Cyclic Variations of Large-Scale Solar Magnetic Fields

V. N. OBRIDKO

IZMIRAN, Troitsk, Moscow Region, 142092, Russia

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The global magnetic field is divided into a basic and an anomalous components. The dates when these components intersect in each solar cycle are called "equilibrium points". It is stated that the equilibrium points determine the natural scale of magnetic cycles. The odd-zonal potential part of the field at the poles and at the equator is considered. It is shown that the anomalous part is much larger than the basic one.

It is commonly believed that magnetic coupling between the solar hemispheres exists only at the minimum of the cycle. However the analysis of experimental data has shown that the coupling between the hemispheres in the epochs of maximum is as close as in the epochs of minimum. Characteristics of large-scale fields in the Sun can be determined by using the main reference points of the solar cycle. The phase of minimum of the solar cycle can be determined more precisely by using the magnetic field recurrence index and the two-dimensional correlation of the large-scale solar field.

One can use indirect information on the polarity of large-scale fields to reveal a quasi-17-year cycle. One can go further and calculate the source surface field using \( H \alpha \) observations. The obtained field structure proves to agree amazingly well with the characteristics obtained from Stanford magnetic measurements.

1. Introduction

The paper is devoted to the study of global magnetic fields in the Sun, their role in solar activity, in coronal processes, and in formation of the heliosphere. This study is essential for understanding the global processes that determine the cyclic behavior of the solar activity.

A combined study of two objects in the Sun—the global field and the heliosphere, is presented. There are reasons to suggest that the structure and intensity variation of global magnetic fields in the Sun is the main factor determining the dynamics of solar activity and the heliosphere over a 22-year solar magnetic cycle. Unfortunately, a thorough analysis of this basic phenomenon is difficult because direct observations of global fields and the heliosphere are only available for 30 years, i.e. a little more than one solar magnetic cycle. Moreover, the data in this 30-year series are very inhomogeneous.

2. The Principal Data Base

As stated above, the main difficulty in studying cyclic variations of global magnetic fields and the heliosphere is due to the absence of sufficiently long data series. We have at our disposal synoptic maps of photospheric magnetic fields for the time interval from Aug. 1959 to Dec. 1978 (Carrington rotations 1417–1648) obtained by the group of Robert Howard at the Mount-Wilson Observatory (MWO). Another series of observations for Jan. 1975–July 1984 (Carrington rotations 1622–1751) was performed under the guidance of J. W. Harvey at the Kitt-Peak Observatory (KPO). And finally, the third series of data was obtained at the John Wilcox Observatory of the Stanford University (WSO) and was made available to us by J. T. Hoeksema. These observations started in May 1976 (Carrington rotation 1641) and are still continued. If the photospheric magnetic field is known, then, using potential approximation and the source surface hypothesis, one can calculate the source surface field, i.e. the field at the origin of the solar wind.
In our analysis, we have used all three data series in spite of their nonuniformity. The data were reduced to a single scale by comparing the overlapping time intervals. As a result, the data on global magnetic fields and on three-dimensional structure of the heliosphere are now available for the past 35 years (more reliable for the past 29 years). We can also use information on the Interplanetary Magnetic Field polarities (SS IMF data) for approximately the same time interval. They can be reliably restored from geophysical data back to 1957, less reliably to 1945, and very unreliably—to 1926. However nobody ever tried to reconstruct the sector structure and the heliospheric current sheet prior to 1960 from solar observations.

Another problem we face when simulating cyclic variations of the heliosphere is how to select appropriate solar indices. A limited number of indices is enough, but they must adequately describe all aspects of such a complex phenomenon as the solar cycle. In this context, the global indices of the magnetic field and the concept of reference points of the cycle seem promising (Kuklin et al., 1986; Obridko and Yermakov, 1989; Kuklin et al., 1989; Obridko et al., 1989a, b; Obridko and Shelting, 1992; Obridko and Kuklin, 1994).

The principal characteristics of the large-scale structure of solar magnetic fields and the global organization of solar activity must be investigated in different phases of a 22-year magnetic cycle. The main physically consistent phases of the cycle must be isolated and the transition points between the phases (reference points of the cycle) must be substantiated.

