INTERNATIONAL JOURNAL OF GEOMAGNETISM AND AERONOMY
VOL. 5, GI2004, doi:10.1029/2004GI000070, 2004

Main phases of the solar cycle in the galactic cosmic ray intensity

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Received 25 May 2004; revised 31 August 2004; accepted 14 September 2004; published 30 October 2004.

[1] The separation of the solar cycle in the modulation of the galactic cosmic ray intensity into the four main phases (the minimum, ascending, maximum, and descending) is considered. We substantiate advantages of such classification, choose as its initial point one of the known classifications, and discuss the special features of the main phases of the solar cycle in the heliospheric and cosmic ray characteristics. The initial assumption on the physical meaning of the sought for classification is proposed. The role of the very local interstellar medium in forming the solar cycle in the heliosphere is briefly discussed. *INDEX TERMS:* 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle; 2104 Interplanetary Physics: Cosmic rays; 2134 Interplanetary Physics: Interplanetary magnetic fields; *KEYWORDS:* Galactic cosmic ray; Very local interstellar medium; Phases of cosmic ray modulation.

Citation: Krainev, M. B. (2004), Main phases of the solar cycle in the galactic cosmic ray intensity, *Int. J. Geomagn. Aeron., 5,* GI2004, doi:10.1029/2004GI000070.

1. Introduction

[2] If we define "heliosphere" as a space surrounding the Sun with the plasma and magnetic field originated on the Sun and controlled by it, this definition implies that in different heliospheric characteristics one can see variations inherent in the surface layers of the Sun. In particular, the main solar variation in the sunspot number, magnetic flux, and so on, known as the 11-year cycle or, simply, solar cycle (SC), is reflected in many heliospheric characteristics. We are interested in isolating the extreme phases (minima and maxima) of the solar cycle in the galactic cosmic ray (GCR) intensity modulation in order to consider both the main long-term variations of the GCR and some specific for these phase GCR effects.

[3] Of course, both the solar cycle and the space, time, and energy distribution of the GCR intensity during solar minima and maxima are the subjects of a great number of papers (see *McDonald* [1998] and *Potgieter et al.* [2001] for the reviews of the observations and modeling, respectively). However, when one discusses the situation in the solar maxima and minima, usually very short periods (two to three solar rotations long) are considered, when the GCR intensity attains its extreme values. Even in cases when the attention is concentrated on the intensity behavior around these extreme points (as in, e.g., our papers devoted to the study either of the GCR intensity dependence on the tilt of the heliospheric current sheet in solar minima [*Krainev and Webber*, 1993b] or of the double-peak structure of the intensity modulation in solar maxima [*Krainev et al.*, 1999]) the boundaries of the periods considered are not substantiated by some physical reasons.

[4] In section 2, after comparing the solar cycle in the GCR intensity and some solar and heliospheric indices we discuss the reasons and merits of isolating the extreme phases in the GCR intensity modulation. Sections 3 and 4 will be devoted (1) to the discussion of some classification which we choose as an initial approximation for our purposes and (2) to outlining and briefly discussing some questions concerning the main solar cycle phases for the GCR intensity modulation. Then we very briefly discuss a topic although not directly relevant to the main subject of the paper but very important for the manifestation of the solar cycle in the heliosphere; namely, we review the general views about the heliospheric surroundings and what would occur if the Sun were slightly off its place in the Galaxy.

2. Solar Cycle in the Solar and Heliospheric Characteristics

[5] In Figure 1 the time history of the relative Zurich sunspot number (R_Z, panel a) is compared for 1950–2003 with those of some heliospheric parameters. The strength of the interplanetary magnetic field B_{IMF} near the Earth

