Mirror instability II: The mechanism of nonlinear saturation

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Abstract. Mirror mode disturbances have been reported in many different space plasma environments. We suggest that these structures are fully evolved mirror mode waves that have achieved the condition for marginal stability against further growth. The limiting form is nonlinear, with field variations of the order of 50% of the average field. We argue that as an initially unstable plasma in a uniform field approaches stability, the particle distributions must separate into trapped and untrapped components that respond differently to the changing field. Most of the trapped particles are excluded from the mirror region. Exclusion sufficient to create marginal stability in the vicinity of the magnetic mirrors can be achieved by relatively small field intensifications. The distribution cannot achieve marginal stability without cooling. We envisage the cooling process as a Fermi deceleration achieved as the magnetic wells become deep and the mirror points move apart. Our analysis is both nonlinear and nonquantitative, but it provides an explanation for various aspects of the observations including the commonly reported feature that the mirror waves look like magnetic holes in the ambient field. We describe the pitch angle dependence of the plasma distribution that results from the processes discussed and note that the predicted distributions compare well with the forms observed in plasma data.

Introduction

Mirror mode waves or disturbances are a common feature of those parts of space where the $\beta$ (ratio of plasma pressure to magnetic pressure) is high ($>1$). They were first identified in data from the terrestrial magnetosheath by Kaufmann et al. [1970] and Kaufmann and Horng [1971]. In recent years, the mode has attracted considerable attention from observers [Tsurutani et al., 1982, 1984, 1992, 1993; Russell et al., 1987; Hubert et al., 1989; Balogh et al., 1992; Lacombe et al., 1992; Song et al., 1992; Anderson and Fuselier, 1993; Fazakerley and Southwood, 1994a, b; Erdős and Balogh, 1994 and personal communication, 1994; Phan et al., 1994; Winterhalter et al., 1994; Leckband et al., 1995; Fazakerley et al., 1995; Hill et al., 1995; Lacombe and Belmont, 1995]. The observations have revealed that this instability occurs not only near Earth but also near comets, near Jupiter, and in the solar wind. Collectively, these papers have provided an increasingly complete picture of the properties of the mirror waves.

Mirror waves are not propagating waves; they arise as the result of an instability that is purely growing in the frame of reference of the plasma [Tajiri, 1967; Southwood and Kivelson, 1993]. The apparent oscillatory (but not often periodic) variation of the field and the plasma pressure observed in space are likely to result from the motion of static structures in the plasma frame moving past the spacecraft.

The mirror instability was identified long ago as a feature of high-$\beta$ magnetohydrodynamics [Rudakov and Sagdeev, 1961]. A linear kinetic theory of the mirror instability was given by Tajiri [1967]. In a previous paper [Southwood and Kivelson, 1993], we elucidated the physical processes implicit in the Tajiri [1967] theory [see also Hasegawa, 1969]. In particular, we pointed out the perhaps surprising fact that the instability is one where resonant particles (in this case particles with small velocities parallel to the field, $v//\beta$) are important. Further work on the growth of the mirror instability, based both on theoretical arguments and computer simulation, has been reported by Gary [1992], McKean et al. [1993], and Fazakerley and Southwood [1994b]. Pantellini et al. [1994] and Pantellini et al. [1995] have discussed the modifications of the resonant particle arguments when a parallel electric field is present. In many cases, the parallel electric field is not significant, as, for example, if a cold electron population is present, and we shall consider this to be the case.

In this paper, we discuss aspects of the nonlinear behavior of the instability. The observed signals can have very large amplitudes, and this fact alone suggests that nonlinearity is likely to be important. Tsurutani et al. [1982], for example, indicate that the magnetic total field strength in typical events in the terrestrial magnetosheath can oscillate between 40 nT and 15 nT. Estimating a “background” field strength of the order of the mean (27.5 nT), one sees that $\Delta B / B$ can be of the order of 1/2, a wave amplitude that certainly requires a nonlinear treatment. The physics in the nonlinear regime may strongly differ from the physics of the linear theory that we described in our previous paper [Southwood and Kivelson, 1993].

Ours is not the first nonlinear theory. The earliest is that of Shapiro and Schevchenko [1964], who describe the nonlinear evolution of the instability using quasi-linear theory. In fact, there are clear empirical reasons for feeling that this theory is inapplicable for the instances of mirror instability detected in space, and it is best if we outline these reasons at the start.

