Correlation of the quasi-biennial oscillations in galactic cosmic rays and in the solar activity indices

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Abstract.
Quasi-biennial oscillation (QBO) is a well-known variation in solar activity, interplanetary parameters, geomagnetic disturbances and cosmic rays. Solar QBO is translated to the space via open magnetic flux and modulates intensity of cosmic rays. The highest negative correlation exists in the QBO of cosmic rays with QBO in the heliospheric magnetic field strength $B$ as well as with QBO in the scalar product $BV$, where $V$ is the solar wind velocity, cosmic ray being delayed by $\approx 1$ month. During $\approx 50$ years of cosmic ray monitoring the QBO periods demonstrated some intermittency. It is argued that the Gnevyshev Gap effect and the step-like changes in the cosmic ray intensity appeared to be a part of QBO in cosmic rays.

1. Introduction
Quasi-biennial oscillation (QBO) is the conventional name of temporal variations with characteristic time of $\approx 0.5$-4 yrs. QBO appears to be the most prevalent quasi periodicity shorter than the 11-yr cycle in solar activity phenomena [1]. Figure 1 demonstrates the QBO in the sunspot area (http://solarscience.msfc.nasa.gov/greenwch.shtml). The 11-year cycle is clearly seen in the monthly averaged and 7-months smoothed data. The lower red curve shows the QBO. Time intermittent period can be seen, and a clear 11-year modulation with higher QBO during solar maxima periods is observed.

The solar QBO has been extensively studied. Their main features can be summarized as follows [2]. The QBO is ubiquitous: it is observed at all levels of the solar atmosphere and even below the photosphere. The QBO is intermittent - there is no stable period, although its amplitude is modulated by the 11-year solar cycle being highest at periods close to the solar maximum. There are some specific features of the solar activity QBO: it is independent in the northern and southern solar hemispheres, however synchronous at each level of the solar atmosphere, it is intermittent and has signs of stochasticity [3]. Many solar researchers believe that QBO is intrinsic to the solar dynamo mechanism [4, 5, 6].

The solar QBO is translated to the heliosphere. It is transferred via open magnetic flux which also demonstrates QBO although not synchronous with the other solar activity indices including solar magnetic field. That is why some researchers stated that there is no correlation between QBO on the Sun and QBO in heliosphere, such as cosmic ray (CR) QBO e.g., [7]. A relevant proxy of open magnetic flux is heliospheric magnetic field [8].
Figure 1. Sunspot area in millionths of solar hemisphere (http://solarscience.msfc.nasa.gov/greenwch.shtml): monthly-averaged (green line) and 7-months smoothed (brown line) data. Lower red curve shows the QBO retrieved as is described in Section 2.

Majority of papers devoted to the QBO in CR are focused on a certain periodicity, such as 1.2 yr, 1.7 yr or 2 yr [9, 10, 11, 12, 13, 14]. Kato et al. [15] found ≈ 1.7 yr and ≈ 1.3 yr periodicities in the Voyager 1 and 2 data on >70 MeV protons, which were distinct up to 40 AU and similar to the QBOs observed at neutron monitors. In this paper we do not try to isolate a certain CR periodicity but address the QBO as a special type of the CR variability and stress the characteristics similar to those of the solar QBO, namely, the permanent existence although with intermittent period and changing phase. We show a close relation between QBO in CR and in the interplanetary magnetic field. The well-known properties of the CR modulation - Gnevyshev effect and the step-like changes in CR intensity are shown to be appearances of QBO.

2. Retrieving of QBO
The QBO is significantly lower than the 11-year variation and besides it is non-stable, therefore it is isolated from the data sets via various technics including rather sophisticated such as empirical mode decomposition analysis [16] and independent component analysis [5]. Here, we use a simple pass-band filter which consists of 7-months and 25-months smoothing of the monthly data with consequent subtraction the latter from the former. 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 periods in between 3-37 months: the amplitudes of the QBO were observed to change by an insignificant amount while phases were not violated.

3. Data selection
The QBO in different solar indices (such as sunspot number and area, H-alpha flares and X-burst numbers, coronal lines intensity) is highly correlated [2]. Because CR are affected by magnetic fields we use here as a solar QBO characteristic an energy index of the photospheric magnetic field $B^2 = B^2/8\pi$. It can be calculated for each solar rotation using the data of observations being performed by the Wilcox Solar Observatory. The sets of the harmonic coefficients completely
determining field components are available at the (http://wso.stanford.edu). The details of calculations are described in [17].