3. Global Magnetology of the Sun: Complementary Fluxes and Natural Scale of Cycles

Let us consider the magnetic flux through one of the solar hemispheres. Since direct measurements give the longitudinal field, we have used a potential approximation to calculate the radial component. For definiteness, we shall henceforth discuss the flux through the northern hemisphere. In principle, the flux may be divided into two components associated with “dark” and “light” regions in the solar photosphere, $\Phi_D$ and $\Phi_L$.

![Fig. 1. $\Phi_B$ (solid line) and $\Phi_A$ (dashed line) fluxes in $10^{21}$ Mx units as a function of time in Carrington rotations (CR). Asterisks mark the equilibrium points, dark and light circles—the maxima and minima of the 11-year solar cycles respectively.](image)
The problem of measuring and studying these components as a function of the solar cycle phases was solved to a first approximation by Grotrian and Kunzel (1950) for $\Phi_D$ and by Babcock and Babcock (1953, 1955, 1959) for $\Phi_L$ only in the 50's of the current century.

Our problem can be formulated as follows. Expand the field, $B$, into two parts—"basic" ($B_B$) and "anomalous" ($B_A$), whose fluxes, $\Phi_B$ and $\Phi_A$, coincide with $\Phi_L$ and $\Phi_D$. The equality of fluxes indicates to the equivalence of fields, $B_B - B_L$ and $B_A - B_D$. As seen below, this type of virtual expansion, $B = B_B + B_A$, really exists under potential approximation and is expressed in terms of the dipole and non-dipole parts of the multipole expansion (Yermakov et al., 1995a). (In the original paper, the authors use "normal" for basic fields.)

First, these new indices ($\Phi_A$ and $\Phi_B$) are comparable in magnitude. Then, both indices are variable in sign and complementary in phase, i.e. the extremum of one index coincides with the zero of the other (probably with a lag). Every flux conserves its sign during a solar cycle, though $\Phi_A$ does it between the two successive minima (coinciding in sign with the leading spot in the given cycle), and $\Phi_B$—between the two successive maxima of the Wolf number cycle. The relation between the time evolution of $\Phi_B$ and $\Phi_A$ resembles the sine and cosine functions if the abscissa originates at the minimum of an odd cycle. After a quasi-biennial filter is applied to give the moving average over 24 rotations, the fluxes in the southern hemisphere differ from their counterpart in the northern hemisphere only by the sign, and thus, the $\Phi_B$ and $\Phi_A$ indices are the odd functions with respect to the equator. In fact, we recover the Hale polarity laws in global form.

For further use, it is convenient to introduce special terms for fluxes with the described properties. We shall call them complementary fluxes. Their important feature is the existence of a moment, $\tau$, at the ascending branch of any solar cycle, when both fluxes become equal (we called it "equilibrium point"). As seen below, the location of these points along the time axis is not random. The equilibrium points in the odd cycles (or, briefly, odd equilibrium points) divide the distance between the even equilibrium points into two equal parts. The overall magnetic flux at these latter points is the same and its time integral within the mentioned limits is equal to zero. In accordance with the rule of Gnevyshev and Ohl (1948), we suggest

Fig. 2. Anomalous flux, $\Phi_B$, as a function of the basic flux, $\Phi_A$, in $10^{21}$ Mx units. The arrows show the time direction.
that the even equilibrium points are situated where one magnetic cycle ends, and another (maybe absolutely independent of the previous one, with its own lifetime) starts, to form a natural scale of successive cycles.

Figure 1 illustrates \( \Phi_B(t) \) and \( \Phi_A(t) \) for cycles 20, 21, and the beginning of cycle 22 (July 1987–Nov. 1992); Fig. 2 shows the relationship between these fluxes in the phase plane (time excluded); and Fig. 3 shows the overall flux through the northern hemisphere, \( \Phi(t) \). All plots in Figs. 1–3 are smoothed by averaging over 24 rotations.