Quasi-linear theory traces the evolution of the spatially independent part of the distribution, while nonlinear terms describing spatial variation (which might be called wave-wave interaction terms) are specifically ignored. It follows that the final nonlinear state that results is spatially uniform. The nonlinear signals detected in space are far from spatially uniform, and thus it does not appear to be appropriate to analyze them in the quasi-linear treatment. We do not know explicitly how the pressure anisotropy causing the instability is generated. Hence one cannot say for sure what aspect of the system invalidates a quasi-linear approach, but we can note that quasi-linear approaches are most valid when growth rate is very small [Shapiro and Schevchenko, 1964].
In considering how fully evolved mirror mode structure develops, it might seem natural to consider how the instability evolves from linear through nonlinear growth (as indeed is done in the quasi-linear approach). However, we know something of the final state, and accordingly, we take a less direct approach by first identifying the conditions that prevail in the final evolved state. We then investigate how that state might develop.

In our approach, we start with the assumption that the fully evolved structure is likely to be characterized by the following:

1. A plasma and field configuration that satisfies the marginal condition for growth of the mirror instability. For a bi-Maxwellian plasma, marginal stability requires \[ \frac{\mu}{\mu_n} \left(1 - \frac{T_e}{T_n} \right) + \frac{B^2}{2\mu_n} = 0 \] (1)

2. A plasma and field configuration that is extremely nonuniform spatially, often with \( B_{\text{min}} \) very small with respect to the unperturbed field.

The first of these conditions is consistent with the final state emerging through evolution from a state unstable to the growth of mirror mode waves (i.e., a state in which the left-hand side of equation (1) is negative). As the mirror structure develops, the field and plasma distribution change, so as to decrease the magnitude of the left-hand side of the equation. One would expect the changes to continue until the inequality becomes an equality and the mirror instability is quenched. Observed signatures of anticorrelated field and particle pressure changes can last for very extended periods of time (cf. Erdős and Balogh, 1994), and thereby provide good empirical support for a model of the fully evolved structure as stable.

The second of these conditions is consistent with observational evidence that mirror waves often appear to be dominated by significant field decreases with little evidence of field compressions. This point has been emphasized by Erdős and Balogh [1994] and Winterhalter et al. [1994], who noticed that the perturbations appear as large depressions in an ambient field with little evidence of field increases. Indeed, Winterhalter et al. refer to these structures as "holes" in the solar wind magnetic field. This interpretation differs from familiar illustrations of the nonlinear limit of the mirror instability, which is pictured as a state in which the plasma becomes a patchwork of regions of higher than ambient and lower than ambient field regions, usually with spatially sinusoidal variations (cf. the sketch in Figure 23 of Hasegawa, 1975). We shall argue that in many situations a sinusoidal spatial structure in the nonlinear phase does not lead to stability: rather, the marginal stability condition can be achieved through slight field compression at the magnetic mirrors but requires substantial field decrease in the magnetic wells.

We will find that in the spatially strongly nonuniform system, resonances of the type discussed by Southwood and Kivelson [1993] are not significant. Instead, the critical distinction is between a part of the plasma population that is trapped in magnetic wells and a part of the population that moves freely through the magnetic mirrors. Fermi acceleration appears necessary in adjusting the thermal properties of the plasma in order to achieve stability.

The Evolved Nonlinear State: Equilibrium Condition

We seek a time stationary state that is not spatially uniform and in which the mirror instability has been suppressed. In the evolved state, the field is made up of magnetic bottles, and the field strength varies, perhaps substantially, both along and across the field. We shall assume that the variation of the field is regular in the sense that the maximum field attained in each mirror has the same value, \( B_{\text{max}} \).

The linear instability theory leads one to expect that the scale length of variations along the field much exceeds that across the field. Also, as in the linear theory, it is the motion of the plasma particles along the field direction that controls the behavior of the system. The condition in the more general case is expressed in terms of the time stationary particle distribution function which we write as \( f(\mu, H) \) because we expect it to depend only on the constants of the motion. In a stationary state, the total particle energy, \( H \), is constant and also one may assume that the magnetic moment invariant, \( \mu \), is conserved. The instability condition can be written quite generally as

\[
\frac{\partial^2 f}{\partial s^2} + \frac{\partial f}{\partial s} \left( \frac{\partial f}{\partial \mu} \right) < 0
\]

which reduces to equation (1) for a bi-Maxwellian.