![Figure 2](image.png)

**Figure 2.** QBO in CR as observed in the stratosphere [18] and with the ground-based neutron monitors (http://www.nmdb.eu/).

As the QBO of interplanetary parameters we examine the heliospheric magnetic field (HMF) strength \( B \), the solar wind velocity \( V \) (http://omniweb.gsfc.nasa.gov/ow.html), and the tilt angle of the heliospheric current sheet, classic version (http://wso.stanford.edu/Tilts.html).

We use the data of CR balloon observations in the Earth’s atmosphere [18] and the data of the ground level neutron monitors (NM) [http://www.nmdb.eu/]. The phases of the CR QBO as retrieved from different observations are similar to each other as it can be seen in Figure 2. Here a coherency of balloon (Murmansk) and two neutron monitors (Climax and Apatity stations) is shown. The monthly data were normalized to March 1987 before passing through the filter. The QBO at other NMs behaves similarly. As examples, coefficients of correlation between CR QBO of different observations are \( R = 0.72 \) (Murmansk vs. NM Huancayo/Haleakala), \( R = 0.88 \) (Murmansk vs. NM Moscow), \( R = 0.90 \) (Murmansk vs. NM Climax). Therefore, to examine correlation between CR and solar/interplanetary activity we further use the NM data. The QBO amplitudes depend on CR energy and will be discussed elsewhere.

4. **Correlation between QBO in cosmic rays and solar/interplanetary indices**

Many papers were devoted to search for a link between CR QBO and QBO in solar activity. It was found that relationship was not stable and rather complicated eg., [7]. The contradiction was solved with understanding of the role of the open magnetic flux of the Sun which has its proxy in the HMF strength [8]. The solar activity indices and the open magnetic flux correlate well for the long-term patterns and badly for the QBO. The correlation coefficient between the 25-month smoothed \( B_2 \) index and HMF \( B \) in 1977.63-2013.38 is \( R = 0.87 \pm 0.01 \) while for the QBO at the same time \( R = 0.25 \pm 0.04 \) (without a lag). That means a good translation into space of a long-term constituent of the solar magnetic field and a significant distortion of the QBO at transfer from lower levels of the solar atmosphere to space. Upper panel of Figure 3 shows QBO in CR and \( B_2 \). In general correlation is low and it becomes better at the CR delay of 3 months. This may be important for understanding transfer from the solar magnetic field to the open magnetic flux and needs a further study. The best correlation is observed between the QBO in CR and HMF strength \( B \) or between CR and the product \( BV \), where \( V \) is the solar wind speed, the CR delay being 1 month. The link of CR QBO to the tilt angle QBO (Figure 3, lower panel) is not simple. There are time periods with good coherency, e.g. from mid 1981 to mid 1987, but afterwards a coherency was violated. It is necessary to study this point further taking into account the tilt angle value.
Figure 3. QBO in cosmic rays and in different indices, from top to bottom panels: $B_2$ index of photospheric magnetic field, heliospheric magnetic field $B$, solar wind velocity $V$, the scalar product of $B$ and $V$, tilt angle of heliospheric current sheet. $R$ denotes a highest correlation coefficient, $D$ is a delay of CR relative to an index in months.

Correlation between the QBO in CR and HMF $B$ in different solar cycles is presented in table 1. It is seen from table 1 that there is no significant difference from one cycle to another.
Table 1. Correlation between QBO in CR and HMF (different cycles).

| Start     | End       | Solar cycle | Delay | $R$   | error |
|-----------|-----------|-------------|-------|-------|-------|
| 1967.54   | 1976.46   | 20          | 1     | -0.74 | 0.04  |
| 1976.54   | 1986.79   | 21          | 2     | -0.70 | 0.05  |
| 1986.87   | 1996.37   | 22          | 0     | -0.74 | 0.04  |
| 1996.46   | 2008.87   | 23          | 1     | -0.66 | 0.05  |
| 2008.96   | 2012.87   | rise of 24  | 1     | -0.74 | 0.07  |

Table 2. Correlation between QBO in CR and HMF (different polarities of the solar magnetic field).

