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Interactive comment on “Mirror mode physics: Amplitude limit” *by* Rudolf A. Treumann and Wolfgang Baumjohann

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General Comment:

1. We thank all four Reviewers for their efforts in evaluating our paper and their (mostly) constructive comments.

From reading the reviews it becomes clear that this whole item is fairly difficult and by far not ultimately explored. We are very well aware of this but have chosen to nevertheless inject the idea into the space plasma community for its unexpected fundamental physical interest and probably also its singularity in application.

We have chosen to formulate this general comment as an answer to the reviewers for making it easier for them to read (and for us to write) the general (anyway overlapping)

response, which is detailed enough, than a response to each minor or larger point in the 4 reviews. The reviewers essentially raise all the same questions. So it makes sense to write a common response.

Nevertheless we also provide brief responses to each reviewer just focussing on their main points. The demanded minor corrections we will do without noting them explicitly. We believe that in science one should have sufficient trust in each other such that those which we consider worth correcting/changing will have be done by resubmission.

In the MS we have made a number of changes (according to the suggestions of the Reviewers and in the spirit of these general comments). All changes are in blue for easy reading.

2. It indeed seems that mirror modes are a rare case, possibly the sole case in high temperature plasma physics where an effect like the one proposed here may take place: pair formation resembling a quantum effect known from superconductivity but this time in a classical system. The idea is based on early work in the 1950ies referring to plasma oscillations (Langmuir waves) which was intended to apply to superconductivity but did not work. It was formally picked up by one later Nobel laureate, Nambu, to show that instead ion sound (exactly the phonos in superconductivity) instead of Langmuir waves would be more promising. But there was nowhere any application in sight.

We have made these calculation more precise to derive the exact and applicable conditions for pairing. We also have shown that the pairing condition can be applied formally to any other plasma wave, even electromagnetic waves. Though this is interesting, it does not mean that it would work. In fact it will not for most waves. The basic problem with this entire approach is the required resonance condition. For electrostatic waves it relies on the approximate equality of the wave phase velocity with the particle speed, a condition very difficult to satisfy because in high temperture plasmas electrostatic phase velocities are generally small, and thus the fast particles will barely interact or enter the required resonance. Electromagnetic waves have higher phase speeds but for them the electric field is perpendicular to the propagation. The required resonance supposes gyrobunching and thus will be rather ineffective. In any case conditions for attractive potentials will be sparse. One of the reviewers complained the restriction to electrostatic waves. His complaint safely be rejected. The exception is KAW which we did not investigate.

3. However, considering the bounce motion of electrons (or ions) in mirrors modes, once they have developed and are of sufficiently large amplitude, which we assume is the quasilinear stable state, is a promising case, possibly the only promising case in plasma. Bouncing particles (electrons and as well ions) have sufficiently low parallel speeds around their mirror points for going into resonance with slow parallel propagating electrostatic waves. This applies only to their parallel speed. This makes attractive potentials probable for a number of the mirror trapped bouncing particles. These attractive potentials are useless of they do not attract another particle of same charge.

However, for attracting another particle one needs to include its effect. Therefore our efforts to calculate the two particle case (the singlet) which resembles Cooper pairs. Three electron interactions (triplets) are improbable. We have checked this but not included. The triplet probability is low, this means, the trapping condition is highly restricted to a narrow range of parameters only, so not being of any importance. We also restricted to electrons here for obvious reasons. The claim to include ions (as put forward by one of the reviewers again) is not unreasonable but not necessary at this stage. For ions similar conditions should hold which are modified by the ion mass and cause different potentials. Calculation would go along same lines.

