A LETTERS JOURNAL EXPLORING
THE FRONTIERS OF PHYSICS

OFFPRINT

**Reply to the Comment by P. K. Shukla and M.
Akbari-Moghanjoughi**

J. VRANJES, B. P. PANDEY and S. POEDTS

EPL, **99** (2012) 65002

Please visit the new website
www.epljournal.org

Reply

Reply to the Comment by P. K. Shukla and M. Akbari-Moghanjoughi

J. VRANJES^{1(a)}, B. P. PANDEY^{2(b)} and S. POEDTS^{3(c)}
¹ Von Karman Institute - Waterloosesteenweg 72, 1640 Sint-Genesius-Rode, Brussels, Belgium, EU

² Department of Physics and Astronomy, Macquarie University - Sydney, NSW 2109, Australia

³ Center for Plasma Astrophysics, and Leuven Mathematical Modeling and Computational Science Center (LMCC), K. U. Leuven - Celestijnenlaan 200B, 3001 Leuven, Belgium, EU

received 8 August 2012; accepted in final form 22 August 2012

published online 24 September 2012

PACS 52.27.-h – Basic studies of specific kinds of plasmas

Copyright © EPLA, 2012

We do not see the point of invoking some classical works on quantum phenomena as Shukla and Akbari-Moghanjoughi do in their Comment. The objective of our letter [1] is clearly defined in our text: works on quantum plasma published in the past few years. Hence, we did not deal with works of “*many distinguished physicists*” who “*laid down foundation to collective interactions in dense quantum plasmas*” about sixty years ago, and we also did not analyze any “*Nobel Prize winning paper*” from 80 years ago. Our concern is how the quantum theory is being used in plasma nowadays and in particular within the fluid plasma theory.

We discussed several criteria in [1] which should be checked before using quantum effects in plasma physics. These include the following ones: i) applicability of fluid theory (discussed in the first paragraph and in table 1); ii) temperature-density relation which follows from de Broglie-Heisenberg relations; iii) the condition of weakly non-ideal plasma (discussed on page 2 and in table 1); and iv) electron degeneracy.

The items i) and iii) are essential for the application of fluid equations, and they are discussed in relation with quantum effects in our work [1]. However, these items have not been tackled at all by Shukla and Akbari-Moghanjoughi. Instead, in their Comment Shukla and Akbari-Moghanjoughi write about “metallic conductors” and “solid density plasma”. We observe that the term “solid density” can hardly have any meaning. On the other hand, in [1] we did not mention at all metallic conductors. Instead of concentrating on real issues, Shukla

and Akbari-Moghanjoughi speak about metallic conductors which are out of scope.

Practically all the Comment by Shukla and Akbari-Moghanjoughi is devoted to the degeneracy temperature (which is our item iv) for which we used 8 lines only).

The worthlessness of the objections by Shukla and Akbari-Moghanjoughi may be seen from *their* criterion for the applicability of classical theory at room temperature:

$$n \ll 10^{24} \text{ m}^{-3}. \quad (1)$$

We note that, for example, the number density for air at room temperature is around $3 \cdot 10^{25} \text{ m}^{-3}$ which is greater than the value given above. Yet, we do not recall anybody using quantum theory to discuss dynamics of air and terrestrial atmosphere. As Shukla and Akbari-Moghanjoughi claim with the number given in eq. (1), the air density and most of the world around requires quantum theory. In fact the true value that should be in eq. (1) is around 4 orders of magnitude greater, *i.e.*, $8.2 \cdot 10^{27} \text{ m}^{-3}$ as follows from our work [1].

The correct value for the degeneracy temperature threshold follows from Fermi-Dirac statistics that can be found in any good book, $T < [h^2/(2m_e\kappa)][n/(2.76\pi)]^{2/3}$, and which consequently yields

$$T < 4 \cdot 10^{-15} n^{2/3}. \quad (2)$$

Here the temperature is in K and the number density in m^{-3} . Taking for example a typical fusion plasma with $n = 10^{20} \text{ m}^{-3}$ yields $T < 0.09 \text{ K}$. Hence, in view of such a low-temperature threshold needed for quantum effects to appear, it is clear that their importance is very limited, as we claimed in [1]; the typographical error $n^{3/2}$ instead of $n^{2/3}$, which Shukla and Akbari-Moghanjoughi refer to, changes nothing in physics and in our conclusions.

^(a)E-mail: jvranjes@yahoo.com

^(b)E-mail: drbp.pandey@gmail.com

^(c)E-mail: Stefaan.Poedts@wis.kuleuven.be

Due to unknown reasons Shukla and Akbari-Moghanjoughi invoke also Saha's ionization criterion into discussion and claim that it "dictates that in order for the plasma to form one must have sufficiently high degree of ionization". This is an absurd statement, and just for the benefit of Shukla and Akbari-Moghanjoughi we stress that an ionized gas is called "plasma" if: 1) the Debye length is well below the system scale; 2) there is a sufficient number of particles per unit volume; and 3) the plasma frequency is well above the collision frequency. These conditions may be discussed without invoking neutrals, therefore the Saha formula has nothing to do with this. Saha's ionization formula merely determines the ionization ratio in a mixture containing gas and charged species, and this only on condition of thermodynamic equilibrium and by assuming an ideal gas, *i.e.*, containing non-interacting species so that the total partition function is just the product of partition functions of all species. In other words, the Coulomb interaction between the species (which implies the collective behavior) is completely ignored. For that reason the Saha equation cannot possibly "dictate" the forming of a plasma, although it nicely describes some of its properties for very weakly ionized gases. This issue, however, is completely out of scope of our work [1], and Shukla and Akbari-Moghanjoughi would do better without it. This is because they talk about ridiculously low ionization of air at room temperature and yet in the same breath they immediately contradict themselves by writing about low-temperature plasmas at

room temperature, from which they derive their wrong criterion given in eq. (1) above.

In their lengthy discussion *related to degeneracy* Shukla and Akbari-Moghanjoughi "*conclude*" that our "*figure and the table displayed in ref. [1] are fallacious, and are of no use for defining the regimes of quantum plasmas*". We observe that our figure and table had nothing to do with degeneracy (the criterion iv)) but with criteria i), ii) and iii) mentioned above, and both figure and table are completely correct and in agreement with any plasma physics textbook. Shukla and Akbari-Moghanjoughi did not provide any argument that would prove the opposite. On the contrary, eq. (1) given above contains a trivially wrong condition given by Shukla and Akbari-Moghanjoughi so it cannot be used against our results.

To make this Reply self-contained and easy to read, here we provide the values of constants used above: $\kappa = 1.3807 \cdot 10^{-23} \text{ J/K}$, $m_e = 9.1094 \cdot 10^{-31} \text{ kg}$, $h = 6.6261 \cdot 10^{-34} \text{ Js}$, $\hbar = 1.0546 \cdot 10^{-34} \text{ Js}$.

We conclude that a) Shukla and Akbari-Moghanjoughi ignored our criteria i) and iii) which are essential for application of fluid dynamics with quantum effects, and b) their criticism of our criteria ii) and iv) is against elementary facts.

REFERENCES

- [1] VRANJES J., PANDEY B. P. and POEDTS S., *EPL*, **99** (2012) 25001.