Chapter-1

A BRIEF OVERVIEW OF PLASMA FIREBALL INSTABILITIES

***Abstract**: This chapter presents a systematically designed brief overview of basic plasma media, plasma fireballs (FBs), and associated instabilities. It enlightens its brief history, fundamental properties, circumstantial behaviours, plasma-accommodated phenomena, and so forth. In this context, we see interesting plasma driven phenomena, such as the plasma FBs, waves and instabilities, their triggering mechanisms, applications in both pure and applied sciences, etc. The formation mechanisms of astroplasmic FBs and two contrasting classes of laboratory plasma FBs, such as, the regular FBs (RFBs) and inverted FBs (IFBs), are elaborated through bifluidic plasma model approach. The atypical properties of such distinct FB categories are contrasted alongside their applicability. It mainly offers a basic portrayal of laboratory plasma FBs and instabilities illustratively.*

1.1 PLASMA MEDIA

The terminology 'plasma' has been coined by the great Czech anatomist and physiologist, Prof. Jan Evangelista Purkinje (1787-1869), to designate a specific component of blood which sustains upon removing the suspended biological cells [1]. In physics, the term 'plasma' has been first used by the American Nobel Laureate, Dr. Irving Langmuir (1881-1957), in 1928. The resembling nature of blood plasma with that of ionized gases carrying intra-medium components (e.g., electrons, ions, dust, etc.) presumably has prompted him to classify the ionized gases (with certain properties) as plasma. Dr. Langmuir's research outcomes (dominantly on laboratory plasma), consequently, have led to the discovery of various natural environments, totally or partially comprising of plasma, thereby signifying the importance of plasma research. Consequently, it has established plasma as the fourth state or a unique state of matter, most widespread in the Universe [1].

Although, laboratory plasma is an outcome of the research centred around ionized gases, these two media vary in terms of certain distinctive properties. One of the distinctive features that differ the plasma medium from ordinary neutral or ionized gases is its property of 'collective behaviour' or 'collective effects'. The long-range electromagnetic forces due to the individual charged plasma constituents make them interact collectively with other surrounding constituents. This evokes the collective behaviour of the plasma constituents to behave as a whole during any plasmic operation instead of as individual entities [2].

Apart from the above collective behaviours, certain other plasmic properties which distinguish it from other states of matter, including ordinary neutral or ionized gases, are macroscopic neutrality, Debye shielding, and plasma oscillations. To illustrate further, in the absence of any external electric or magnetic field, the plasma is macroscopically found to possess equal numbers of negative and positive constituents within a volume, making the net charge equating to zero. This volume must not be very small to hinder natural accommodation of sufficient number of charges. Yet must not be very large to witness any spatial temperature variation, as it influences the charge density. Any small-scale deviation from net-zero charge across the assumed volume could generate an electrostatic potential energy far enormous in contrast to the thermal particle kinetic energy in the medium. The restoring energy is equivalent to several million Kelvin for balancing the potential energy associated with the charge imbalance [2].

The Debye length (λ_D), characterising the associated Debye shielding phenomenon, establishes the second property of plasma. Here, λ_D signifies the typical distance beyond which the influence of any introduced charged constituent is not effectively experienced by other charges within the plasma. Debye length (λ_D) is also the scale beyond which the charge neutrality always holds in a plasma without external influence. The constituent charged plasma particles arrange themselves spatially in such a way that they shield electric field of any introduced charge particle or conducting body, forbidding any field penetration through themselves. This special property of plasma constituents to shield any introduced charges is termed as the Debye shielding and the width up to which this shielding occurs is designated as the Debye scale length (λ_D). As a result, any introduced electric test charge in the plasma medium interacts with other charges only within a range of λ_D radius. This shielding effect and the λ_D-scale sets one of the fundamental conditions of plasma existence. The condition is that the characteristic dimension of the plasma chamber (L) must be much larger than λ_D, i.e., $L \gg \lambda_D$. This also helps in deducing the second condition of plasma existence, $n\lambda_D^3 \gg 1$ (i.e., supercritical Debye number); here, n is charge number density and $n\lambda_D^3$ is the total number of plasma constituents within a Debye sphere [2, 3].