A familiar consequence of writing the condition this way (e.g., Southwood and Kivelson, 1993) is that the mirror condition can be linked directly to the spatial variation of the distribution. In a nonuniform field \( \partial\phi(s) \), where \( s \) is a coordinate measured along the direction of the field, one may write

\[
\frac{\partial f}{\partial s} = \frac{\mu}{B} \frac{\partial B}{\partial s} \frac{\partial f}{\partial \mu}
\]

Hence, as previous authors have pointed out (e.g., Taylor, 1966; Southwood, 1976; Southwood and Kivelson, 1993), the mirror instability condition becomes a condition on the total (magnetic plus gas) pressure, namely,

\[
2\pi \rho \int_0^B \left( \frac{\partial f}{\partial \mu} \right) \left( \frac{\partial f}{\partial s} \right) ds < 0
\]

It follows that, in a nonuniform field, the marginal condition for the mirror instability is

\[
\frac{\partial}{\partial s} \left( \frac{\partial f}{\partial s} \right) < 0
\]

This form generalizes equation (1) and allows for the fact that a bi-Maxwellian distribution cannot be specified in terms of fixed \( T_e\) and \( T_i\) along a flux tube. We expect the final evolved state to satisfy condition (5), and we ask how the development of spatial structure can modify the plasma distribution so that this condition is satisfied everywhere along a flux tube.

Trapping and Particle Energization

If both pressure and field are nonuniform along \( B \), then it follows from equation (3) that the distribution retains a dependence on magnetic moment (and thus pitch angle) in the final state. This is not surprising, as particles of different pitch angle respond in very different ways to the evolution of the instability. For example, particle energy change can be strongly pitch angle dependent.

In the nonuniform field generated by the instability, the magnetic mirror "force" \( -\nabla V(\mathbf{B}) = -\nabla V_B \mathbf{B} \) describes the guiding center motion of particles parallel to the magnetic field. Particles with small pitch angles will travel along the field, alternately speeding up as the field decreases and slowing down as they approach the points where the field strength \( B \) is maximum. This
response acts to increase \( n \) in regions of large \( B \) and decrease it in regions of small \( B \). A response that strengthens the inequality of equation (4). On the other hand, once the disturbance amplitude is finite, the mirror effect can be large enough to reverse the sense of parallel motion for some fraction of the distribution. The exclusion of a part of the distribution decreases \( n \) near the mirrors, but, more important, it creates a trapped population bouncing back and forth in a region bounded by adjacent maxima in the magnetic field. The trapped particle density is largest in the field minima, and this may act to enhance or reduce the inequality in equation (4), depending on how the energy of the particles has changed in the process. At any point where the field strength is \( B \), the trapped population are those particles with pitch angles, \( \alpha \), where

\[
\frac{\pi}{2} > |\alpha| > \sin^{-1}\left(\frac{B}{B_{\text{max}}}\right)^{\frac{1}{2}}
\]

Figure 1 is a schematic illustration of the distinction between the behavior of trapped and untrapped particles. It emphasizes the fact that in a mirror structure, the spatially varying pressure of the untrapped particles along the flux tube produces conditions even more unstable than those of the initial uniform state. On the other hand, the development of regions of enhanced field also creates a trapped population of particles that never reach the mirror field and, at least near the field maximum, reduce the degree of instability.

As the instability develops, the trapped population finds itself bouncing back and forth within an ever-deeper magnetic well. This particle trapping appears to us to be the critical feature in determining the structure of the nonlinear evolved state [Facsko and Southwood 1994b; Pantellini et al., 1994]. The number of particles trapped in the wells increases with decreasing \( B_{\text{min}} \).

