APPENDIX-A

NON-THERMAL GES-BOHM SHEATH CRITERION

The solar observations founded on various missions in the past reveal that beyond a heliocentric radial distance greater than 0.3 au, the solar wind electrons can be categorized into three distinct population classes (sub-distributions) depending on their thermo-statistical behaviours[†]. Their distributions accordingly have the core (with energy ≤ 50 eV); and the halo and strahl (with energy ≥ 50 eV), depicted clearly as in figure A1.

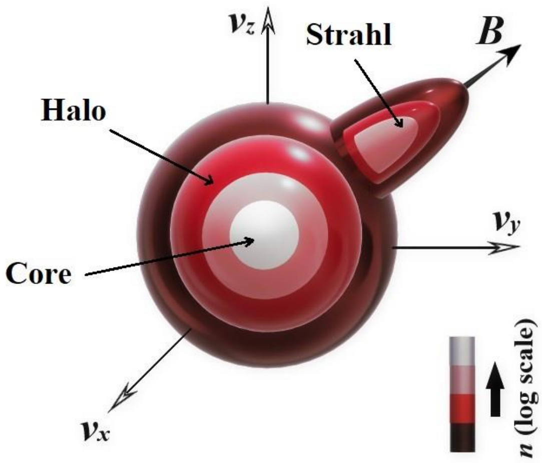

Figure A1: *A cartoonist sketch of the normal solar wind electron population density distribution (n) with the corresponding velocity sub-distributions (core, halo, strahl). The relatively cool and dense electron population at the centre with isotropic velocity forms the core. The less-dense and less-isotropic suprathermal electron population constitutes the halo. The electron beam strongly aligned to the interplanetary magnetic field (**B**) with relatively higher velocity is called the strahl.*

The core accommodates 90–95 per cent of the constitutive electrons. The core population is well described by the Maxwellian distribution (thermal) law. Here, the electrons are thermalized due to the high collisional nature in the low-energy regime [1, 2]. The halo and the strahl include the remaining 5–10 per cent of the solar electrons. They are suprathermal in nature due to fewer collisions in the high-energy regime [1, 2]. These are thermo-statistically well described with the help of the κ-distribution function.

[†]Sarma, P. and Karmakar, P. K. Solar plasma characterization in Kappa (κ)-modified polytropic turbomagnetic GES-model perspective. *Monthly Notices of the Royal Astronomical Society*, 519(2):2879-2916, 2023.

The core and halo electrons are relatively isotropic as compared to the strahl electrons which usually travel away from the Sun along (or sometimes opposite to) the interplanetary magnetic field [1]. It is speculated that the suprathermal electrons being less affected by collision, can carry the memory of their origin, and thus, exhibit memory effects. But the exact physical mechanisms behind their origin and evolution still remain openly elusive [2]. Therefore, the strategic inclusion of the non-thermal electron population in the proposed GES formalism is quite realistic, and hence, the corresponding Bohm sheath criterion is extremely worth exploring.

In order to derive the modified Bohm sheath criterion relevant in the context of the κ-modified polytropic turbomagnetic GES formalism (as explored in **Chapter-2, Chapter-3** and **Chapter-4**), we follow the standard procedure of functional monotonicity in association with the energy conservation law [3]. The energy conservation principle gives the solar ionic speed at the sheath-exit region in the presence of active gravito-electrostatic coupling effects can be expressed in the customary notations as

$$u = \left[u_0^2 + \frac{2e}{m_i}(\phi_0 - \phi) - 2(\psi_0 - \psi) \right]^{1/2} . \tag{A1}$$

The ion continuity equation in the same solar plasma region in the steady form can be given as

$$n_0 u_0 = n_i u \ . \tag{A2}$$

A combination of equations (A1) and (A2) yields the ion number density as

$$n_i = n_0 \left[1 + \frac{2e}{m_i u_0^2}(\phi_0 - \phi) - \frac{2}{u_0^2}(\psi_0 - \psi) \right]^{-1/2} . \tag{A3}$$

