Chapter-7

THESIS SUMMARY AND FUTURE SCOPE

A theoretical investigation of the key properties of the diverse fluids extending from the laboratory to astrophysical spatiotemporal scales is performed. Various fluid dynamical models to explore the stellar structures and their evolutions have been systematically described and critically analysed. It illustratively presents sensible stellar parametric factors previously remaining unaddressed and unexplored despite its extensive relevance.

The focal concern of the compiled thesis can broadly be classified into two different stellar plasma environments. The first one is turbulent magneto-active GES-model based solar plasma system with non-thermal κ-distributed electrons. The next one is the basic GES-model based solar plasma system with diverse negative ionic species. The interchapter cohesion is strengthened through a unique type of quasi-linear gravito-electrostatic coupling of self-gravitating SIP (non-Newtonian) and the point-gravitating SWP (Newtonian). It is needless to say that the same formalism is also applicable to other sun-like stars with intermediate surface temperature. All the possible analytical, numerical and graphical approaches are made to explore the equilibrium properties and structure of the above-mentioned diversified stellar plasma systems. The main conclusions drawn from the comprehensive investigation together with the possible future scope are lastly briefed.

7.1 CONCLUDING REMARKS

1. In **Chapter-2**, the idealistic solar plasma-based GES-model is appropriately refined by proper inclusion of the realistic solar plasma structuring parametric factors such as the effects of non-thermal electronic thermo-statistics (κ-distributed), magnetic field actions, and fluid turbulence. The new equation of state here incorporates the relevant barometric corrections caused by the fluid turbulence (logatropic in nature), non-thermal polytropicity, and Lorentz force action simultaneously. Numerical analysis of the time-stationary model equations yields an interesting feature of the SIP volume, and hence the SSB, showing its shrinking nature with an increase in the electron non-thermality. This is due to the collisional nature variation of the electrons with the ionic fluid with varying κ-values. The electric potential is independent of electron non-thermality. The entire non-thermal solar plasma flow dynamics is studied with the Mach number and the current

density profiles. At the last, a comparative study of the key results from our present model analysis is performed with other widely accepted model-based results.

2. In **Chapter-3**, the key properties (gravity, electric potential and field, Mach number, and electric current density) of the GES-model based solar plasma system, incorporating the non-thermality of the electrons (indicated by the κ-value), magneto-activity and plasma fluidic turbulence are re-evaluated by studying their inhomogeneity scale length profiles. These plots show their spatial uniformity behaviours for various electronic non-thermality extents as well as relative temperatures of the plasma constituents. It is clear that the SIP self-gravity and electric current density show abrupt uniformity transition. On the other hand, the SWP gravity, electric potentials in the SIP and SWP, electric fields in the SIP and SWP, Mach number in the SIP and SWP, and the SWP electric current density show unhurried spatial uniformity transition.

3. In **Chapter-4**, the self-structurization of the bounded solar plasma medium is studied by looking into the behaviours of the electron population in the SIP, and the electric and self-gravity field gradients with their corresponding fields against the heliocentric radial distance, as per the modified GES-model based solar plasma system. This model is refined by judiciously incorporating electron non-thermality, magneto-activity and fluid turbulence. A sharp dense self-gravity dominated region is clearly revealed against the diffused SIP medium to exist from the heliocenter to 0.2 λ_J in the SIP for the first time.

4. In **Chapter-5,** various key equilibrium properties of the Sun in a modified GES-model fabric are explored. Here, the basic model is refined methodically by proper inclusion of the realistic negative ionic species for the first time. Numerical analysis of the equilibrium model governing equations reveals an interesting property of the SIP, showing its shrinking nature with an increase in the negative ion concentration in the constitutive fluid medium. However, this GES-shrinking behaviour is not affected by the mass of the negative ions and temperature of the plasma constituents. Such SIP features can be well explained by the shielding nature between the opposite polarity plasma constituents. The spatial variation of the electric potential is found to be independent of the negative ion concentration, their mass and plasma constituent temperature in both the SIP and SWP. The solar plasma flow behaviour is studied with the Mach number and current density profiles for various relevant physical parametric variations. In the SWP, the sonic

transition of the Mach number is found to be highly sensitive to the positive ion-to-electron temperature ratio. The current density is sensitive to the negative ion density as well as the positive ion-to-electron temperature ratio in both the SIP and SWP. The self-organization of the SIP constituents is explored with their radial density variation along with their spatial gradient behaviours. It is interestingly found that the SIP deviates significantly from the idealistic plasma quasi-neutrality condition.

