11-year solar cycle. Sol. Phys. **51**, 175–183 (1977). doi:10.1007/BF00240455

N. Gyenge, T. Baranyi, A. Ludmány, Migration and extension of solar active longitudinal zones. Sol. Phys. **289**, 579–591 (2014). doi:10.1007/s11207-013-0424-3

D.H. Hathaway, The solar cycle. Living Rev. Sol. Phys. **7**, 1 (2010). doi:10.12942/lrsp-2010-1

M.E. Hill, D.C. Hamilton, S.M. Krimigis, Periodicity of 151 days in outer heliospheric anomalous cosmic ray fluxes. J. Geophys. Res. **106**, 8315–8322 (2001). doi:10.1029/2000JA000380

J.T. Hoeksema, Global solar magnetic fields. NASA STI/Recon Technical Report N **92**, 29421 (1991)

R. Howe, J. Christensen-Dalsgaard, F. Hill, R.W. Komm, R.M. Larsen, J. Schou, M.J. Thompson, J. Toomre, Dynamic variations at the base of the solar convection zone. Science **287**, 2456–2460 (2000). doi:10.1126/science.287.5462.2456

R. Howe, R. Komm, F. Hill, J. Christensen-Dalsgaard, T.P. Larson, J. Schou, M.J. Thompson, J. Toomre, Rotation-rate variations at the tachocline: an update. J. Phys. Conf. Ser. **271**(1), 012075 (2011). doi:10.1088/1742-6596/271/1/012075

K. Ichimoto, J. Kubota, M. Suzuki, I. Tohmura, H. Kurokawa, Periodic behaviour of solar flare activity. Nature **316**, 422–424 (1985). doi:10.1038/316422a0

E.V. Ivanov, V.N. Obridko, B.D. Shelting, Quasi-biennial oscillations of the solar magnetic fields, in *Solar Variability: from Core to Outer Frontiers*, ed. by A. Wilson. ESA Special Publication, vol. 506, (2002), pp. 847–850

K. Jain, S.C. Tripathy, F. Hill, How peculiar was the recent extended minimum: a hint toward double minima. Astrophys. J. **739**, 6 (2011). doi:10.1088/0004-637X/739/1/6

S.J. Jiménez-Reyes, R.A. García, A. Jiménez, W.J. Chaplin, Excitation and damping of low-degree solar p-modes during activity cycle 23: analysis of GOLF and VIRGO sun photometer data. Astrophys. J. **595**, 446–457 (2003). doi:10.1086/377304

S.J. Jiménez-Reyes, W.J. Chaplin, Y. Elsworth, R.A. García, R. Howe, H. Socas-Navarro, T. Toutain, On the variation of the peak asymmetry of low-l solar p modes. Astrophys. J. **654**, 1135–1145 (2007). doi:10.1086/509700

B. Joshi, A. Joshi, Intermediate-term periodicities in soft x-ray flare index during solar cycles 21, 22 and 23. Sol. Phys. **226**, 153–161 (2005). doi:10.1007/s11207-005-5716-9

R.P. Kane, Evolutions of various solar indices around sunspot maximum and sunspot minimum years. Ann. Geophys. **20**, 741–755 (2002). doi:10.5194/angeo-20-741-2002

R.P. Kane, Differences in the quasi-biennial oscillation and quasi-triennial oscillation characteristics of the solar, interplanetary, and terrestrial parameters. J. Geophys. Res. **110**, 1108 (2005a). doi:10.1029/2004JA010606

R.P. Kane, Short-term periodicities in solar indices. Sol. Phys. **227**, 155–175 (2005b). doi:10.1007/s11207-005-1110-x

R.P. Kane, Which one is the 'GNEVYSHEV' GAP? Sol. Phys. **229**, 387–407 (2005c). doi:10.1007/s11207-005-7451-7

R.P. Kane, A detailed comparison of cosmic ray gaps with solar gnevyshev gaps. Sol. Phys. **236**, 207–226 (2006). doi:10.1007/s11207-006-0142-1

C. Kato, K. Munakata, S. Yasue, K. Inoue, F.B. McDonald, A 1.7-year quasi-periodicity in cosmic ray intensity variation observed in the outer heliosphere. J. Geophys. Res. **108**, 1367 (2003). doi:10.1029/2003JA009897