The plasma moment relevant to stability is the pressure, not the density, so we must also consider how the energy of the trapped and untrapped particles changes as the field changes. The energization of the particles is by betatron acceleration. In the guiding center limit, one has

\[
\dot{W} = \frac{dW}{dt} = \mu \frac{\partial B}{\partial t}
\]

At one extreme in the population are those (trapped) particles located at the field minima. Those which have \( \alpha = \pi/2 \) do not move at all along the field. They must lose energy. The energy change of these particles is computed from the conservation of \( \mu \):

\[
\Delta W_{\text{tr}} < 0 \quad \Delta V_{\text{tr}} > 0 \quad \Delta n, \Delta \rho, < 0 \quad \Delta n, \Delta \rho, _{> 0}
\]

\[
\Delta \rho_{\perp}, \Delta n > 0 \quad \Delta \rho_{\parallel}, \Delta n < 0 \quad \Delta \rho_{\perp}, \Delta \rho_{\parallel} > 0
\]

Figure 1. A schematic illustration of the distinction between the orbits of untrapped (upper panel) and trapped (lower panel) particles in a mirror geometry. Local velocity, density, and perpendicular pressure perturbations for adiabatic responses are characterized below each panel.

At the opposite extreme are those (untrapped) particles with \( \alpha = 0 \). For these particles, \( \mu = 0 \), and there is no energization at all. It seems reasonable to postulate that the energy of untrapped particles is much less affected by the instability than the energy of the trapped particles because they move both through accelerating and decelerating fields. The trapped particles, which experience greater changes in energy, take the role that we have attributed to the resonant particles in the linear instability.

As we have noted, near the center of the well the trapped particles necessarily lose perpendicular energy and total energy: this is likely to be an important element of the instability saturation process. However, not all trapped particles need lose energy during the instability development. Particles whose mirror points have been moving together as the field has weakened may have gained energy. These particles, if any, will be likely to have mirror points on the edge of the well. The way in which the changing field configuration leads to Fermi acceleration of part of the distribution and deceleration of part of the distribution is illustrated in Figure 2 for a sinusoidally varying magnetic field in which the amplitude of the field variation is increasing with time. In successive snapshots, it is clear that particles mirroring close to the minima see their mirror fields moving apart and thus cool. Particles mirror close to the maxima see their mirror fields converging and thus gain energy. The sinusoid is a special case, but the process is quite general.

It is thus clear that adjustments of the fraction of the particles that is trapped in the wells are controlled largely by the ratio \( B_{\text{min}}/B_{\text{max}} \), while the pressure in the wells is controlled by the time variation of the field magnitude along the field direction associated with the development of the spatial structure. These features of the spatial variation can be varied independently to achieve the total pressure balance required in equilibrium.

**Saturation Mechanisms**

The separation of the distribution into trapped and untrapped parts and the different responses expected for each lead us to propose two different saturation mechanisms, one that operates at the peak field and one that operates in the magnetic wells. Both work in parallel to suppress the instability.

We assume that we start with a pathological distribution that is uniform but satisfies the instability condition (2). The instability then develops, and the field becomes nonuniform. Let us first consider what happens where the field increases. As the field rises, the density and pressure will drop as particles with large pitch angles are excluded from the rising field region by the mirror effect and the onset of trapping. Eventually, simply by dint of the pressure reduction, we can envisage that condition (5) can be achieved locally and lead to suppression of growth at the mirror location.

We illustrate the effect explicitly by computing \( \Delta K \), the amount by which the distribution exceeds the instability requirement, that is, we calculate the left side of equation (2) as a function of \( B \) at the mirror position

\[
\Delta K = \frac{\omega}{2\pi} \frac{dW}{dB} \left[ B^2 \mu \frac{\partial f}{\partial \mu} + B^2 \right] = 0
\]

As the field increases, the exclusion of the trapped particles from the distribution causes the pressure to drop. In Figure 3 this effect is illustrated for a bi-Maxwellian plasma for which \( T_r/T_i \) = 2 and the initial plasma \( \beta_i = 2 \). (\( \beta_i \) is the ratio of the perpendicular pressure \( \rho_{\perp} \) to the magnetic pressure \( B^2/2\mu_0 \)).
Figure 2. The way in which the changing amplitude of a sinusoidally varying magnetic field causes Fermi acceleration of part of the distribution and deceleration of part of the distribution. The time sequence of the wave amplitude is from the solid curve to the heavy dashed curve. (a) Perturbations at three different times. (b) Bounce orbits of representative particles mirroring at field strengths larger than the mean field (heavy solid line) and smaller than the mean field (heavy dashed line). (c) The bounce orbits of these same particles at a time when the amplitude has grown. The mirror point fields remain unchanged, but their spatial locations have separated for the one mirroring at the lower field magnitude and have converged for the one mirroring at the higher field magnitude.