| Start     | End       | $A$ sign | Delay | $R$   | error |
|-----------|-----------|----------|-------|-------|-------|
| 1970.87   | 1980.04   | $>0$     | 1     | -0.79 | 0.04  |
| 1980.12   | 1990.87   | $<0$     | 1     | -0.67 | 0.03  |
| 1990.96   | 2000.87   | $>0$     | 0     | -0.79 | 0.03  |
| 2000.96   | 2012.96   | $<0$     | 1     | -0.70 | 0.04  |

This result does not confirm a conclusion of [19] about low correlation of the CR QBO with HMF $B$ in the solar cycles 21 and 23. No visible changes in the CR and HMF $B$ QBO during the whole period of observations are seen also in Figure 3 (second panel from the top). We believe a reason of discrepancy with [19] to be in their method of the QBO isolation, which is more complicated than our way.

Table 2 demonstrates the same as table 1 but for periods of positive and negative polarities of the solar magnetic field (http://wso.stanford.edu). Here, as usual, $A>0$ refers to positive radial component of magnetic field in the northern solar hemisphere. We see that the QBO correlation is higher during the $A>0$ periods, however, statistics is too small.

Figure 4. Left panel: power spectra density of QBO vs. period in months for the Climax neutron monitor (green line) and heliospheric $B$ (blue line) in 1966-1978; middle panel: the same but in 1979-2005. Right panel: PSD spectra for the Climax NM in three different periods of time. PSD is given in the units of 99% confidence level.
Further evidence of a close link between QBOs in CR fluxes and HMF $B$ is shown in Figure 4 (left and middle panels). The power spectrum densities (PSD) of CR and HMF $B$ are plotted for 1966-1978 and 1979-2005. For convenience, the PSD is given versus period in months.

5. QBO and 1.7 year variation in cosmic rays
A majority of researchers draw attention to certain periodicities in CR such as 1.7 yr or 1.3 yr variations [10, 11, 12, 15, 20] and others. We believe that QBO in CR are caused by the QBO in the solar activity. It was shown [2, 3] that solar QBO is intermittent and have signs of stochasticity. On the one hand, the CR QBO may be more stable than solar one, and on the other hand the period of CR monitoring is too short in comparison with solar activity observations which prevents from finding any stochasticity. To examine the problem we took the Climax NM data ([http://ulysses.sr.unh.edu](http://ulysses.sr.unh.edu)) - the oldest CR data set (QBO can be extracted from 1952-2005) - divided it in 3 subsets and calculated the PSD spectra. The results are plotted in the right panel of Figure 4. The main periods are 2.25 yr and 3 yr in 1952-1969; 1.7 yr in 1970-1987; 1.8 yr and 2.2 yr in 1989-2005. The same periodicities exist in HMF $B$ as it is depicted on the left and middle panels of Figure 4 for the time of simultaneous observations of Climax and HMF. We conclude that the CR QBO is actually dynamic, although, some selectivity in the CR QBO may be present.

6. QBO, Gnevyshev Gap and the step-like variations in cosmic rays
Gnevyshev Gap is a temporal damping of solar activity just around of maximum of the 11-year solar cycle [21]. These gaps are clearly seen in the sunspot area (upper part of Figure 1). Similarly to QBO, Gnevyshev Gap is observed virtually in all solar and solar-terrestrial indices [22] and references therein. Moreover, like QBO, Gnevyshev Gap appearance is rather intermittent as it is also seen in Figure 1. Bazilevskaya et al. [23] suggested that Gnevyshev Gap in solar activity is an appearance of QBO. In particular, absence of Gnevyshev Gap in some solar cycles is explained by independence of QBO in the northern and southern solar hemispheres and their occasional anti-phase around solar maximum. Later it was supported by [24], although an alternative explanation exists e.g., [25]. Similar to any other variation of solar activity Gnevyshev Gap modulates the CR intensity, where it looks as a temporal weakening of modulation, i.e. as a temporal increasing of CR intensity in the maximum of solar activity. The Gnevyshev effect is clearly seen in Figure 5, where the data of the Moscow NM for three solar cycles are plotted. Gnevyshev Gap is indicated by brown arrows. The red curves is the QBO extracted from the CR intensity. It is seen that Gnevyshev Gap in CR is one of the QBO maximum. The QBO in HMF (values are multiplied by -3) is also shown by the grey curves, thereby confirming that Gnevyshev effect in CR is a part of QBO.