4. Staying with electrons it becomes clear from our calculation that two electrons with close-by mirror points and in approximate resonance with ion sound (in our case because of the parallel electric field and phase speed) can under the derived conditions form pairs. For any equatorial electron pitch angle distribution inside the mirror there will be a distribution of bounce-mirror points along the magnetic field, and hence a

distribution of pairs along the magnetic field. Calculating it requires inclusion of the pitch angle distribution (which we did not do at this stage of the theory). Once the pair has formed it has nearly same speed as the ion sound plus a small oscillation around the mirror point. If the pair is stable, which is quite a different question, which we did not investigate but which is of importance, requiring further analysis, then all energy of motion is in the perpendicular speed with very little left for the oscillation around the mirror point.

We have shown, that the electrons which form pairs must have energies above but very close to thermal energy. Hence their perpendicular speed is roughly thermal, from which follows that they have all about same gyroradius, depending only on the location in the magnetic field. In this sense they are coherent while not bunched by no means, as the phase of the gyration plays no role for the pair. It is their parallel motion which determines the paring.

5. The question is whether they can escape or not from the mirror points in order to return into bounce, a question raised by two reviewers. This is the question of stability. Since this requires solving the stability problem, a different paper, we have not attacked it. However, there is an interesting argument: at the mirror point Z=s_m and if they remain in resonance with the ion sound whose velocity is unaffected in this interaction, then they will become locked at the mirror points and drop out from bouncing. Locking depends on the energy in the rudimentary oscillation velocity u around the mirror point. The pair here at its common mirror point has zero parallel speed U=0. So it needs to become catapulted out in order to continue bouncing. If the remaining energy in the jitter motion uˆ2, the small amplitude oscillation, exceeds the trapping potential, then the mirror force will take over and the trapping will not be stable, the restoring force of the bounce will destroy the pair and reinject the two electrons into the general bouncing. For some of the electronic population this will be the case. However, for some it will not, becasue being in resonance with the ion sound phonon (which has nothing in common with the bounce force) these pairs with small uˆ2 become extracted

from bounce and will be stable and consequently become locked to the phonon for comparably long time near the mirror points s_m.

In addition, of course, it is also possible that the destroyed pairs will be replaced by new ones which form in interaction with other ion sound waves, the equivalent in Cooper pairs which form and decay and form anew. Since the particles have no identity this replacement implies that there will always be a certain number of pairs even though this number may fluctuate. Thus one expects that a continuous population of (electron) pairs exists in a mirror mode. Either electrons, which we investigated, or ions which also may form pairs under modified conditions which we dared to investigate here.

6. Now there are a number of questions:

First, is it necessary to include the Lorentz force (as one of the reviewers demanded)? The answer is clearly no. For pair formation it is definitely not necessary as long as one does not refer to electromagnetic waves (see above) and stay in the nonrelativistic domain (which we did). So at this stage it seems unnecessary to call for the Lorentz force. That part of it which refers to the bounce, the mirror force, is incuded in the calculation by reference to the bounce motion. The above arguments suffice in this respect.

Second: we took into account ion sound waves for two reasons. They are almost always present and have parallel relatively high phase speeds in favour of application in mirror modes to electrons. Most other electrostatic waves have perpendicular electric fields, Bernstein modes for instance. Electromagnetic waves, whistlers for instance have favourably high parallel speeds but perpendicular electric fields as well. Hence their interaction with electrons is strongly modified and much more complicated. Resonance requires cyclotron resonance and thus is restricted to a different group of electrons in spite of their advantage, the higher phase speed. In principle the basic equation for the potential holds also for them as well (we have given the condition in the paper) but the resonance condition must be reinterpreted. We do not see any reason to do this at this stage. This would be a totally different investigation. The same argument applies for ions to ion-cyclotron waves.

Third: we have not investigated the stability of electron pairs but in the above gave arguments that at least a group of electrons will build up stable pairs.

