**Chapter-6**

# CONCLUSIONS AND FUTURE PROSPECTS

***Abstract:*** *This is the resultant thesis concluding chapter, concisely derived from the individual chapter summaries resulting from the distinct studies already presented before. The future outlooks of these accomplished analyses are presented alongside. It summarily presents an overall glimpse of broad applicability and future scope of the compiled thesis.*

## 6.1 CONCLUDING REMAKRS

The primary aim of this compiled thesis, as already discussed in the first chapter, is to present an analytical overview of the various instabilities excitable within a laboratory plasma fireball (FB) system. The various instability characteristics are studied through a bifluidic plasma model and with corroborating outcomes resembling the experimental reporting. The instabilities are studied using both small-order linear (2$^{nd}$-Chapter), intermediate-order quasilinear (3$^{rd}$- and 4$^{th}$-Chapters), and large-order nonlinear (5$^{th}$-Chapter) formalisms. The distinguishing features of these individual methodologies are also compared and presented in tabular forms. It is noteworthy that various applicational outcomes of instability research across the laboratory and astrophysical scenarios are also explored. The various component chapters composed of the plasma FB instability analyses and their relevant applications are presented in a chapter-wise fashion as follows.

**Chapter-1**

**A BRIEF OVERVIEW OF PLASMA FIREBALL INSTABILITIES**

(i) This chapter presents a brief account on the chronological development of plasma research in the fluid model approach.

(ii) The instabilities excitable within a plasma FB system and their applications in other fields are presented.

(iii) The appropriate formalisms of such instabilities are discussed.

**Chapter-2**

**SHEATH PLASMA RESONANCE IN INVERTED FIREBALLS**

(i) The linear sheath plasma resonance instability is analysed using a bifluidic plasma model formalism.

(ii) The dispersion relation developed due to Fourier transformation is solved both analytically and numerically with the similar results yielding experimentally reported evanescent and standing wave-like characters [1, 2] shown graphically.
(iii) The IFB is proved to behave as a cavity resonator for frequencies below a threshold.
(iv) The higher density is proved to act a damping agent against the instability.

**Chapter-3**
**QUASILINEAR ANALYSIS OF PLASMA FIREBALL SHEATH INSTABILITY**
(i) The plasma fireball sheath (PFBS) instability is analysed herein in the purview of quasilinear perturbation formalism using a bifluidic plasma model.
(ii) This chapter shows that peakonic structures could result even from linear ordinary differential equation also against the traditional peakonic pictures of fully nonlinear dynamical systems [3, 4].
(iii) The atypical eigen-patterns are fairly consistent and correlative with experimental findings on PFBS potential structures reported before [5].

**Chapter-4**
**QUASILINEAR SHEATH PLASMA INSTABILITY ANALYSIS IN INVERTED FIREBALLS**
(i) This chapter reports the sheath plasma instabilities (SPIs) in an inverted fireball (IFB) system through a quasilinear bifluidic perturbation formalism.
(ii) The chapter proves the experimentally reported 180° phase difference in between the electric field and electronic (ionic) movements during the SPI excitation [1].
(iii) This phase difference is proved to be originating due to the nonzero electronic (ionic) inertia during the high-frequency SPI excitation [2].

**Chapter-5**
**NONLINEAR ANALYSIS OF REGULAR PLASMA FIREBALL SHEATH INSTABILITY**
(i) The PFBS instability is analysed herein using a bifluidic model formalism up to the fourth-order nonlinearity.
(ii) This chapter shows escalating (amplifying) plasma parameters with their order of nonlinearity, which indicates the unstable equilibrium state of the PFBS system [6].

(iii) The investigated peakonic pattern structures are fairly bolstered by both the asymptotic boundary conditions predicted theoretically [6] and the PFBS instability observations reported experimentally [5].

## 6.2 FUTURE PROSPECTS

It is worth mentioning that most of the analyses included in this thesis are done in the lower-order linear and quasilinear formalism. The 5$^{th}$-chapter is an only exception which deals with 4$^{th}$-order nonlinear analysis. Therefore, it must be admitted that the possibility for a higher-order nonlinear analysis of all the explored plasma FB instabilities is yet open, as the same could not be accomplished during this research tenure. The higher-order nonlinear analyses are mathematically cumbersome. Therefore, different software programs are utilized to numerically solve the final closure governing differential equations of corresponding orders. Besides, this thesis is focally based on a specific bifluidic laboratory plasma FB analyses without any third component. Therefore, the higher-order analyses can be done either with the established bifluidic model or other conventional plasma models, such as kinetic theory model, single particle model, hybrid-model, etc. The similar plasma models can also be utilized for astroplasmic FB analysis with certain required parametric modifications.