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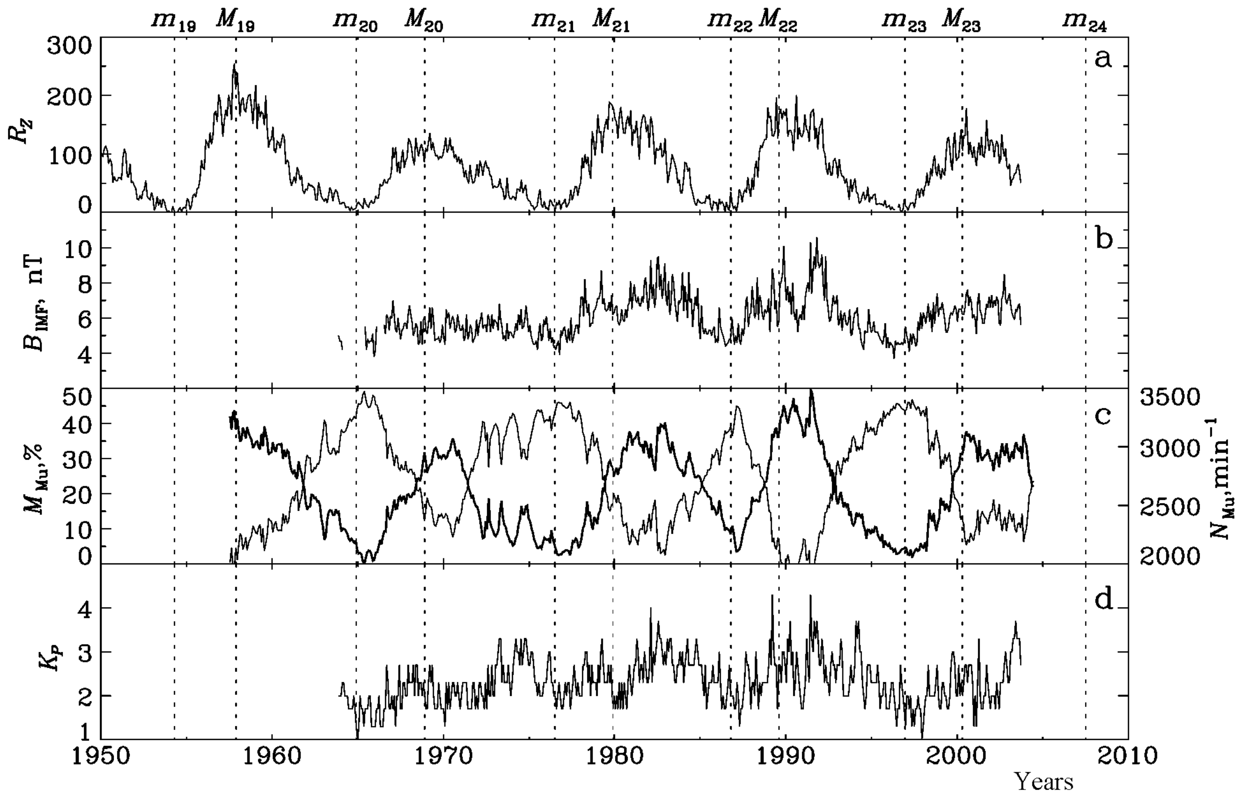

Figure 1. Solar cycle in the various solar and heliospheric characteristics.

is depicted in panel b. Panel c shows the GCR intensity (the count rate of the omnidirectional Geiger counter in the maximum of the transition curve in the stratosphere at Murmansk, the thin line in counterphase with the sunspot number, right y axis) and its modulation with respect to 1965 solar minimum, $M_{\rm Mu} = (N_{\rm Mu}^{1965} - N_{\rm Mu})/N_{\rm Mu}^{1965} \times 100\%$, where $N_{\rm Mu}^{1965}$ is the count rate for May 1965 (the thicker line in phase with the sunspot cycle, left y axis). The magnetospheric Kp index is shown in Figure 1d. (The 27-day or monthly average data (except $N_{\rm Mu}$) are taken from http://nssdc.gsfc.nasa.gov/omniweb/ow.html.) The thin vertical dotted lines show the maxima labelled with M (and the solar cycle number as a subscript) and minima (m) in the 13-month smoothed sunspot number.

[6] As one can see from Figure 1, the solar cycle in the GCR intensity modulation is the most pronounced and smooth when compared with other heliospheric indices shown. Besides the solar cycle in the GCR intensity modulation reminds that in the sunspot number in the most degree. The probable cause of these facts is that the GCR intensity, even measured at one point in the heliosphere, is in fact the global heliospheric index, as the GCRs effectively "average" relevant heliospheric characteristics along their way to the point of measurement.