C. Katsavrias, P. Preka-Papadema, X. Moussas, Wavelet analysis on solar wind parameters and geomagnetic indices. Sol. Phys. **280**, 623–640 (2012). doi:10.1007/s11207-012-0078-6

M.N. Khramova, E.V. Kononovich, S.A. Krasotkin, Quasi-biennial oscillations of global solar-activity indices. Sol. Syst. Res. **36**, 507–512 (2002)

A. Kilcik, A. Ozguc, One possible reason for double-peaked maxima in solar cycles: is a second maximum of solar cycle 24 expected? Sol. Phys. **289**, 1379–1386 (2014). doi:10.1007/s11207-013-0407-4

A. Kilcik, V.B. Yurchyshyn, V. Abramenko, P.R. Goode, A. Ozguc, J.P. Rozelot, W. Cao, Time distributions of large and small sunspot groups over four solar cycles. Astrophys. J. **731**, 30 (2011). doi:10.1088/0004-637X/731/1/30

R. Knaack, J.O. Stenflo, Spherical harmonic decomposition of solar magnetic fields. Astron. Astrophys. **438**, 349–363 (2005). doi:10.1051/0004-6361:20052765

R. Knaack, J.O. Stenflo, S.V. Berdyugina, Periodic oscillations in the North-South asymmetry of the solar magnetic field. Astron. Astrophys. **418**, 17–20 (2004). doi:10.1051/0004-6361:20040107

R. Knaack, J.O. Stenflo, S.V. Berdyugina, Evolution and rotation of large-scale photospheric magnetic fields of the Sun during cycles 21-23. Periodicities, North-South asymmetries and r-mode signatures. Astron. Astrophys. **438**, 1067–1082 (2005). doi:10.1051/0004-6361:20042091

M.B. Krainev, G.A. Bazilevskaya, V.S. Makhmutov, Solar magnetic field and dynamic phenomena in cosmic rays. Adv. Space Res. **29**, 331–336 (2002). doi:10.1016/S0273-1177(01)00593-2

N.A. Krivova, S.K. Solanki, The 1.3-year and 156-day periodicities in sunspot data: wavelet analysis suggests a common origin. Astron. Astrophys. **394**, 701–706 (2002). doi:10.1051/0004-6361:20021063

K. Kudela, J. Rybák, A. Antalová, M. Storini, Time evolution of low-frequency periodicities in cosmic ray intensity. Sol. Phys. **205**, 165–175 (2002). doi:10.1023/A:1013869322693

K. Kudela, H. Mavromichalaki, A. Papaioannou, M. Gerontidou, On mid-term periodicities in cosmic rays. Sol. Phys. **266**, 173–180 (2010). doi:10.1007/s11207-010-9598-0

P. Kumar, S. Talon, J.-P. Zahn, Angular momentum redistribution by waves in the sun. Astrophys. J. **520**, 859–870 (1999). doi:10.1086/307464

A. Lara, A. Borgazzi, O. Mendes Jr., R.R. Rosa, M.O. Domingues, Short-period fluctuations in coronal mass ejection activity during solar cycle 23. Sol. Phys. **248**, 155–166 (2008). doi:10.1007/s11207-008-9153-4

M. Laurenza, M. Storini, S. Giangravè, G. Moreno, Search for periodicities in the IMP 8 charged particle measurement experiment proton fluxes for the energy bands 0.50-0.96 MeV and 190-440 MeV. J. Geophys. Res. **114**, 1103 (2009). doi:10.1029/2008JA013181

M. Laurenza, A. Vecchio, M. Storini, V. Carbone, Quasi-biennial modulation of galactic cosmic rays. Astrophys. J. **749**, 167 (2012). doi:10.1088/0004-637X/749/2/167

K.G. Libbrecht, M.F. Woodard, Solar-cycle effects on solar oscillation frequencies. Nature **345**, 779–782 (1990). doi:10.1038/345779a0

M. Lockwood, Long-term variations in the magnetic fields of the sun and the heliosphere: their origin, effects, and implications. J. Geophys. Res. **106**, 16021–16038 (2001). doi:10.1029/2000JA000115