A modified form of the electrostatic Poisson equation (equation (2.5)) near the sheath-edge with the application of the derived ionic density (equation (A3)) can accordingly be derived as

$$\partial_r^2 \phi + \left(\frac{2}{r}\right)\partial_r \phi = \frac{n_0 e}{\varepsilon_0}\left[\left\{ 1 - \left(\frac{2}{2\kappa - 3}\right)\frac{e\phi}{k_B T_0} \right\}^{(1-2\kappa)/2} - \left\{ 1 + \frac{2e}{m_i u_0^2}(\phi_0 - \phi) - \frac{2}{u_0^2}(\psi_0 - \psi) \right\}^{-1/2} \right]. \tag{A4}$$

Applying the same normalization procedure as followed in the above mentioned chapters on equation (A4), we have

$$\partial_\xi^2 \Phi + \frac{2}{\xi}\partial_\xi \Phi = \left(\frac{\lambda_J}{\lambda_{De}}\right)^2 \left[\left\{ 1 - \left(\frac{2}{2\kappa - 3}\right)\Phi \right\}^{(1-2\kappa)/2} - \left\{ 1 + \frac{2}{M_0{}^2}(\Phi_0 - \Phi) - \frac{2}{M_0{}^2}(\Psi_0 - \Psi) \right\}^{-1/2} \right]. \tag{A5}$$

Equation (A5) is the non-linear sheath evolution equation in our current GES formalism. We now multiply the both sides of equation (A5) with $\partial_\xi \Phi$ and integrate it with respect to ξ from the sheath-entrance ($\sim \xi_0 = 3$) to the sheath-exit ($\sim \xi = 4$) regions in the radial direction for an analytic solution. Mathematically, the above operations can be expressed as

$$\int_{\xi_0}^{\xi}\left\{\left(\partial_\xi^2 \Phi + \frac{2}{\xi}\partial_\xi \Phi\right)\partial_\xi \Phi\right\}\partial\xi = \left(\frac{\lambda_J}{\lambda_{De}}\right)^2 \int_{\xi_0}^{\xi}\left[\left\{1-\left(\frac{2}{2\kappa-3}\right)\Phi\right\}^{(1-2\kappa)/2}\partial_\xi \Phi\right]\partial\xi -$$

$$\left(\frac{\lambda_J}{\lambda_{De}}\right)^2 \int_{\xi_0}^{\xi}\left[\left\{1+\frac{2}{M_0{}^2}(\Phi_0-\Phi)-\frac{2}{M_0{}^2}(\Psi_0-\Psi)\right\}^{-1/2}\partial_\xi \Phi\right]\partial\xi \,. \qquad \text{(A6)}$$

The LHS of equation (A6) for a smooth and monotonic potential structure transition in accordance with the universal energy conservation law results in the following inequality:

$$\frac{1}{2}\left\{(\partial_\xi \Phi)^2 - (\partial_\xi \Phi_0)^2\right\} + 0.67\,[ln(\xi/\xi_0)] > 0 \,. \qquad \text{(A7)}$$

A systematic simplification of the RHS of equation (A6) gives the mathematical shape of the Bohm criterion for the GES formation as

$$M_0 > \sqrt{2.36\left[\left\{1+\left(\frac{1.5}{2\kappa-3}\right)\right\}^{2\kappa-1}-1\right]^{-1}} \,. \qquad \text{(A8)}$$

The above inequality is known as the equivalent Bohm sheath criterion in our presented κ-modified polytropic turbomagnetic GES formalism. It may be repeated that, in the above derivation, all the symbols with a subscript '0' indicate the corresponding quantity in the sheath-entrance in the radial direction. All symbols without any subscript mean the respective quantity in the sheath-exit region along the same radial direction. It is clearly evident that the Bohm threshold velocity is dependent on the electron non-thermality extent as indicated by the κ-value.

In figure A2, we depict the profile of the Bohm-Mach number varying with κ in accordance with the critical form of the inequality (A8). It is seen herewith that the sensible Mach flow values in realistic solar situations mostly lie above the critical line $M=M_0=0.8$. It is interestingly found further that the non-thermally modified Bohm threshold value ($M_0 \approx 0.8 \sim 1$) obtained here is fairly in good agreement with the thermally modified one $M_0 \approx \sqrt{2} \sim 1$ previously reported in the same context elsewhere [4]. As a consequence, it hereby lays down a fair reliability check-up of our proposed analytic calculation scheme for the non-thermally modified Bohm condition for the steady GES structure formation against the previous concomitant results in a scale invariant form for the first time.