Fourth: we have not considered ions so far. Their interaction with ion sound might possibly cause similar effects. The potential will be different though because of their mass, but they favourably have slower velocities which in pairing might make them lesser dependent on bouncing than electrons which, however, is not known to us whether it is favourable or not. Possibly their contribution is important in view of the application to mirror modes where they are anyway trapped and bounce as well around. If they pair, however, their reduced deendence or even independence on the mirror points will not have a positive effect on the evolution of the mirror mode. This contrasts electrons where some pairs remain locked at the mirror points. But at this stage we refrain from applying the theory to ions even though it seems simple. The formal equation will be the same. We are happy with having solved the difficult problem for singlet paired electrons.

Focussing on electrons was central to our approach. However the basic equations hold as well for ions and for any other plasma wave which satisfies the resonance. This is quite clear physics. Hence, the theory, with ittle changes, applies to them. We have not checked the effect of their larger inertia. Both possibilities exists that ion pairs are less or more stable. In any case their effect might be similar whether stronger or weaker is a question of a separate investigation.

Fifth: We have not investigated in any detail the role the large perpendicular anisotropy of the pairs plays in the evolution of other instabilities, in particular the electron mirror mode. We have just mentioned the fact in the paper.

It is however clear that if a large number of electron pairs is locked in gyration, then the large anisotropy will contribute mainly to the electron mirror mode which is smaller scale and has been observed. Maybe its observation at comparably large amplitude is already proof of the reality of electron pairing. This we have not investigated. In addition the electron anisotropy could also exite resonant whistlers, which have also been observed.

Sixth: Our application to the amplitude of mirror modes is just heuristically motivated. It is based on the assumption that a sufficiently large number of electron pairs is locked in gyration with nearly same gyration speed which implies a current. We were speaking about “coherence” but do not mean phase coherence, just gyration coherence. The pairs are not bunched but contribute to a surface current whose magnetic effect is diamagnetic thus increasing the depletion of the magnetic field. This we have heuristically accounted by estimating the susceptibility. It is clear that pressure balance in this case must be provided by instreaming of untrapped plasma along the magnetic field from outside the mirror bubble. We simply assumed that pressure balance is given. However this theory is preliminary.

Seventh: there is the question on what we called coherence. It should be clear to everyone that coherence here is not phase coherence or bunching. Locking in pairs and escaping from bounce by having all energy in the perpendicular at almost same thermal speed means that all pairs gyrate at about same gyroradius for the field value at a given s_m forming a shell of nearly common radius. This shell thus carries the diamagnetic surface current whose effect we estimated giving a heuristic argument. This is meant by coherence, not phase coherence which is nonsensical as it is not generated by pairing.

Eighth: The final question we address here (leaving aside a number of others) concerns pressure balance. Clearly quasilinear theory provides pressure balance. However if additional expansion of the magnetic field is generated then pressure balance must be restored. A minor contribution is caused by magnetic stresses in the surface current, as is well known. However the main effect is due to inflow of quasi-neutral plasma from the environment along the magnetic field. This plasma has very small

perpendicular energy, less than required for bouncing. Magnetic moment conservation will cool it in perpendicular direction when approaching the centre. However, its mere number increases the pressure in the mirror bottle to account for pressure balance. So, pressure balance will be warranted in this way.

It would be very interesting if observations could be designed to check these proposals or to vindicate them. If it could be confirmed experimentally that pairing in a classical plasma is possible as proposed here, then mirror modes would be the ideal place to check for all the effects listed. Maybe observation of large amplitude electron mirror modes and localized large amplitude whistlers, both excited by the large perpendicular anisotropy of the pair component, are indications of pairs. In any case, identification of pairs is an interesting task to be performed experimentally because of its deep physical meaning.

Once more, we express our thanks to the intriguing and important comments of all 4 reviewers. We have answered here the main questions which concerned mostly around the non-solved problem of stability of pairs. Our investigation is a first step in that direction, while investigation of stability would be the next step before including the pitchangle distribution, constructing the real spatial distribution of pairs and for the stable pair population developing the microscopic theory of the magnetic susceptibility. We shall includ changes accordingly (in blue again) into the resubmission.

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