The curves for \( \Phi_B(t) \) and \( \Phi_A(t) \) in Fig. 1 display the complementarity features mentioned in the Introduction. The flux values reach \( 10^{22} \) Mx. One can readily see 3 intersection or equilibrium points in the growth phase of the cycles: \( \tau_{20} = 1528 \) CR (Nov. 1967), \( \tau_{21} = 1669 \) CR (June 1978), and \( \tau_{22} = 1805 \) CR (July 1988). Since these points are reliably identified, they can be used to determine the natural scale of solar cycles. Then, the distance \( \tau_{22} - \tau_{20} = 278 \) CR (20.7 years) is the length of the “tenth” magnetic cycle, divided exactly in half by the \( \tau_{21} \) curve (which implies a certain time symmetry).

It is interesting to note that all three equilibrium points coincide with the reference points, \( t_{mA} \), of the corresponding cycles (see below, Section 6).

The complementary fluxes at \( \tau_{20} \) and \( \tau_{22} \) have practically the same value equal to \(-3.45 \times 10^{21} \) Mx. Therefore the phase curve in Fig. 2 (without self-intersections!) is closed, passing twice through the same bisectrix point. The complementary fluxes at \( \tau_{21} \) are \( 1.84 \times 10^{21} \) Mx. However we do not know yet whether the curve will pass through the same point at \( \tau_{23} \). The overall flux behaviour is illustrated in Fig. 3. The \( \tau_{21} \) equilibrium point coincides with the minimum between the \( \Phi_B(t) \) and \( \Phi_A(t) \) maxima. Such a splitting does not occur in even cycles, when the \( \tau_{20} \) and \( \tau_{22} \) points do not stand out. It is interesting to note that the overall flux, \( \Phi \), integrated over the entire magnetic cycle (i.e. from \( \tau_{20} \) to \( \tau_{22} \)) goes to zero. It looks as if the end of one cycle and the beginning of another were two independent acts. Note that separate integration of each complementary flux does not give zero.

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Fig. 3. The sum of the \( \Phi_B \) and \( \Phi_A \) fluxes in \( 10^{21} \) Mx units as function of time in CR. Conventions are the same as in Fig. 1.
4. Polar and Equatorial Field Characteristics

Consider the zonal-odd part of magnetic field at two critical points: at the pole ($\theta = 0$), where $B_r$ is the only component present, and at the equator ($\theta = \pi/2$), where $B_\theta$ is eliminated by longitude averaging in every rotation, zonal-odd part of $B_r$ is zero and only $B_\theta$ is present (Yermakov et al., 1995b). The plots in Figs. 4–8 are smoothed by averaging over 24 rotations.

A combined plot of the polar and equatorial fields for the past 25 years is illustrated in Fig. 4. One can see that the extremum of the polar field falls on the minimum, and the extremum (absolute) of the equatorial field—on the maximum of solar activity.

The division of these components into a basic (dipole) and an anomalous (non-dipole) parts is shown in Figs. 5 and 6. In the polar field, both components are seen to reach their maximum values at the sunspot minimum. However, the anomalous (non-dipole) component exceeds significantly the basic one, which is in conflict with widespread intuitive views. Since the local fields vanish at the minimum of the cycle, it is not clear what can account for such a large non-dipole component at that time.

In the equatorial field, the basic and the anomalous component change in anti-phase, but the anomalous component again exceeds the basic one at the Wolf number maximum. This question will be discussed in more detail in the next section.

At $\theta \to 0$, $B_\theta$ and $B_r$ tend to zero as $\sin \theta$. Figure 7 illustrates the behaviour of their limiting values, $B_\theta/\sin \theta$ and $B_r/\sin \theta$, at the pole. In the same way, $B_r$ and $B_\rho$ at $\theta \to \pi/2$ tend to zero as $\cos \theta$. The behaviour of $B_r/\cos \theta$ and $B_\rho/\cos \theta$ at the equator is shown in Fig. 8. Besides, we introduce useful parameters, $q = B_\theta/B_r$ and $p = B_r/B_\rho$, having a simple geometrical meaning, which is easy to show. For example take some vector on the solar limb in the meridional half-plane ($\rho, z$) at a point with the polar angle, $\theta$. Its extension to the $z$ axis will give intercept $q$. The normal to this vector at its application point, extended to the $\rho$ axis, will give intercept $p$. Both segments are measured in solar radii from the center of the Sun. The relation between $p$ and $q$ can be written as: $p \sin \theta + q \cos \theta = 1$.