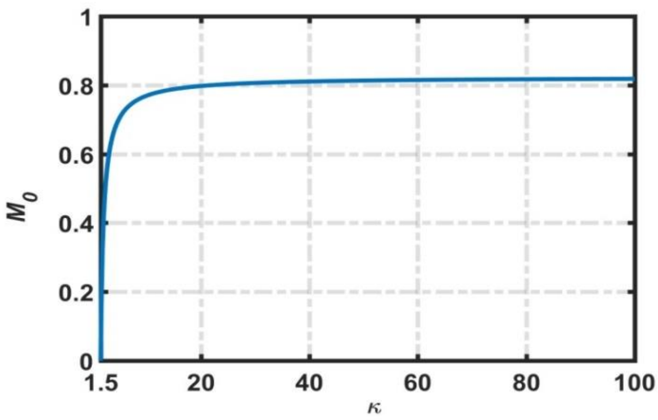

Figure A2: *Profile of the non-thermally modified threshold Bohm sheath criterion (M_0) in the GES framework with variation in the realistic solar κ-value.*

It is to be noted here that the Bohm sheath condition on the laboratory scales of space and time refers to the evolution of supersonic sheath in the absence of gravity. However, the derived non-thermally modified Bohm criterion in the presented analysis signifies the formation of subsonic sheath in the presence of self-gravity action. It is further found that the new Bohm condition on the threshold Mach value of our current concern is dependent on the non-thermality spectral index significantly in the high non-thermality corner ($1.5 < \kappa < 20$) and it tends to attain its asymptotic Boltzmann (thermal) limit after $\kappa \sim 30$. In the laboratory circumstances, however, the constitutive electrons in the steady state follow the Boltzmann (equilibrium) distribution law [3]. As a result, the laboratory Bohm sheath criterion ($M > 1$) is usually validated only for the thermal electronic regime defined by $\kappa \to \infty$.

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APPENDIX-B

THERMAL GES-BOHM SHEATH CRITERION WITH NEGATIVE IONS

The presence of diverse negative ionic species in the solar and other stellar atmospheres has been well revealed by various observational methods in the past [1, 2]. The photoionization of the metal atoms in the cool stellar environments yields the electrons, which in turn, result in the formation of the negative ions, like H^-, Cl^-, C^-, S^-, OH^-, C_2^-, CN^-, SH^-, H_2O^-, etc. [3]. The consideration of such negative ionic species is inevitable in the study of stellar plasma phenomena. Therefore, a tactical inclusion of the negative ion population in the GES-based solar plasma formalism is quite judicious and realistic. As a consequence, the corresponding Bohm sheath criterion for the modified GES-structure and subsequent solar plasma flow phenomena in the active presence of diverse negative ions is quite worth investigating[†].

In order to methodically derive the equivalent Bohm sheath criterion in the GES-model based solar plasma formalism with negative ions (as explored in **Chapter-5** and **Chapter-6**), the standard approach of energy conservation principle along with the functional monotonicity rules are applied [4]. Accordingly, the positive ion speed at the sheath-exit location in the radially outward direction relative to the solar centre in the usual solar plasma symbolism [5] can be written as

$$u_+ = \left[u_{0+}^2 + \frac{2e}{m_+}(\varphi_0 - \varphi) - 2(\psi_0 - \psi)\right]^{1/2}. \tag{B1}$$

The ion continuity equation in the sheath forming region can be expressed as

$$n_{0+}u_{0+} = n_+ u_+ . \tag{B2}$$

The combination of equations (B1)-(B2) gives positive ion number density as

$$n_+ = n_{0+}\left[1 + \frac{2e}{m_+ u_{0+}^2}(\varphi_0 - \varphi) - \frac{2}{u_{0+}^2}(\psi_0 - \psi)\right]^{-1/2}. \tag{B3}$$

Similarly, the negative ion number density as per the energy principle is obtained as

$$n_- = n_{0-}\left[1 + \frac{2e}{m_- u_{0-}^2}(\varphi - \varphi_0) - \frac{2}{u_{0-}^2}(\psi_0 - \psi)\right]^{-1/2}. \tag{B4}$$

[†]Sarma, P. and Karmakar, P. K. Effects of negative ions on equilibrium solar plasmas in the fabric of gravito-electrostatic sheath model. *Scientific Reports*, Under Review, 2023.