[7] We also use Figure 1c to illustrate what GCR characteristics and effects we keep in mind when we are seeking to isolate the solar cycle extreme phases in the GCR intensity modulation. One can see that at some time ($t = t_m^{\rm GCR}$) about a few months after the SC minimum the GCR intensity peaks at its local maximum, while at some time ($t = t_M^{\rm GCR}$) after the maximum in R_Z the GCR intensity reaches its local minimum. If one knows the GCR intensity J_m, corresponding to the minimum of solar activity (and better still, its dependence on the particle energy, position in the heliosphere etc.), it is possible to study the so-called residual GCR intensity modulation, $J_{IS} \rightarrow J_m$, of the interstellar intensity JIS to that corresponding to the most quiet Sun, J_m. As the J_m changes when one moves to the past solar cycles (it can be done with the GCR radioactive tracers [*McCracken and McDonald*, 2001]), the long-term or secular variation of the heliospheric and solar activity can be studied. Similarly, knowing also the GCR intensity J_M, corresponding to the maximum of solar activity, the 11-year GCR intensity modulation can be studied, $J_m > J_M$. Besides one can see that both the value of J_m and the form of the intensity time profile around it are different for the successive solar cycles, which is due to opposite polarity distribution of the large-scale interplanetary magnetic field, which in turn is the manifestation of the 22-year, or magnetic, solar cycle. Around solar activity minima this polarity is usually described by the quantity $A = +1$ or $A = -1$, which sign coincides with that of the radial component of the high-latitude magnetic field in the northern photosphere. So the 22-year variation in the GCR intensity, $J_{m,+} \leftrightarrow J_{m,-}$, can be studied (the second subscript stands for the sign of A).

[8] However, it is clear that to determine in proper way the above extreme values ($J_{m,+}$, $J_{m,-}$, and J_M) one should consider the GCR behavior in some time intervals $t_m^1 < t < t_m^2$

and $t_M^1 < t < t_M^2$ around $t_m^{\rm GCR}$ and $t_M^{\rm GCR}$, respectively, when this behavior and the physical processes forming it have some features common to the interval in question and distinguishing it from the preceding and following solar cycle phases. We call these intervals the minimum and maximum or extreme phases of the solar cycle. As one can see from Figure 1c beside being useful in defining the extreme GCR intensity values, the minimum SC phase is characterized by the processes forming the intensity time profiles different for the successive solar cycles while the maximum solar cycle phase is characterized by the double-peak structure (or Gnevyshev Gap effect [see *Krainev et al.*, 1999]) in the GCR intensity modulation.

3. Vitinsky-Kuklin-Obridko Solar Cycle Phase Classification

[9] As we are interested in isolating the solar cycle extreme phases in the GCR intensity modulation and as this solar cycle is very similar to that in R_Z, we looked at the known SC phases classifications for the photospheric (and nearby) activity and found that of Ju. I. Vitinsky, V. G. Kuklin, and V. N. Obridko (VKO) [*Obridko and Shelting*, 1992, 2003; *Vitinsky et al.*, 1986] to be the best as an initial point.

[10] First, let us describe some terms we widely use. The development of the solar cycle can be described as the interaction of the toroidal (T, B_φ) and poloidal (P, B_r) subphotospheric magnetic fields and the alternating transition of the energy from T to P fields and back. Accordingly at the photosphere one can see the phenomena of the T branch of solar activity (sunspots with the ordered toroidal magnetic fields and other objects (active regions) linked to them) and those of the P branch (much weaker but large-scale poloidal magnetic fields at the polar latitudes and between the active regions, also polar faculae, etc).