The step-like behavior of CR intensity, which is also clearly seen in Figure 5, was discussed in several papers. In the beginning the steps were considered as a result of CR modulation by the global merged interaction regions (GMIR) of HMF which were formed by coronal mass ejections (CME), shocks and fast-speed flow of solar wind at distance of $\approx 10$ a.u. [26]. However, Cane et al. [27] proved the step-like events in CR to be simultaneous with the solar magnetic field variations derived from photospheric observations alone. Wibberenz and Cane [28] formulated main features of the "medium-term modulation events" as related to variations in the open magnetic flux carried by solar wind. Wibberenz and Cane [28] showed also that such events are distributed throughout the 22 year cycle and are not restricted to phases of high solar activity. Actually, these findings manifest the same features as the CR QBO. Green arrows in Figure 5 prolonged by the light grey lines indicate the step-like changes in the CR intensity. Similarly to Gnevyshev Gap they appear to be a part of QBO. Similar conclusion was drawn by Vecchio et al. [29].
Figure 5. Cosmic ray intensity as observed at the Moscow neutron monitor (blue lines) and QBO in cosmic rays (red curves) and HMF B (multiplied by -3, grey curves). Brown arrows indicate the Gnevyshev effect in CR, green arrows mark the step-like changes in the cosmic ray intensity.

7. Discussion
The results of this work clearly show a generic link between the solar QBO and the CR QBO. Both variations exist permanently; they have irregular intermittent periods of ≈ 0.4-4 yr and stochastic changes of the phase. The amplitude of the QBO in CR is less modulated by an 11-year cycle as can be seen from comparison of figures 1 and 2. However, negative correlation with the QBO in HMF strength, which is a good proxy for the open magnetic flux of the Sun, is seen in figure 3 and is confirmed by the calculated correlation coefficients throughout the whole period of observation. This result does not agree with conclusions of [19], where a low correlation if any was found between QBO in CR and HMF strength in the solar cycles 21 and 23 as well as during the solar maximum phases 1978-1982 and 1998-2002. Indeed, values of correlation coefficient depend on the time period taken for analysis. However, our estimation of correlation coefficients yields $R=-0.68\pm0.07$ with CR delay by 3 months in 1978-1982, and $R=-0.54\pm0.09$ with no lag in 1998-2002. The cause of discrepancy with [19] in our opinion is a different approach to the QBO retrieval. Our method is rather simple but it is robust and shows an overall correlation between the CR and HMF QBOs. On the other hand, the empirical mode decomposition technique applied by [19], may stress absence of correlation at selected periodicities (see their Table 1). Further analysis is necessary to understand a nature of the found discrepancy.

A mechanism of the QBO modulation may have some difference from mechanisms of the 11-year modulation. The best correlation of QBO in CR and the scalar product $BV$ is similar to results of [31], where the long-term behavior of the CR intensity and diurnal anisotropy was analyzed. $BV$ gives the magnitude of the interplanetary electric field carried by the solar wind and leads to CR convective flow away from the Sun with a speed $V$. The found correlation underlines a role of convection in the QBO generation.

Difference in the correlation coefficients for the $A>0$ and $A<0$ periods may be indicative of the drift influence. It can be noticed in figure 3 that a lack of correlation between the QBO in CR and heliospheric tilt angle was observed before 1981, in 1988- mid 1990, and in 2005-2008, which could be connected with the intermittent drift contribution to the QBO in CR. However, it is interesting that at the same time periods correlation between the QBO in the HMF strength and heliospheric tilt angle was also violated. Study of the QBO dependence on heliospheric latitude would be elucidating.

Small delays of the CR QBO relative to HMF $B$ QBO argues for a diffusion mechanism of
the QBO acting within ≈10 a.u. However, Kato et al. [15] found significant QBO in the CR intensity observed by Voyagers 1 and 2 in the outer heliosphere in 1980s and 1990s, i.e. at the distance of ≈10-40 AU from the Sun. Kato et al. [15] suggested that the long-lived GMIR still may play a role in the QBO propagation through the heliosphere.

The QBO in CR opens some other points for further investigation. Transfer from the solar magnetic field to the open magnetic flux on different time scales is an open question [30], and relation between variabilities in the open magnetic flux and CR is not understood also. A question about possible selectivity of periods in the CR QBO remains to be open. Also, a peculiarity may exist in the relation of CR - HMF B QBO during the solar magnetic field reversal [32].

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7.2. Reference lists
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