These plasma conditions are unstable according to equation (4). The plot shows the density, the particle pressure, the total (thermal plus magnetic) pressure, and $\Delta K$. We have assumed that the plasma responds adiabatically, conserving $\mu$ and $W$. When the field has increased by 13%, $\Delta K = 0$, and the marginal condition has been achieved.

The same mechanism cannot work in the regions where the field decreases. Certainly, in the center of the well no particles are excluded, and if $\mu$ and $W$ are conserved, the density and the thermal pressure rise. Of course, the field pressure itself decreases, but the total pressure continues to rise as the field magnitude gets smaller. This is illustrated in Figure 4, which shows the evolution of the density, the particle pressure, and the total pressure for a bi-Maxwellian distribution as $B$ decreases but the particles conserve $\mu$ and $W$. Evidently, the constant total pressure condition required for stability by equation (4) is not satisfied. Indeed, the marginal instability condition cannot be achieved without modifying the way that the distribution $f(\mu, W)$ varies with $\mu$ and $W$.

Clearly, some particle cooling beyond that imposed by adiabaticity is required in order to achieve stability. Furthermore, Figure 5, which shows separately the density and pressure of trapped and untrapped particles, makes it clear that the cooling must affect the trapped particles. In Figure 6, we show the effect of an alternative scenario in which, as the field decreases, all of the trapped particles cool by reducing their total energy by an amount proportional to the local decrease in field:

Figure 3. The variations of the perpendicular pressure, the density, and the total (thermal plus magnetic) pressure of a bi-Maxwellian plasma responding adiabatically to an increasing magnetic field. The initial plasma conditions are $T_\perp/T || = 2$, and the initial plasma $\beta_\perp = 2$. Density is measured in units of the initial density, pressure is given in units of $B_0^2/2\mu_0$, and the field is measured in units of $B_0$. Also plotted is $\Delta K$ of equation (9), the amount by which the distribution exceeds the instability requirement.
Figure 4. For the same initial plasma conditions and normalization as Figure 3, the variation of the perpendicular pressure, the density, and the total (thermal plus magnetic) pressure as a function of $B$ for $B < B_m$, assuming that the particles conserve $\mu$ and $W$ as the field changes.

\[ \Delta W = \mu \Delta B = W'(\Delta B/B) \]  

This expression is correct near the center of the well for the locally mirroring particles but otherwise overestimates the potential cooling. It is evident from Figure 6 that this extreme cooling takes the system well beyond the pressure reduction required to satisfy the stability condition.

We suggest therefore that the trapped particles are cooled in a manner less extreme than envisaged in obtaining Figure 6 and that the system cools until the distribution in the well attains the marginal condition (5). The cooling that is required for the trapped particles in the well can readily be produced by moving magnetic mirrors. Deceleration occurs if the magnetic mirrors move apart. The approach to stability is then achieved by a combination of a decrease of field between the magnetic mirrors and a motion of the magnetic mirrors away from the minimum in the well, which cools the distribution.

Quantitative explanations of how the configuration of the system evolves require us to remember that trapped particles can gain or lose energy. Equation (7) shows that only those particles that penetrate a region of increasing field can ever gain energy. For trapped particles that bounce back and forth, the mean rate of change of energy is the local rate given by equation (7) appropriately averaged over the fraction of the well in which the particle is bouncing, i.e.,

Figure 5. As for Figure 4 but separately for (a) trapped and (b) untrapped particles.

Figure 6. As for Figure 4 but showing (a) the pressure and density of the trapped distribution if particles conserve $\mu$ but decrease energy by the betatron process as they move into weaker fields and (b) the contribution of the untrapped distribution added assuming that untrapped particles conserve both $\mu$ and $W$. 

\[ p_{\text{untrapped}} = p_{\text{total}} - p_{\text{trapped}} \]
\[ \dot{W} = \frac{1}{\tau_B} \int \frac{\partial B}{\partial t} \frac{ds}{v_{\parallel}} \mu \]  

(11)

where \( \tau_B \) is the trapping period and the integral is taken over a full bounce.