[11] In Figure 2 the Carrington rotation-averaged sunspot area (available at http://science.nasa.gov/ssl/PAD/SOLAR/greenwch.htm) (Figure 2a) and latitude range occupied by the spots (Figure 2b) are shown for each hemisphere (the solid curves for Northern and the dotted ones for Southern Hemispheres) for 1980–1999, the polarity of the sunspots (the sign of B_φ) being also reflected by the thickness of the lines. The line-of-sight component of the north and south polar photospheric magnetic field as seen from the Earth (available at http://sun.stanford.edu/˜wso/) is depicted in Figure 2c. Also shown by the shading are the periods isolated by *Obridko and Shelting* [2003] as the extreme phases.

[12] Without going into details, we can give the following brief description of the solar cycle main phases (according to *Vitinsky et al.* [1986] but using our (T and P) terms): (1) min, $t_{Dm} < t < t_{mD}$, the minimum phase, the period when the sunspots with the old and new azimuthal polarities (B_φ) coexist; the strength of the T phenomena reaches its minimum, while that of the P branch attains its maximum; (2) Asc, $t_{mD} < t < t_{Am}$, the ascending phase, the period when both T and P phenomena are pronounced, characterized by the spontaneity of the activity; (3) Max, $t_{AM} < t < t_{MD}$, the maximum phase, the period when the strength of the P phenomena reaches its minimum and their dipole-like polarity changes sign, while the T branch is at its maximum with the pronounced double-peak structure; (4) Des, $t_{MD} < t < t_{Dm}$, the descending phase, when again both T and P phenomena are pronounced but characterized by the recurrence of the activity.

[13] The boundaries of the main phases (t_{mA}, t_{AM}, t_{MD}, t_{Dm}), introduced by *Vitinsky et al.* [1986] as the reference points of the solar cycle) are determined for the last solar cycles by *Obridko and Shelting* [2003] from the careful study of the sunspots, polar faculae, filaments etc. and widely using the data (available at http://sun.stanford.edu/˜wso/) on the large-scale magnetic fields both on the photosphere and at the base of the heliosphere. It is this particular interest in the very important for the heliosphere solar P phenomena, that determined our choice of the above classification as the best initial point in our search for the SC phases in the GCR intensity modulation.

4. Discussion of the Solar Cycle in the Heliosphere and the Main Phases for the GCR Intensity Modulation

[14] In the heliosphere there are also phenomena which are closely related to T branch of solar activity as characterized by their strength (not polarity) and not dependent on the phase of the magnetic cycle: the change of the strength of the regular and fluctuating components of the interplanetary magnetic field, the change of the distribution of the solar wind parameters etc. Similarly, there is a heliospheric phenomenon, which is related to the development of the P activity on the Sun: the formation and change of the dipole-like polarity distribution of the interplanetary magnetic field with the global current sheet dividing two magnetic hemispheres. However, in the course of the transition from the photosphere to the inner heliosphere the accelerating and expanding solar wind is influenced by both T and P branches of solar activity. So the resulting heliospheric characteristics could not be assigned exclusively to T or P branches. Rather, they could be classified as changing with the 11-year or 22-year periods (11-year and 22-year branches), both bringing the imprints of T and P types of solar phenomena.

[15] The GCR intensity is governed by the heliospheric factors of both 11-year and 22-year branches. Some notions about the sought for SC main phase classification for the GCR modulation are quite obvious. For example, the time boundaries of the phases should shift forward as one moves from the Sun to the solar wind termination shock and then gradually wash away by the periphery of the heliosphere due to the superposition of many previous cycles there.

[16] However, first we should decide what physical meaning we ascribe, e.g., to the extreme SC phases for the GCR intensity modulation. There is an important difference between the VKO classification for the solar activity itself and the sought for SC phase classification for such test particles