Y.-Q. Lou, Rossby-type wave-induced periodicities in flare activities and sunspot areas or groups during solar maxima. Astrophys. J. **540**, 1102–1108 (2000). doi:10.1086/309387

Y.-Q. Lou, Y.-M. Wang, Z. Fan, S. Wang, J.X. Wang, Periodicities in solar coronal mass ejections. Mon. Not. R. Astron. Soc. **345**, 809–818 (2003). doi:10.1046/j.1365-8711.2003.06993.x

R. Lukianova, K. Mursula, Changed relation between sunspot numbers, solar UV/EUV radiation and TSI during the declining phase of solar cycle 23. J. Atmos. Sol.-Terr. Phys. **73**, 235–240 (2011). doi:10.1016/j.jastp.2010.04.002

K. Maeda, Quasi-biennial cycles in cosmic ray intensity. J. Atmos. Sci. **24**, 320–322 (1967). doi:10.1175/1520-0469(1967)024<0320:QBCICR>2.0.CO;2

H. Mavromichalaki, P. Preka-Papadema, I. Liritzis, B. Petropoulos, V. Kurt, Short-term variations of cosmic-ray intensity and flare related data in 1981–1983. New Astron. **8**, 777–794 (2003). doi:10.1016/S1384-1076(03)00066-6

T.S. Metcalfe, A.P. Buccino, B.P. Brown, S. Mathur, D.R. Soderblom, T.J. Henry, P.J.D. Mauas, R. Petrucci, J.C. Hall, S. Basu, Magnetic activity cycles in the exoplanet host star epsilon Eridani. Astrophys. J. Lett. **763**, 26 (2013). doi:10.1088/2041-8205/763/2/L26

L.I. Miroshnichenko, Solar cosmic rays in the system of solar terrestrial relations. J. Atmos. Sol.-Terr. Phys. **70**, 450–466 (2008). doi:10.1016/j.jastp.2007.08.027

D. Moss, Non-axisymmetric solar magnetic fields. Mon. Not. R. Astron. Soc. **306**, 300–306 (1999). doi:10.1046/j.1365-8711.1999.02510.x

D. Moss, Dynamo models and the flip-flop phenomenon in late-type stars. Mon. Not. R. Astron. Soc. **352**, 17–20 (2004). doi:10.1111/j.1365-2966.2004.08125.x

D. Moss, J. Brooke, Towards a model for the solar dynamo. Mon. Not. R. Astron. Soc. **315**, 521–533 (2000). doi:10.1046/j.1365-8711.2000.03452.x

D. Moss, D.M. Barker, A. Brandenburg, I. Tuominen, Nonaxisymmetric dynamo solutions and extended starspots on late-type stars. Astron. Astrophys. **294**, 155–164 (1995)

X. Moussas, J.M. Polygiannakis, P. Preka-Papadema, G. Exarhos, Solar cycles: a tutorial. Adv. Space Res. **35**, 725–738 (2005). doi:10.1016/j.asr.2005.03.148

J. Murakozy, A. Ludmany, Cycle dependence of the longitudinal-latitudinal sunspot motion correlations. Astron. Astrophys. **486**, 1003–1007 (2008). doi:10.1051/0004-6361:20078456

K. Mursula, J.H. Vilppola, Fluctuations of the solar dynamo observed in the solar wind and interplanetary magnetic field at 1 AU and in the outer heliosphere. Sol. Phys. **221**, 337–349 (2004). doi:10.1023/B:SOLA.0000035053.17913.26

K. Mursula, B. Zieger, The 1.3-year variation in solar wind speed and geomagnetic activity. Adv. Space Res. **25**, 1939–1942 (2000). doi:10.1016/S0273-1177(99)00608-0

K. Mursula, B. Zieger, J.H. Vilppola, Mid-term quasi-periodicities in geomagnetic activity during the last 15 solar cycles: connection to solar dynamo strength to the memory of Karolen I. Paularena (1957–2001). Sol. Phys. **212**, 201–207 (2003). doi:10.1023/A:1022980029618