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**Fig. 4.** Components $B_r$ (solid line) at the pole and $B_\theta$ (dashed line) at the equator in G as a function of time in Carrington rotations (CR). Dark and light circles show the maxima and minima of the 11-year solar cycles, respectively.
Fig. 5. Basic (solid line) and anomalous (dashed line) parts of $B_r$ at the pole in Gauss as a function of time in CR. The other conventions are the same as in Fig. 1.

Fig. 6. Basic (solid line) and anomalous (dashed line) parts of $B_\theta$ at the equator in Gauss as a function of time in CR. The other conventions are the same as in Fig. 1.
Fig. 7. $B_\theta / \sin \theta$ (solid line) and $B_\phi / \sin \theta$ (dashed line) at the pole in G as a function of time in CR.

Fig. 8. $B_r / \cos \theta$ (solid line) and $B_\phi / \cos \theta$ (dashed line) at the equator in G as a function of time in CR.
Both curves in Fig. 7 are synchronous, and zero points coincide with the phase of solar minimum. The ratio of the curves (outside the zero points) gives $q$ of the order of 0.6–0.7 (the field deviates from the polar axis). In Fig. 8, the zero points fall on the phase of maximum, and the ratio of curves (outside the zero points) gives $p$ of the order of 0.8–0.9 (the field shifts to the equator). This corroborates the anomalous character of the polar and the equatorial fields, at least near the minimum and the maximum of the cycle, respectively. If the field lines are identified with polar rays, we can state that the anomalous character of the polar field was first reported in 1950 by van de Hulst (1950), who measured the $q$-parameter for polar rays from the eclipse corona pictures, and obtained the value close to that given above. The result was corroborated later, e.g. by Saito (1958) and Nesmyanovich (1962).

5. Magnetic Coupling of the Hemispheres

From Figs. 1–3, we see that the total flux through a hemisphere at the maximum of the cycle is not zero: the net anomalous flux is very large, while the basic (dipole) flux goes to zero. The same result is inferred from Fig. 4, where $B_\theta$ at the equator reaches its extremum value in the period of solar maximum. Skylab observations revealed high loops connecting active regions in different hemispheres. However, those loops lay high in the corona and appeared at the descending branch of the cycle. In our case, the coupling between the hemispheres in the epochs of maximum is observed at the photospheric level. It can be estimated as follows. Figure 9 illustrates the time dependence of the measured longitudinal flux, $B_p \sin \theta$, and its ratio to the integral absolute flux, $|B_p \sin \theta|$. Calculations carried out in potential approximation using $B_p$ lead to the same result. As seen from the figure, about 40% of the flux tubes close over the equator, and the sign of the meridional component of the magnetic field remains constant almost all over the cycle. The latter may be important for geophysical forecasting. We interpret this phenomenon proceeding from

![Fig. 9. Flux of the measured longitudinal field, $B_p \sin \theta$, as a function of time (solid curve and left-hand ordinate axis), as well as the ratio of this flux and the integral absolute flux $|B_p \sin \theta|$ (dashed curve and the right-hand ordinate axis).]
disbalance of fluxes of the leading and the following polarities in sunspot groups discovered by Grotrian and Künzel (1950) and discussed in later work (Irgashev, 1977; Gopasyuk and Lasareva, 1987).

6. Global Field Indices and Reference Points of the Cycle

Large-scale field characteristics can be determined by using the main reference points of the cycle (Kuklin et al., 1986, 1989; Obridko and Kuklin, 1994). The concept of reference points is very important. These points manifest fundamental changes in the regime of space-time organization of solar activity, rather than showing a mere jump of the time derivative of one or another index. The knowledge of the reference points lays a new foundation for the problem of solar activity prediction. The reference points are determined from main parameters by rather a complicated procedure. Their simplified meaning is as follows: $t_{mA}$ and $t_{AM}$ are, respectively, the beginning and the end of the ascending phase of the cycle, and $t_{MD}$ and $t_{DM}$—the beginning and the end of the descending phase. Besides, point m denotes the minimum, and point M—the maximum of the cycle.