5. In **Chapter-6**, the solar plasma element flow behaviours in the field of gravito-electrostatic interaction in the modified GES-model framework are explored for the first time. Here the refined GES-model includes diverse realistic negative ionic species. The solar plasma is assumed to be made up of inertialess Maxwell-Boltzmann distributed electrons, and positive and negative ionic inertial fluids. The self-organization in the SIP mass and the net electric charge is studied with the radial gradient variations of the self-gravity and electric fields. A SIP-location with δ-insensitive gravity gradient is seen. The nature of plasma element dynamics with varying mass and electric charge is thoroughly investigated in the defined gravito-electrostatic phase space. It depicts the solar material clumping nature in the SIP. This clumping behaviour obtained herewith matches with the observational result that the heavy negative ion formation is not favoured in the SIP.

7.2 FUTURE DIRECTIONS

We admit that the presented chapters composing the thesis are rooted in some ideal approximations. Consequently, further refinements are necessary for dealing with more realistic situations. The wide scopes of futuristic ameliorations are highlighted below.

1. The limitations, and hence future scopes related to the considered κ-modified polytropic turbomagnetic GES-model based solar plasma system as explored in **Chapter-2**, **Chapter-3** and **Chapter-4** are as follows:

i. The temperature anisotropy originated in the presence of magnetic field is ignored for analytical simplicity. Consequently, the incorporation of solar plasma temperature anisotropy opens a new scope of refinement of our model in the future research [1-3].

ii. We have considered standard kappa (κ) distribution (SKD) of electrons in non-relativistic regime for our model formulation. It is recently reported in the literature about a regularized kappa (κ) distribution (RKD), which removes all the usual SKD-divergences that appear with the macroscopic velocity moments, such as pressure, temperature, and heat flux. The RKD also extends the range of kappa to $0 < \kappa < \infty$ against the SKD with kappa $3/2 < \kappa < \infty$ [4, 5]. It is also consistent with the extensive entropy unlike the SKD [5]. We, however, at present ignore such modifications of the electron population distribution. Therefore, a further solar study centred on the GES framework in light of the RKD law may open a new platform for future investigations to analyse more realistic scenarios.

iii. The equation of state developed in our study does not include the effects of the presence of relativistic electron dynamics, degeneracy pressure effects, and population of excited states of the plasma constituent species that have been verified by diversified observational methods [6]. As a result, investigation of the solar plasma system under the GES fabric with the inclusion of the above-mentioned factors opens a further opportunity to make the present model better applicable in the realistic solar plasma contexts.

2. The restrictions of, and hence emerging prospects of future research from the GES-model based solar plasma system with the diverse negative ionic species, as explored in **Chapter-5** and **Chapter-6** are as follows:

i. The magnetic field-induced effects, viscosity, and effective rotational effects are ignored for analytic simplicities, like the original GES-model fabric [7, 8].

ii. The complications originating from plasma fluid turbulence, and thermo-statistical distribution laws of the constitutive non-thermal species [9-11] are overlooked for analytical simplicity.

iii. The temperature anisotropy, originated in the presence of magnetic field [1-3] is also not taken into account.

iv. The model formalism ignores the non-radial flow effects in the SIP caused by the complex solar interior magnetic field structures [12], solar wind atomic particle acceleration caused by the radiation pressure at the cost of Doppler Effect [13].

v. The equation of state neglects the effects of relativistic electron dynamics, population of excited plasma constituent species, and degeneracy pressure. These are however verified by diverse observational techniques and theoretical predictions, as seen in the literature [6].

Consequently, a proper inclusion of the above-mentioned realistic solar plasma characteristics should open a new scope of refined investigations in the future research, founded on the current GES-model based solar plasma scenarios.

3. The recent data acquired by the heavy ion sensor (HIS) on board the Solar Orbiter (SolO) has confirmed the presence of various heavy elemental species ranging from He to Fe, with their respective broad range of possible charged states. Such measurements have well supported the investigations of local physical processes occurring in the solar atmosphere. It is also well known that such heavy ionic species can be utilized as tracers of the solar wind origin and their acceleration mechanism within the corona [14]. In the present investigations, we omit such diverse positive ionic species for analytic simplicity. As a consequence, analysis of the effects of such positive ionic heavy elemental species in the solar plasma flow dynamics in the GES-model fabric will hopefully open a new window for the future research in the solar and sun-like stellar plasma systems in a wider perspective.

4. It has been reported recently in the literature that the jets or jetlets driven by the interchange magnetic reconnection near the coronal base region could be the source of particle heating and hence, acceleration of the solar wind particles to supersonic speed [15]. The future solar observations, yet to be performed by the Parker Solar Probe (PSP) along with the SolO missions [1, 16], are expected to shed more light on the link between the magneto-activities and the solar wind driving mechanisms. Therefore, such onsite experiments could hopefully pose another venture in the reliability and validation of our model investigation with the judicious incorporation of the above highlighted realistic factors in the real solar astronomic scenarios.

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