K. Nagashima, S. Sakakibara, I. Morishita, Quiescence of GLE-producible solar proton eruptions during the transition phase of heliomagnetic polarity reversal near the solar-activity-maximum period. Int. Cosm. Ray Conf. **3**, 29 (1991)

A.A. Norton, J.C. Gallagher, Solar-cycle characteristics examined in separate hemispheres: phase, gnevyshev gap, and length of minimum. Sol. Phys. **261**, 193–207 (2010). doi:10.1007/s11207-009-9479-6

V.N. Obridko, B.D. Shelting, Quasi-biennial oscillations of the global solar magnetic field. Astron. Rep. **45**, 1012–1017 (2001). doi:10.1134/1.1426132

V.N. Obridko, B.D. Shelting, Occurrence of the 1.3-year periodicity in the large-scale solar magnetic field for 8 solar cycles. Adv. Space Res. **40**, 1006–1014 (2007). doi:10.1016/j.asr.2007.04.105

V.P. Okhlopkov, Distinctive properties of the frequency spectra of cosmic ray variations and parameters of solar activity and the interplanetary medium in solar cycles 20–23. Mosc. University Phys. Bull. **66**, 99–103 (2011). doi:10.3103/S0027134911010188

K. Oláh, Z. Kolláth, T. Granzer, K.G. Strassmeier, A.F. Lanza, S. Järvinen, H. Korhonen, S.L. Baliunas, W. Soon, S. Messina, G. Cutispoto, Multiple and changing cycles of active stars. II. Results. Astron. Astrophys. **501**, 703–713 (2009). doi:10.1051/0004-6361/200811304

A. Özgüç, T. Ataç, J. Rybák, Temporal variability of the flare index (1966–2001). Sol. Phys. **214**, 375–396 (2003). doi:10.1023/A:1024225802080

P.L. Pallé, C. Régulo, T. Roca Cortés, Solar cycle induced variations of the low L solar acoustic spectrum. Astron. Astrophys. **224**, 253–258 (1989)

C. Petrick, K. Matthes, H. Dobslaw, M. Thomas, Impact of the solar cycle and the QBO on the atmosphere and the ocean. J. Geophys. Res., Atmos. **117**, 17111 (2012). doi:10.1029/2011JD017390

E.P. Popova, N.A. Yukhina, The quasi-biennial cycle of solar activity and dynamo theory. Astron. Lett. **39**, 729–735 (2013). doi:10.1134/S1063773713100046

V.E. Reznikova, K. Shibasaki, R.A. Sych, V.M. Nakariakov, Three-minute oscillations above sunspot umbra observed with the solar dynamics Observatory/Atmospheric imaging assembly and nobeyama radioheliograph. Astrophys. J. **746**, 119 (2012). doi:10.1088/0004-637X/746/2/119

I.G. Richardson, H.V. Cane, The ∼150 day quasi-periodicity in interplanetary and solar phenomena during cycle 23. Geophys. Res. Lett. **32**, 2104 (2005). doi:10.1029/2004GL021691

I.G. Richardson, H.V. Cane, E.W. Cliver, Sources of geomagnetic activity during nearly three solar cycles (1972–2000). J. Geophys. Res. **107**, 1187 (2002). doi:10.1029/2001JA000504

E. Rieger, G. Kanbach, C. Reppin, G.H. Share, D.J. Forrest, E.L. Chupp, A 154-day periodicity in the occurrence of hard solar flares? Nature **312**, 623–625 (1984). doi:10.1038/312623a0

J. Rodríguez-Pacheco, J.J. Blanco, B. Heber, R. Gómez-Herrero, Energetic particles measured in and out of the ecliptic plane during the last Gnevyshev gap. Sol. Phys. **281**, 491–499 (2012). doi:10.1007/s11207-012-9977-9

A. Ruzmaikin, A.C. Cadavid, J. Lawrence, Quasi-periodic patterns coupling the sun, solar wind and the earth. J. Atmos. Sol.-Terr. Phys. **70**, 2112–2117 (2008). doi:10.1016/j.jastp.2008.09.013

J. Rybák, A. Antalová, M. Storini, The wavelet analysis of the solar and cosmic-ray data. Space Sci. Rev. **97**, 359–362 (2001). doi:10.1023/A:1011805923567