We have introduced an index that represents the mean square field at the solar surface or at any other surface of a given radius, including the source surface, (Obridko and Yermakov, 1989). The characteristic cyclic curves of these full and partial indices (zonal and sectorial) form the “certificate” of a reference point. Besides the cyclic curve at the source surface is very much like the curve plotted from measurements of the Sun as a star. By comparing different solar indices with the Wolf numbers and the global field indices, one can determine the scale of a given process in the Sun. In particular, it turned out that coronal holes were controlled by global fields (and contrary to the wide-spread opinion, did not rotate as a solid body (Obridko and Shelting, 1989, 1992)).

Figure 10 illustrates the behaviour of the global field index. The figure is based on more extensive material than used in Obridko and Shelting (1992). The reference points of three solar cycles are indicated.

To specify some characteristic points of the cycle, one can use the geomagnetic activity recurrence index, IR, suggested by Levitin et al. (1995). (Similar indices were introduced before by Sargent (1982) and Bumba and Heina (1990).)

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**Fig. 10.** Global field index (years 1965–1993).
Figure 11 represents the following curves (from bottom to top):

1) the IR(N) index calculated for the whole bulk of data on geomagnetic aa-index and smoothed over 6 rotations; the lower scale shows the numbers of 27-day intervals, beginning with March 21, 1868;

2) the monthly mean Wolf numbers, W, smoothed over 6 months; the number of the month counted from January 1749 is given in the middle scale.

The upper scale is used to show time in years: the whole time interval covers the years 1868 to 1989 (solar activity cycles 11–21). The maxima and the minima of the cycles are marked on the bottom panel with vertical solid and dashed lines, respectively.

Figure 11 demonstrates the capability of the recurrence index (IR) to identify the calendar dates of the main phases and characteristic points of the solar cycle, especially the dates of solar minima. As seen from the figure, IR decreases sharply in the epochs of solar minimum, becoming 1/3 to 1/6 of its maximum value for several months. The minimum value of IR is reached some time after the calendar solar minimum. This delay seems to be associated with the duration of the minimum phase: the lowest IR is observed at the end of the minimum phase (reference point $t_{mA}$). Then, the recurrence index begins to grow slowly, but it remains small for a long time, oscillating in a random way within the range of 0.2–0.4. Such a behaviour is observed all the time during the ascending branch and the maximum of the sunspot cycle, in fact, up to the point, $t_{MD}$, where the phase of maximum ends and the decay phase begins. It is a critical point, where many authors report the sign reversal of the solar magnetic field to take place and the “prolonged” 17-year solar cycle to begin (e.g. see Makarov et al., 1986, 1987). From this moment, the recurrence index grows rapidly to reach its maximum value around or just prior to the calendar date of the solar minimum. It is a manifestation of the well-known stable recurrence of geomagnetic disturbances during the descending branch of solar activity. Then, the recurrence is upset and IR sharply drops to minimum—the cycle is over.

Fig. 11. From top to bottom: IR(N) index smoothed over 6 points, monthly mean Wolf numbers smoothed over 6 points. The scale at the bottom shows the numbers (N) of 27-day intervals beginning with March 21, 1868; the scale in the middle shows the numbers of the months counted from January 1794; the scale at the top is used to identify time in years. Vertical solid lines denote the maxima and dashed lines—the minima of the solar cycles.
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The large-scale solar magnetic field measurements for 1986–1990 obtained at WSO (Stanford) have been used to see how the time variation of the recurrence index is related to the space-time distribution of solar activity. A correlogram has been plotted by calculating the coefficient of linear correlation of the given and the following rotations for every latitude.

Figure 12 represents a correlogram for cycle 21: the abscissa on the lower panel shows Carrington rotations, the ordinate shows the sine of solar latitude*. The upper panel illustrates the dynamics of the recurrence index as a function of time, the 27-day intervals being numbered like in Fig. 11. The

*Note that the correlation coefficient was calculated by subtracting the mean values. Thus, the correlation coefficient at each latitude was found relative to the small-scale field component. This accounts for the fact that in spite of general similarity of the high-latitude fields, minor fluctuations in the polar zone do not correlate. I am grateful to T. Hoeksema who called my attention to this particularity.