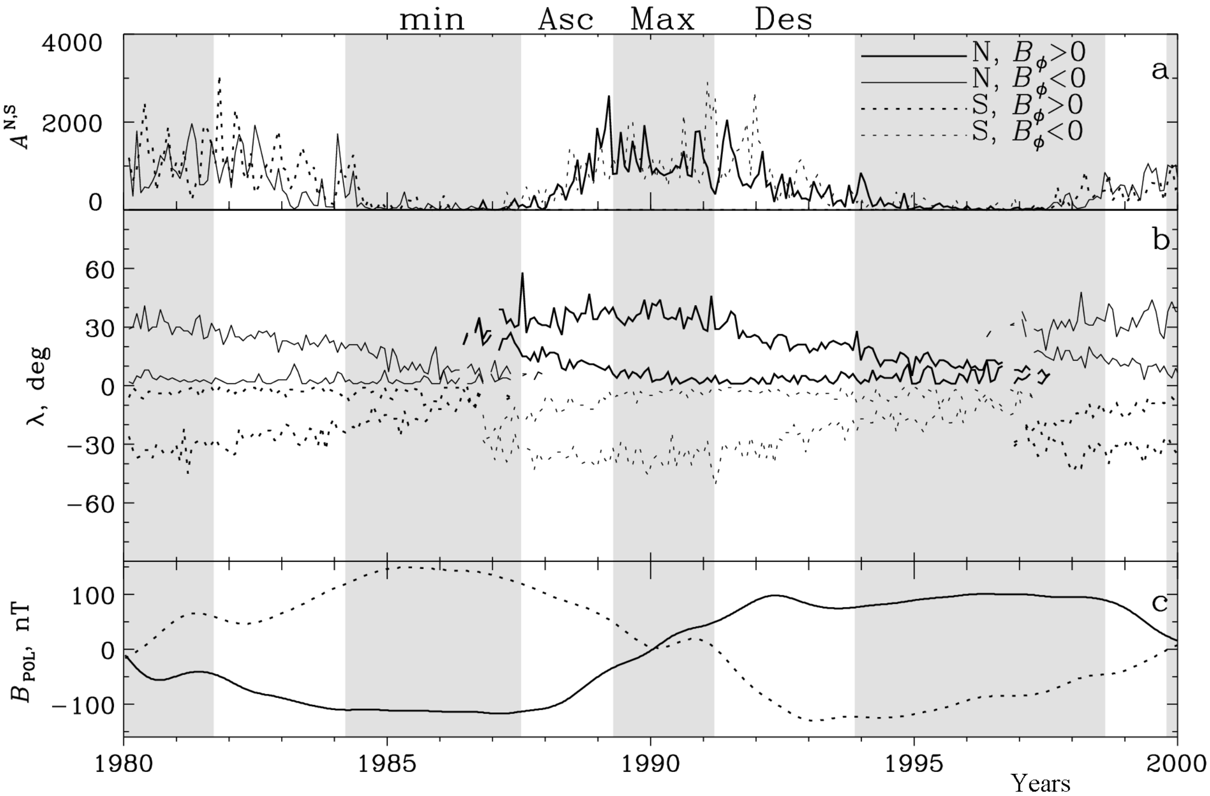

Figure 2. Illustration of the development of the solar cycle in toroidal and poloidal solar magnetic fields and the VKO classification.

as the GCRs. On the Sun even in the extreme phases both T and P branches are important. Contrary, for the GCR modulation the extreme phases in principle could be characterized by the small influence on the GCR intensity of one of the modulating factors. So our initial assumption is that during the SC minimum phase the GCR behavior is mainly determined by the 22-year branch of the heliospheric activity (the drifts in the dipole-like magnetic field etc.), while in the SC maximum phase the heliospheric 11-year phenomena (the diffusion in the fluctuating magnetic field etc.) play the decisive role. As the initial grounds for such a hypothesis can serve the definitions of the maximum (the maximum in T and minimum in P branches) and minimum (the opposite situation) phases of the solar cycle on the Sun in the VKO classification. Besides the GCR effects observed during the maxima of solar activity (the double-peak structure of the modulation and the energy hysteresis) are approximately the same for different solar cycles and types of particles [*Krainev et al.*, 1983, 1999], i.e., do not manifest the magnetic cycle. Contrary, the main GCR effect observed during the minima of solar activity (the different forms of the time profile of the intensity during successive minima of solar cycles) depends both on the polarity of the interplanetary magnetic field and on the sign of the particle's charge, although there is, probably, some smaller manifestation of the changes in the diffusion (T branch) [*Krainev and Webber*, 1993a].