The equivalent electrostatic Poisson equation near the sheath-edge can be expressed after inclusion of the above derived densities of the plasma species as

$$\partial_r^2\varphi+\left(\frac{2}{r}\right)\partial_r\varphi=\frac{e}{\varepsilon_0}\left[n_{e0}\exp\left(\frac{e\varphi}{k_BT_e}\right)+n_{0-}\left\{1+\frac{2e}{m_-u_{0-}^2}(\varphi-\varphi_0)-\frac{2}{u_{0-}^2}(\psi_0-\psi)\right\}^{-1/2}-n_{0+}\left\{1+\frac{2e}{m_+u_{0+}^2}(\varphi_0-\varphi)-\frac{2}{u_{0+}^2}(\psi_0-\psi)\right\}^{-1/2}\right]. \quad \text{(B5)}$$

After application of the same normalization scheme as applied in **Chapter-5** and **Chapter-6**, the above equation can be expressed as

$$\partial_\xi^2\Phi+\left(\frac{2}{\xi}\right)\partial_\xi\Phi=\left(\frac{\lambda_J}{\lambda_{De}}\right)^2\left[(1-\delta)\exp(\Phi)+\delta N_{0-}\left\{1+2\left(\frac{m_+}{m_-}\right)\frac{1}{M_{0-}^2}(\Phi-\Phi_0)-\frac{2}{M_{0-}^2}(\Psi_0-\Psi)\right\}^{-1/2}-N_{0+}\left\{1+\frac{2}{M_{0+}^2}(\Phi_0-\Phi)-\frac{2}{M_{0+}^2}(\Psi_0-\Psi)\right\}^{-1/2}\right]. \quad \text{(B6)}$$

Equation (B6) is the nonlinear sheath evolution equation in the present GES-formalism. Here, equation (B6) is now multiplied by $\partial_\xi\Phi$ and integrated with respect to ξ from the illustrated sheath-entrance ($\xi_0=3.5$) to the sheath-exit ($\xi=4$) in the radially outward direction (figure 5.1) for analytical simplicity. The above operations can be mathematically written as

$$\int_{\xi_0}^{\xi}\left\{\left(\partial_\xi^2\Phi+\frac{2}{\xi}\partial_\xi\Phi\right)\partial_\xi\Phi\right\}\partial\xi=\left(\frac{\lambda_J}{\lambda_{De}}\right)^2(1-\delta)\int_{\xi_0}^{\xi}\{(\exp\Phi)\partial_\xi\Phi\}\partial\xi+$$

$$\left(\frac{\lambda_J}{\lambda_{De}}\right)^2\delta N_{0-}\int_{\xi_0}^{\xi}\left[\left\{1+2\left(\frac{m_+}{m_-}\right)\frac{1}{M_{0-}^2}(\Phi-\Phi_0)-\frac{2}{M_{0-}^2}(\Psi_0-\Psi)\right\}^{-1/2}\partial_\xi\Phi\right]\partial\xi-$$

$$\left(\frac{\lambda_J}{\lambda_{De}}\right)^2 N_{0+}\int_{\xi_0}^{\xi}\left[\left\{1+\frac{2}{M_{0+}^2}(\Phi_0-\Phi)-\frac{2}{M_{0+}^2}(\Psi_0-\Psi)\right\}^{-1/2}\partial_\xi\Phi\right]\partial\xi\cdot \quad \text{(B7)}$$

The LHS of the above equation for the development of a uniform monotonic potential structure (as confirmed by figure 5.2) yields the following inequality

$$\frac{1}{2}\left[(\partial_\xi\Phi)^2-(\partial_\xi\Phi)_0^2\right]+0.784\ln\left(\frac{\xi}{\xi_0}\right)>0\cdot \quad \text{(B8)}$$