S.H. Saar, A. Brandenburg, Time evolution of the magnetic activity cycle period. II. Results for an expanded stellar sample. Astrophys. J. **524**, 295–310 (1999). doi:10.1086/307794

K. Sakurai, Quasi-biennial variation of the solar neutrino flux and solar activity. Nature **278**, 146–148 (1979). doi:10.1038/278146a0

D.J. Schove, Sunspot turning-points and aurorae since A.D. 1510. Sol. Phys. **63**, 423–432 (1979). doi:10.1007/BF00174546

S. Sello, Wavelet entropy and the multi-peaked structure of solar cycle maximum. New Astron. **8**, 105–117 (2003). doi:10.1016/S1384-1076(02)00192-6

A. Serebryanskiy, D.-Y. Chou, Comparison of solar cycle variations of solar p-mode frequencies from GONG and MDI. Astrophys. J. **633**, 1187–1190 (2005). doi:10.1086/491467

T. Shirai, Time variation of the solar neutrino fluxes from Super-Kamiokande data. Sol. Phys. **222**, 199–201 (2004). doi:10.1023/B:SOLA.0000043565.83411.ec

S.M. Silverman, R. Shapiro, Power spectral analysis of auroral occurrence frequency. J. Geophys. Res. **88**, 6310–6316 (1983). doi:10.1029/JA088iA08p06310

R. Simoniello, W. Finsterle, D. Salabert, R.A. García, S. Turck-Chièze, A. Jiménez, M. Roth, The quasi-biennial periodicity (QBP) in velocity and intensity helioseismic observations. The seismic QBP over solar cycle 23. Astron. Astrophys. **539**, 135 (2012a). doi:10.1051/0004-6361/201118057

R. Simoniello, K. Jain, S.C. Tripathy, S. Turck-Chiéze, W. Finsterle, M. Roth, Seismic comparison of the 11- and 2-year cycle signatures in the sun. Astron. Nachr. **333**, 1018 (2012b). doi:10.1002/asna.201211813

R. Simoniello, K. Jain, S.C. Tripathy, S. Turck-Chièze, C. Baldner, W. Finsterle, F. Hill, M. Roth, The quasi-biennial periodicity as a window on the solar magnetic dynamo configuration. Astrophys. J. **765**, 100 (2013). doi:10.1088/0004-637X/765/2/100

Y.P. Singh, S. Gautam Badruddin, Temporal variations of short- and mid-term periodicities in solar wind parameters and cosmic ray intensity. J. Atmos. Sol.-Terr. Phys. **89**, 48–53 (2012). doi:10.1016/j.jastp.2012.07.011

M. Storini, M. Laurenza, Solar activity effects on muon data. Mem. Soc. Astron. Ital. **74**, 774 (2003)

M. Storini, G.A. Bazilevskaya, E.O. Fluckiger, M.B. Krainev, V.S. Makhmutov, A.I. Sladkova, The GNEVYSHEV gap: a review for space weather. Adv. Space Res. **31**, 895–900 (2003). doi:10.1016/S0273-1177(02)00789-5

M. Storini, K. Kudela, E.G. Cordaro, S. Massetti, Ground-level enhancements during solar cycle 23: results from SVIRCO, LOMNICKY STIT and LARC neutron monitors. Adv. Space Res. **35**, 416–420 (2005). doi:10.1016/j.asr.2004.12.020

J. Sykora, The coronal responses to the large-scale and long-term phenomena of the lower layers of the sun. Sol. Interplanet. Dyn. **91**, 87–104 (1980)

M.J. Thompson, Temporal variations of the sun's internal structure and dynamics: a theoretical perspective, in *SOHO 10/GONG 2000 Workshop: Helio- and Asteroseismology at the Dawn of the Millennium*, ed. by A. Wilson, P.L. Pallé. ESA Special Publication, vol. 464, (2001), pp. 39–44

I. Tuominen, S.V. Berdyugina, M.J. Korpi, Starspot cycles from Doppler imaging and photometric time series as nonlinear dynamo. Astron. Nachr. **323**, 367–370 (2002). doi:10.1002/1521-3994(200208)323:3/4<367::AID-ASNA367>3.0.CO;2-E