[17] It should be noted that such hypothesis implies some specific scenarios for rather poorly studied processes in the heliosphere: the attenuation but not just rotation of the magnetic hemispheres with the global current sheet as the reversal of the high-latitude solar magnetic field proceeds; the formation of the regular and fluctuating heliospheric magnetic field also by the sunspot-like activity on the Sun and not only by the large-scale solar magnetic fields, etc.

5. Very Local Interstellar Medium and the Solar Cycle in the Heliosphere

[18] The general characteristics of the heliosphere, its di-

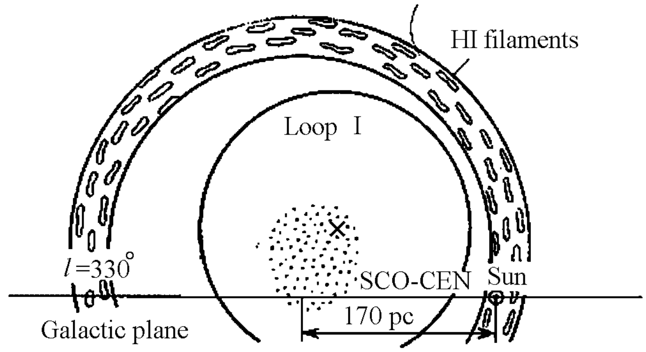

Figure 3. Sun's position near the SCO–CEN stellar association [*Bochkarev*, 1990].

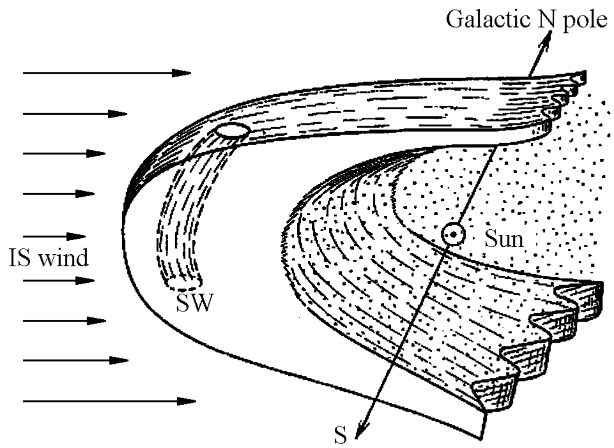

Figure 4. The Sun's position near the local HI cloud [*Bochkarev*, 1990].

mensions, the form of the main surfaces, etc., depend heavily on the properties of the very local interstellar medium, surrounding the heliosphere in the Galaxy. Consequently many properties of the near-Earth space would be quite different from the present ones if the Sun were a trifle off its present position, the fact often forgotten in formulating the list of the cosmic factors important for the Earth. Figure 3 from *Bochkarev* [1990] illustrates the position of the Sun with respect to the Scorpion–Centaurs (SCO–CEN) stellar association which center is about 170 Pc from the Sun, while Figure 4 from *Bochkarev* [1990] shows much nearer solar area surroundings, namely, the Sun's position with respect to the local HI cloud (about 10 Pc from the Sun) and the dense Sancini-van Woerden filament inside it.

[19] We shall not go into detail [see *Bochkarev*, 1990], just mention that now the Sun is in the worm (temperature $T \approx 104$ K) and rather rare (density $n \approx 10^{-1}$ cm^{-1}) weakly ionized hydrogen, the heliospheric dimensions being about 200 AU. If the Sun shifted to the SCO–CEN association by about 10–20 Pc (compare with the 10 kPc distance from the center of the Galaxy!) it would be surrounded by 2 order of magnitude denser and colder hydrogen and there is even a possibility that the whole heliosphere could be inside the Earth's orbit, and the Earth would be without any solar wind, the solar cycle and other GCR variations etc.! If somebody shifted the Sun 10–20 Pc more it would be in the SCO–CEN cavity with highly rarefied ($n \approx 10^{-3}$ cm^{-1}) and hot ($T \approx 106$ K) gas and the dimensions of the heliosphere could be much greater than now. Then the phase shift of the solar cycle in the inner and outer parts of the heliosphere would be great and the solar cycle in the GCR intensity would look quite different from how it looks now [see *Krainev and Webber*, 2004].

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