A methodical simplification of the RHS of equation (B7), considering the results obtained from equation (B8), yields the following analytic inequality

$$(1-\delta)\exp(\Phi)>N_{0+}\left\{1+\frac{2}{M_{0+}^2}(\Phi_0-\Phi)-\frac{2}{M_{0+}^2}(\Psi_0-\Psi)\right\}^{-1/2}. \quad \text{(B9)}$$

Now, from equation (B9), one gets the Bohm sheath criterion in the present context given as

$$M_{0+}>\sqrt{\frac{0.626-2(\Psi_0-\Psi)}{(1-\delta)^{-2}N_{0+}^2\exp(2.344)-1}}\text{, for } 0\le\delta<1/15. \quad \text{(B10)}$$

The above inequality is recognized as the equivalent Bohm sheath criterion for the modified GES formation in the presented GES-formalism. In the above derivation, the negative ion concentration in the sheath region is neglected, as supported by figure 5.10. It may be restated here that the symbols with “0” subscript denote the corresponding quantity at the sheath-entrance location in the SIP. The symbols without any subscript indicate the respective quantities in the sheath-exit location along the radially outward direction. It is seen that this threshold velocity is δ-sensitive, and is applicable for the practical range $0 \le \delta < 1/15$.

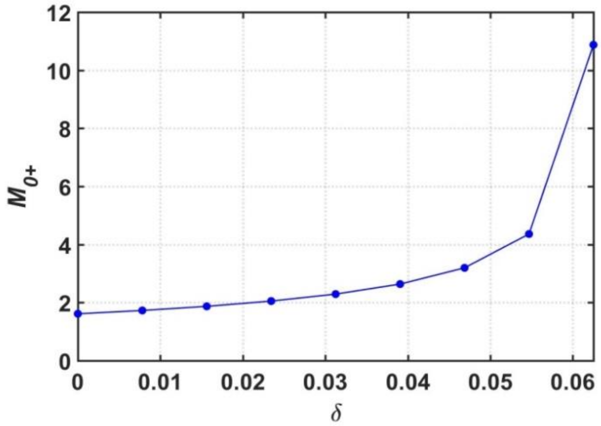

Figure B1: *Profile of δ-modified Bohm sheath criterion for positive ion (M_{0+}) in the GES fabric with practically allowed δ-variation (with fixed $m_i/m_-=1$, $T_i/T_e=1$ and $T_-/T_e=1$).*

As shown in figure B1, the profile of the Bohm Mach number with varying negative ion concentration is portrayed according to equation (B10). It is seen that the realistic Bohm Mach values are supersonic and it increases in magnitude with an increase in the δ-value and vice-versa. In other words, an increase in the negative ion concentration causes higher positive ion drifting speed to account for the loss of ions in the sheath. Interestingly, it is found further that the δ-modified Bohm threshold ion-speed value for δ=0 ($M_{0+} >$ 1.61) obtained here is in good agreement with the basic GES-picture without negative ions ($M_0 > \sqrt{2} \sim 1.41$) previously reported elsewhere [6]. Consequently, it pronounces a fair reliability of the presented GES-based analysis with negative ions against the previously reported basic GES-formalism in a simplified form without negative ions, for the first time.

A comparative analysis of the equivalent Bohm sheath criterion in terms of the Bohm threshold velocity values derived previously without [6] and presently with negative ions in the current study can be given as: $\Delta M_{0+}/M_0 \times 100\% = [(M_{0+} - M_0)/M_0] \times 100\%$ = 14.18%, where $M_{0+} \approx 1.61$ and $M_0 \approx 1.41$ as already shown above. Thus, it is found herein that there is a noticeable increment in the Bohm threshold velocity value of the plasma flow in the sheath-entrance point in the presence of the negative ions. Therefore, it can be inferred herein, that the presence of negative ions (even if in a minor quantity) can enhance the loss process of the positive ions in the sheath region. So, the positive ions drift with higher speed into the sheath region to compensate the positive ion loss for endurance of the bounded GES structure in a steady-state form. This process is highly prominent towards the higher δ-values as seen from figure B1. It shows how the negative ion inclusion in our study of the modified GES formation condition (Bohm threshold criterion) is well justified and validated.