The third criterion for plasma definition lies in the plasma (angular) frequency (ω_p) superseding the intercomponent (angular) collision frequency (ω_{cc}), i.e., $\omega_p \gg 2\pi\nu_{cc}$. Any small-scale perturbation in the plasma medium from its homogeneous equilibrium state in the form of charge relocation creates nonzero net electric charge in the periphery. The nonzero net charge yields nonzero electrostatic potential resulting into subsequent restoring of the charges through intra-plasmic movements. The backward moving charges (due to restoring) often overshoot from their previous equilibrium position generating an oscillation known as the plasma oscillation with a frequency termed as the plasma (angular) frequency (ω_p). This oscillation is very rapid for the plasmic ions to harmonize with; therefore, they behave as almost massive immobile charged objects. Hence, the plasma (angular) frequency is technically equivalent to the electron (angular) frequency ($\omega_p \approx \omega_{pe}$). So, the terms plasma (angular) frequency (ω_p) and electron plasma (angular) frequency (ω_{pe}) are used indistinguishably in the plasmic operations [3].

The intra-component and inter-component collisions tend to damp these collective oscillations by gradually reducing their oscillation amplitudes. For the electron plasma oscillations to sustain, the electron-neutral collision frequency (ν_{ne}) must be lesser than the electron plasma frequency (ν_{pe}), i.e., $\nu_{ne} < \nu_{pe}$. Having this inequality opposite would not let the electrons behave independently and an equilibrium with the neutrals would be forced by the electron-neutral collisions instead. This inequality constitutes the fourth condition of plasma existence, which is $\omega\tau > 1$. Here, $\tau = 1/\nu_{ne}$, is the average time between successive electron-neutral collisions. It implies that the time required for the electron-neutral collisions must be larger than the characteristic time required for changing relevant plasma parameters during any plasmic operation [3].

With the discussion of various conditions of plasma formation and its properties, which distinguish it from the remaining other states of matter, we discuss the various environments, where plasma formation occurs both naturally and are also produced through special arrangements. The various plasma environments vary in terms of their density, temperature, frequency, etc. The temperature of the plasma is noticed to have a widespread range from 10 to 10^8 K, whereas the number density has a range of 10^4 m^{-3} to 10^{24} m^{-3}. The various plasma environments may chronologically be arranged in ascending number densities as follows: interstellar medium, interplanetary medium, ionosphere, solar atmosphere, thermonuclear plasma, MHD generators, etc. The generation of plasma in these arrangements occur either through photoionization or electric discharge. The first method deals with photonic interaction of neutrals and photons of energy corresponding to the ionization potential of the present gases. In the second method, which is used for laboratory plasma production, an electric field of kV cm^{-1} order is used through some infused gases. The previously free electrons present therein acquire velocity corresponding to the ionization potential of the gases resulting into their ionization and plasma production.

Merely switching off the electric field or even weakening it below threshold stops the electronic movements. The recombination phenomenon of the plasma electrons and ions soon turn them into a neutral gaseous form [3].

The plasma in the astrophysical environments discussed before plays active role in astrostructure formation through the Jeans instability processes. Here, the imbalance of gravitational compression and thermal expansion (due to fusion) trigger initial collapse (under some circumstances) forming stars. These stars remain active and radiant as long as the fusion fuel to balance further gravitational contraction exists. This intermediate balance is much needed for a star to be stable throughout its stellar lifetime [4].

Although the plasma study is equally relevant in both laboratory and astrophysical environments, but this thesis emphasizes primarily on laboratory plasma with occasional highlights of astroplasmic scenarios. The plasma is studied herein through a bifluidic model. Here, the individual plasmic constituents, such as electrons and ions behave as two individual fluids with different sets of governing equations. The fluid consideration of plasma can be justified with some plasmic properties complying with the standard fluid characteristics as given below:

(a) The macroscopic scale length (L) of any plasmic system is larger than the collisional mean free path (l) of the individual plasma constituents, i.e., $L \gg l$ [5],
(b) The intrinsic random velocities of the plasma constituents are unable to carry away any introduced particle far away from the point of deposition [5],
(c) The plasma medium is unable to withstand tangential and shearing forces [6].

The fluid model consideration is comparatively simpler and yields accurate results for both laboratory and astrophysical environments. In the laboratory plasma system under consideration, all plasmic operations have been analysed with the help of a fluid plasma model. It has been proven repeatedly that the bifluidic plasma model is successful in recreating results which are in good agreement with the experimental reporting.