In this context, it should be added that there are numbers of astrophysical events and large-scale experiments where the FB model holds good. A few of such events are Gamma-ray burst (occurs due to inter-shock interactions similar to the inter-pulse interactions in SPR driven IFBs) during star collapse [7], Magnetar energy emission (occurs due to weaker magnetosphere reflected x-ray bursts similar to sheath reflected weaker SPR pulses in IFBs) [8], Meteor radio afterglow (occurs primarily due to electrostatic plasma oscillations converting to EM radiation as observed with EM harmonics in SPR excited IFBs) [9], quark-gluon plasma (QGP, occurs due to enclosed high thermal energy conditions, similar to the IFB structures) [10], and so forth.

To summarise, the fireball model can be used for the above natural phenomena with modified gravitational potential and magnetic field incorporated into the analysis. For the QGPs, apart from the above modifications, a quantum plasma fireball model may be properly implemented in refining the presented analysis.

There are some other fields also where the knowledge of the various FB instabilities is useful, such as satellite antenna, electrodynamic tethers, etc. [1, 2]. The plasma FB is an outcome of the plasma-electrode interaction [11]. Therefore, any FB related exploration is an addition to the knowledge of the fundamental plasma physics also. Thus, it is necessary to add that all possible instabilities in the plasma FB (or plasma-electrode) systems with various geometries, such as the Rayleigh-Taylor instability (due to density difference in sheath and bulk plasma) [12], Kelvin-Helmholtz instability (shear of flows among different fluids) [13], Streaming instability (anti-parallel fluid flows due to plane electrode) [14], Potential relaxation instability (due to variable potential electrode) [6] are future objectives awaiting widespread long explorations.

**REFERENCES**

[1] Stenzel, R. L. High-frequency instability of the sheath-plasma resonance. *Phys. Fluids: Plasma Phys.*, 1(11):2273-2282, 1989.

[2] Stenzel, R. L., Ionita, C. and Schrittwieser, R. Dynamics of Fireballs. *Plasma Sources. Sci. Technol.*, 17(035006):1-11, 2008.

[3] Degasperis, A., Holm, D. D. and Hone, A. N. W. A new integrable equation with peakon solutions. *Theor. Math. Phys.*, 133(2):1463-1474, 2002.

[4] Holm, D. D. and Hone, A. N. W. A class of equations with peakon and pulson solutions. *J. Nonlin. Math. Phys*. 12(1):380-394, 2005.

[5] Stenzel, R. L., Gruenwald, J., Ionita, C., et al. Sheaths and double layers with instabilities. *J. Technol. Space Plasmas*, 2(1):1–70, 2021.

[6] Chen, F. F., *Introduction to plasma physics and controlled fusion*, New York: Plenum Press; 1984.

[7] Meng, Y. Z., Geng, J. J. and Wu, X. F. The photosphere emission spectrum of hybrid relativistic outflow for gamma-ray bursts. *MNRAS*, 509(4):6047-6058, 2022.

[8] Demidov, I. and Lyubarsky, Y., Radiatively driven evaporation from magnetar's surface. *MNRAS*, 518(1):810-820, 2023.

[9] Varghese, S. S., et al. Spatially resolved observations of meteor radio afterglows with the OVRO-LWA. *Journal of Geophysical Research: Space Physics*, 129(2): e2023JA032272, 2024.

[10] Harabasz, S., Florkowski, W., Galatyuk, T., Gumberidze, M., Ryblewski, R., Salabura, P., Stroth, J. Thermal model description of the particle spectra in the few-GeV energy regime, *EPJ Web of Conferences*, 259(11008):1-4, 2022.

[11] Stenzel, R. L., Ionita, C. and Schrittwieser, R. Dynamics of Fireballs. *Plasma Sources. Sci. Technol*., 17(035006):1-11, 2008.

[12] Pandey, B. P. and Roy, S. An explanation of the sheath plasma instability. *Phys. Plasmas*, 10(1):5-8, 2003.

[13] D'Angelo, N. Kelvin—Helmholtz Instability in a Fully Ionized Plasma in a Magnetic Field. *Phys. Fluids*, 8(9):1748–1750, 1965.

[14] Desjardins, T. R. and Gilmore, M. The potential relaxation instability in a helicon plasma. *Phys. Plasmas*, 25(6):062117(1-10), 2018.