It is to be noted in the present context that the Bohm threshold criterion in the laboratory scaled electronegative plasma can be expressed as [7]

$$M_{0+} \geq \left[\frac{k_B T_e (1+\alpha_0)}{m_+ (1+\alpha_0 \gamma)} \right]^{1/2}, \tag{B11}$$

considering quasi-neutrality in the sheath edge region. Here, $\alpha_0 \equiv n_{0-}/n_{0e}$ and $\gamma \equiv T_e/T_i$. So, it can be immediately interpreted that if α_0 is not too small, and γ is large (i.e., for cold ions), the negative ions highly reduce the Bohm Mach value [7]. On the contrary, in our model, the opposite behaviour is noticed from figure B1. The physical reason behind such behaviour may be attributable to the significant deviation from the quasi-neutrality condition of the SIP, as elaborately explored in the **Chapter-5**.

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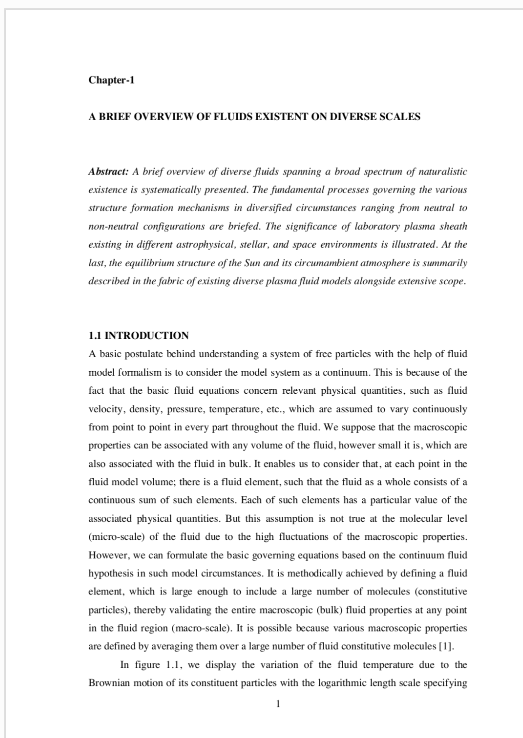

Chapter-1

A BRIEF OVERVIEW OF FLUIDS EXISTENT ON DIVERSE SCALES

Abstract: *A brief overview of diverse fluids spanning a broad spectrum of naturalistic existence is systematically presented. The fundamental processes governing the various structure formation mechanisms in diversified circumstances ranging from neutral to non-neutral configurations are briefed. The significance of laboratory plasma sheath existing in different astrophysical, stellar, and space environments is illustrated. At the last, the equilibrium structure of the Sun and its circumambient atmosphere is summarily described in the fabric of existing diverse plasma fluid models alongside extensive scope.*

1.1 INTRODUCTION

A basic postulate behind understanding a system of free particles with the help of fluid model formalism is to consider the model system as a continuum. This is because of the fact that the basic fluid equations concern relevant physical quantities, such as fluid velocity, density, pressure, temperature, etc., which are assumed to vary continuously from point to point in every part throughout the fluid. We suppose that the macroscopic properties can be associated with any volume of the fluid, however small it is, which are also associated with the fluid in bulk. It enables us to consider that, at each point in the fluid model volume; there is a fluid element, such that the fluid as a whole consists of a continuous sum of such elements. Each of such elements has a particular value of the associated physical quantities. But this assumption is not true at the molecular level (micro-scale) of the fluid due to the high fluctuations of the macroscopic properties. However, we can formulate the basic governing equations based on the continuum fluid hypothesis in such model circumstances. It is methodically achieved by defining a fluid element, which is large enough to include a large number of molecules (constitutive particles), thereby validating the entire macroscopic (bulk) fluid properties at any point in the fluid region (macro-scale). It is possible because various macroscopic properties are defined by averaging them over a large number of fluid constitutive molecules [1].

In figure 1.1, we display the variation of the fluid temperature due to the Brownian motion of its constituent particles with the logarithmic length scale specifying

1

Astrophysical Fluid Structurization in Diverse Solar Environs

by Pankaj Sarma

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