1.2 PLASMA FIREBALL

With a brief introduction of the plasma medium with its various aspects as above, it is now assumed that a suitable foundation has been constructed to begin the discussion on plasma fireball (FB), which is the primary focus of this entire thesis. The following sections present the plasma FB formation, its varieties, different relevant instabilities, various fundamental and applicational values, and so forth.

The plasma FB is a glow discharge phenomenon observed both in the laboratory as well as in astrophysical environs. Although the dimension of the FB across the two environs varies, but there is a similarity in their formation mechanism and the associated instabilities. For a laboratory plasma FB, introducing an anode (or cathode) into the plasma drifts the mobile electrons towards (or away from) it across the sheath. The fast electrons, if accelerated enough to excite the neutrals present within the sheath through collision, may lead to the formation of a plasma FB glow. The FB glow occurs through the release of the excited energy in the form of visible light. Therefore, the anode biasing must be ensured to be high enough to knock out valance electrons from the neutrals or at least excite them for subsequent energy release to form the FB glow. Whereas, in the astrophysical scenarios, the meteors, while moving across the Earth's atmosphere due to the gravitational drift, generate sufficient hydrostatic pressure. It results in the excitation of the gases underneath, emitting light energy and forming the FB glow successively [7, 8].

With a brief introduction of plasma FBs and their formation mechanism in both laboratory and astrophysical environs, the only laboratory plasma FB is discussed hereafter, as this thesis mainly reports analyses and outcomes on laboratory plasma FBs.

1.2.1 CLASSIFICATION OF LABORATORY FIREBALLS

Depending on the anode morphology, laboratory plasma FBs are classified vastly into two categories, namely, the regular FB (RFB) and the inverted FB (IFB). As discussed before, if the plasma submerged solid anode is replaced with a hollow meshed anode, the FB glow forms inside the anode instead of forming outside it. This special category of trapped FBs is designated as an IFB. The sheath forms inside the anode embracing it. The ambient plasma electrons while drifting through the tiny holes on the meshed anode collide inelastically with the neutrals inside the anode exciting them to form the FB glow therein [9]. The IFB has certain atypical properties against the RFB which are distinctively discussed in this chapter and also highlighted elaborately in the successive chapters.

Although the RFBs and IFBs are similar in terms of their excitation dynamics, but there are several aspects significantly distinguishing them. An image (Fig. 1.1) showing the different FBs and a table (Table 1.1) comparing their differences are presented below.

As it is clearly seen, in the RFB, the FB glow forms outside the anode and in the IFB, the FB glow forms inside the anode. The glow formation dynamics (electron-neutral inelastic collision) in both the FBs is the same.

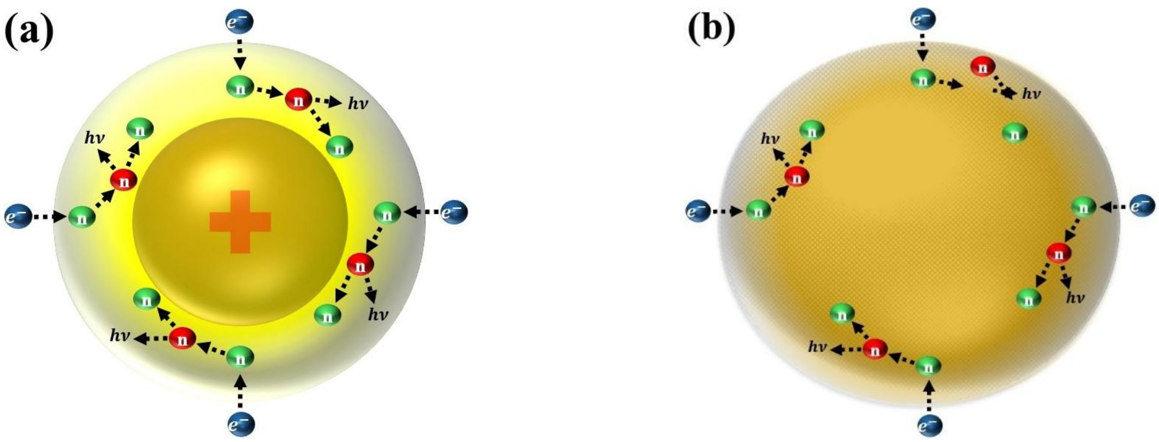

Figure 1.1: *Schematics showing the formation mechanism of an (a) RFB (solid smooth anode) and (b) IFB (hollow meshed anode).*

A table enlisting the differences as well as similarities in between the RFB and IFB are given below.