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Fig. 12. Correlogram (isolines of the linear correlation coefficients, R, of the large-scale solar magnetic field at a given latitude from rotation to rotation) for solar cycl 21: the abscissa axis shows the numbers of Carrington rotations, the ordinate axis—the sine of the latitude. The isolines of low correlation (from −0.2 to 0.4 with 0.05 steps) are plotted as dashed lines, the isolines of high correlation (from 0.6 to 0.85 with 0.05 steps)—as solid lines. The upper panel illustrates the dynamics of the recurrence index, IR(N). The numbers of 27-day intervals are given at the top.
Fig. 13. Source surface field structure based on H-alpha measurements (left panel) and photospheric JWO magnetic measurements (right panel) for selected Carrington rotations in the 21-st solar cycle.
correlogram consists of isolines of low correlation (coefficient from -0.2 to 0.4; dashed lines with a step of 0.05) and high correlation (coefficient from 0.6 to 0.85, solid lines with a step of 0.05).

At the beginning of the cycle (\(t_{mA}\) point—end of minimum and beginning of growth) the correlation is abruptly violated at all heliolatitudes. A narrow tongue of non-correlation penetrates from high heliolatitudes to the equatorial zone. On the correlogram, it is manifested as a vertical band of low correlation. Then, the band breaks down to form three zones of correlation. This process is followed by a sharp growth of correlation at mid latitudes near the \(t_{MD}\) point (end of maximum and beginning of decay) or, rather, near the \(t_{pm}\) point (pre-minimum introduced by Danilchev et al. (1986)). After that, the zone of high correlation drifts slowly towards lower latitudes, like the Maunder “butterflies”, and reaches the equatorial region by the following solar minimum. Several rotations later, at a moment corresponding to \(t_{mA}\), a new burst of non-correlation occurs at all heliolatitudes. As calculated for cycles 21 and 22, the mentioned moments, \(t_{mA}, t_{MD},\) and \(t_{mA}\), fall on Carrington rotations 1661–1665, 1712, and 1801–1807, respectively.

Note that the equilibrium points introduced above in Section 3 and determining the natural boundaries of the cycles are situated near the \(t_{mA}\) point. It implies that the phase of minimum must be considered part of the previous sunspot cycle.

Comparison of the IR curve with the correlogram shows that cyclic variations of the recurrence index of geomagnetic activity is determined by cyclic variations in the large-scale solar magnetic field correlation in the equatorial zone, taking into account that the Earth changes its position relative to the solar equator by \(\pm 7.25^\circ\) during an annual rotation.

7. Reconstruction of Global Fields from Indirect Data

The results described above are based on a limited amount of data mainly for cycles 20–21. To augment the statistics, one can use vast information on the polarity of large-scale fields obtained from indirect data, including H-alpha observations since 1915 (Makarov et al., 1986, 1987). Let us calculate the index equal to the difference of areas occupied by the northern and the southern polarity in each rotation and in each hemisphere. Then, add together and subtract the obtained values for the two hemispheres to find the latitude and time dependences of the index, both even, and odd about the equator. It turned out that the odd component reveals a quasi-17-year cycle (allowing for the precursor). The even component mainly displays a 2-year cycle, and the field shifts polewards. A pronounced boundary occurs at the latitude of \(-40^\circ\), where the field distribution changes sharply (Obridko et al., 1989b; Obridko and Gaziev, 1992).

As shown by Obridko and Gaziev (1992), the two systems of field records (the direct and indirect H\(\alpha\) measurements) display a good agreement, including the even component relative to the equator. On the other hand, the correlation coefficient for these systems is rather low in the equatorial zone owing to the contribution of unfiltered small-scale fields in H-alpha.

One can go further and calculate the source surface field using H-alpha observations. In this case, instead of polarities we use the fields of \(\pm 300\) microtesla and then, as usual, expand the obtained maps into Legendre polynomials by the method described above (see Section 3). At first sight, the attempt seems invalid, because H-alpha observations provide only the field polarity. However the obtained field structure (see Fig. 13) prove to be amazingly similar to the characteristics obtained from the Stanford magnetic measurements. This is obviously due to the fact that the source surface field structure is mainly determined by large-scale weakly variable background fields. Thus, a possibility arises to reconstruct the heliosphere since 1915.

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