J.F. Valdés-Galicia, V.M. Velasco, Variations of mid-term periodicities in solar activity physical phenomena. Adv. Space Res. **41**, 297–305 (2008). doi:10.1016/j.asr.2007.02.012

J.F. Valdés-Galicia, V.M. Velasco, B. Mendoza, Mid term cosmic ray quasi periodicities and solar magnetic activity manifestations. Int. Cosm. Ray Conf. **2**, 211 (2005)

A. Vecchio, V. Carbone, On the origin of the double magnetic cycle of the sun. Astrophys. J. **683**, 536–541 (2008). doi:10.1086/589768

A. Vecchio, V. Carbone, Spatio-temporal analysis of solar activity: main periodicities and period length variations. Astron. Astrophys. **502**, 981–987 (2009). doi:10.1051/0004-6361/200811024

A. Vecchio, M. Laurenza, V. Carbone, M. Storini, Quasi-biennial modulation of solar neutrino flux and solar and galactic cosmic rays by solar cyclic activity. Astrophys. J. Lett. **709**, 1–5 (2010). doi:10.1088/2041-8205/709/1/L1

A. Vecchio, M. Laurenza, D. Meduri, V. Carbone, M. Storini, The dynamics of the solar magnetic field: polarity reversals, butterfly diagram, and quasi-biennial oscillations. Astrophys. J. **749**, 27 (2012a). doi:10.1088/0004-637X/749/1/27

A. Vecchio, M. Laurenza, M. Storini, V. Carbone, New insights on cosmic ray modulation through a joint use of nonstationary data-processing methods. Adv. Astron. **2012**(2012b). doi:10.1155/2012/834247

Y.-M. Wang, The sun's large-scale magnetic field and its long-term evolution. Sol. Phys. **224**, 21–35 (2004). doi:10.1007/s11207-005-4982-x

Y. Wang, N.R. Sheeley Jr., On the fluctuating component of the sun's large-scale magnetic field. Astrophys. J. **590**, 1111–1120 (2003). doi:10.1086/375026

Y.-M. Wang, J. Lean, N.R. Sheeley Jr., Role of a variable meridional flow in the secular evolution of the sun's polar fields and open flux. Astrophys. J. Lett. **577**, 53–57 (2002). doi:10.1086/344196

C.L. Wolff, The rotational spectrum of g-modes in the sun. Astrophys. J. **264**, 667–676 (1983). doi:10.1086/160640

M.F. Woodard, R.W. Noyes, Change of solar oscillation eigenfrequencies with the solar cycle. Nature **318**, 449 (1985)

T.V. Zaqarashvili, M. Carbonell, R. Oliver, J.L. Ballester, Magnetic rossby waves in the solar tachocline and rieger-type periodicities. Astrophys. J. **709**, 749–758 (2010a). doi:10.1088/0004-637X/709/2/749

T.V. Zaqarashvili, M. Carbonell, R. Oliver, J.L. Ballester, Quasi-biennial oscillations in the solar tachocline caused by magnetic rossby wave instabilities. Astrophys. J. Lett. **724**, 95–98 (2010b). doi:10.1088/2041-8205/724/1/L95

T.V. Zaqarashvili, R. Oliver, J.L. Ballester, M. Carbonell, M.L. Khodachenko, H. Lammer, M. Leitzinger, P. Odert, Rossby waves and polar spots in rapidly rotating stars: implications for stellar wind evolution. Astron. Astrophys. **532**, 139 (2011). doi:10.1051/0004-6361/201117122

S.I. Zharkov, E. Gavryuseva, V.V. Zharkova, On phase relation between toroidal and poloidal magnetic fields in the solar cycle 23, in *Proceedings of the International Astronomical Union, IAU Symposium*, vol. 247, (2008), pp. 39–45. doi:10.1017/S1743921308014634

N.V. Zolotova, D.I. Ponyavin, Impulse-like behavior of the sunspot activity. Astron. Rep. **56**, 250–255 (2012). doi:10.1134/S1063772912030080

T.H. Zurbuchen, A new view of the coupling of the sun and the heliosphere. Annu. Rev. Astron. Astrophys. **45**, 297–338 (2007). doi:10.1146/annurev.astro.45.010807.154030