Now any particle that detects only decreasing field must lose energy over time. A particle that reaches the rising field region does so inevitably near its mirror point, where it moves slowly along \( B \); thus it is likely to gain energy over a bounce orbit. Over many bounces, the particles that see their mirror points moving together (see Figure 2) gain energy and those that see them moving apart, lose energy. Substantial cooling, which we have shown is necessary, can be obtained if the mirror points continue to move apart.

Empirically, one can try to deduce from spacecraft observations which case is likely to pertain in any given event. A pattern of fluctuations in which the compressions of \( B \) last on average longer than the rarefactions of \( B \) would suggest that heating occurs for a substantial fraction of the particles. Shorter duration compressions and longer lasting rarefactions such as those cited previously are symptomatic of a situation where most of the bouncing particles lose energy. As it is likely that the motion of the spacecraft is oblique to the structure, the interpretation is not foolproof, but it is surely suggestive.

Our analysis implies that any heating that occurs as the mirror structures evolve will affect particles of intermediate pitch angle in the center of the well, which may mirror in regions where the field increases as the instability develops. We have indicated why these particles can gain energy. In Figure 7, we sketch various scenarios of evolution for distribution function contours. Figure 7a shows the original bi-Maxwellian elliptic contours of constant phase space density. In Figure 7b, we show schematically the contours that arise when particle energy changes linearly with \( B \) and we mark \( \alpha_c \), the limiting pitch angle that separates trapped and untrapped particles, and \( \alpha_p \), the pitch angle of particles that mirror where the field has the unperturbed field magnitude. In Figure 7c we show the form of the contours that would result if the particles near the trapping boundary (especially those with pitch angles just slightly larger than \( \alpha_c \)) were heated preferentially.

Leckband et al. [1995] have examined a case of nonlinear mirror waves in the terrestrial magnetosheath. They averaged distribution functions measured in wave troughs and plotted (their Figure 2b) the ratio of the distribution function to a bi-Maxwellian fit. For the event examined, \( \alpha_c = 30^\circ \). The predominant feature of the Leckband et al. [1995] plot is that there is pronounced peak in the distribution function at pitch angles above \( \alpha_c \). Despite the fact that peak does not extend over all energies, we feel that the distortion of the distribution function is qualitatively consistent with the suggestions made here.

In our picture, the field strength in the mirrors required for saturation would differ little from the ambient field. The fields, associated with significant changes in the field magnitude, would be expected to extend much farther along the flux tubes than the enhanced field regions. This could be the explanation of the predominance of depressed field regions over strong field evident in the Leckband et al. [1995] event.

**Consequences of the Scenario**

We have proposed that two separate mechanisms act to stabilize growing mirror disturbances in a high-\( B \) plasma. Both depend on the process of particle trapping identified by Fazakerley and Southwood [1994b] and Pantellini et al. [1994]. The final evolved state is likely to be one where the total perpendicular pressure (field plus plasma) does not vary along the field (condition (5)). In the part of the disturbance where the background field is enhanced, the primary saturation mechanism is through trapping which precludes particles from penetrating the higher field. This produces locally a net decrease in particle pressure and thus allows the marginally stable state to be attained. Changes in particle energy are not important in the high field region. In contrast, in the wells, we have shown that marginal stability cannot be attained without cooling some part of the trapped distribution. We have demonstrated that the required degree of cooling is not extreme. The particles with 90\(^\circ\) pitch angle lose energy directly in proportion to the decrease in field. The assumption that all trapped particles lose energy in the same way is surely an overestimate, and it produces cooling greater than that needed for stabilization. Thus, some less extreme cooling effect is required. The deceleration that the

![Figure 7](image-url)
particles experience if trapped in separating magnetic mirrors appears likely to provide the required change.

If our speculation on stabilizing mechanisms is correct, one may note that several observed features of the waves may be explained. First, we can rationalize the suggestion of Erdös and Balogh [1994] and Winterhalter et al. [1994] that the mirror events correspond to the development of holes in a background field rather than alternate compressions and rarefactions of the field. Our approach suggests that slight compression suffices to return a plasma to marginal stability near the mirrors, but large reductions in the field are required in the wells in order to cool the trapped population enough to stabilize the system. Qualitative aspects of measured plasma distributions in the wells also appear to be consistent with our model.

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