Table 1.1: Differences between RFB and IFB

S. No.	Item	RFB [Source]	IFB [Source]
1	FB location	On electrode (anode) surface [7, 10]	Inside electrode (anode) [9]
2	Electrode morphology	Solid (non-grid) [7, 10]	Meshed (grid) [9]
3	Glow region	Sheath region [7, 10]	Within electrode (but not so in sheath) [9]
4	Collision and ionization region	Outside the electrode [7]	Inside the electrode (anode) [9]
5	Electric potential	Radially dependent [11]	Constant inside the IFB [9]
6	Electric field	Spatially variant outside the anode [11]	Zero inside the anode [9]
7	Electron density	Variable in entire FB [7, 11]	Gaussian inside and constant just outside electrode [9]

8	FB geometry	Independent of anode geometry [7]	Dependent on anode geometry [9]
9	Ripple factor	More in FB current [10]	Less in FB current [13]
10	Magnetic FB	Extensively studied [7]	Infancy stage [11]
11	Spatial dimension	Predominantly dependent on anode volume and pressure [7]	Determined by reticular anode grid [9]
12	Astrophysical relevancy	Strong [11, 12]	Weak [11]
13	Dominant instabilities	TSI, SPI, SII, PRI, RTI [11]	KHI, SPI, SII [11]
14	Geometric size	Smaller [11]	Larger [9]
15	Cavity resonance	Not possible	Possible

1.2.2 INSTABILITIES IN PLASMA FIREBALLS

The plasma FB operation leads to the excitation of a plethora of waves and eigenmodes in the sheath region. The primary source of the free energy quintessential for the excitation of the instabilities is provided by the electrode with external biasing. Studying these instabilities are relevant from both the fundamental and applicational values of plasma FB research. It must be mentioned that the formation of a sheath around an introduced conductor in plasma is a ubiquitous phenomenon, whereas the plasma FB glow formation is special case after the sheath formation. Therefore, the instabilities formed in a plasma FB system are predominantly similar with those formed in the sheath plasma system. Some of the dominant instabilities which excite in a plasma FB system are the two-stream instability (TSI), the sheath plasma resonance (SPR) instability [14], the potential relaxation instability (PRI), the secondary ionization instability (SII), the Rayleigh-Taylor instability (RTI), the Kelvin-Helmholtz instability (KHI), and so forth [10, 11, 13].

It is noteworthy that some of these instabilities not only form in charged plasma fluid but also in neutral fluids like sea water, clouds, etc. [15, 16]. This further proves the relevance of FB study and associated instabilities from purely applicational perspective. This thesis comprises of a few of such instabilities excitable in the plasma FB systems specifically termed as the plasma FB instabilities.

1.3 MOTIVATION AND OBJECTIVE

A pure curiosity, application of plasma FB research in both pure and applied fields and associated relevant instabilities across the fields is the motivating force behind the plasma FB research. An overview of the relevance of plasma FB research and other associated instabilities are presented henceforth to demonstrate their practical applicability. The plasma FBs are reported to be relevant in the following fields

(a) The harmonics radiated by the FB anodes during the instabilities replicate that of spacecraft antennas in the astroplasmic region. Changing the sheath width or electron transit time across the sheath changes the frequency (or wavelength) of radiation [17]. Hence, the FB sheath research could find application in the astroplasmic antennas also.

(b) The formation of magnetized FBs helps in producing patterned nanodots on GaSb substrate. These patterned nanodots are useful in magnetic data storage, sensorics, and logics, etc. The one-step FB method to produce patterned nanodots is more time- and cost-effective against the conventional two-step nanodot fabrication method [18].

(c) The depletion region in junction diodes resembles the plasma sheath formed during the plasma conductor interaction. The former acts as a barrier in between the n-type and p-type regions, whereas the latter separates the electrode and the ambient plasma. It may also be added that a field free cold plasma and the sheath behave as an inductor and capacitor, respectively [19]. Thus, a link in between the plasma and semi-conductor electronics may be established for further studies.

(d) The magnetars or magnetic neutron stars produce energy due to intra-body magnetic field re-structurization. The produced energy depending on its magnitude either remains trapped within the star or emanates outwards. This is same as SPR instability excited inside an IFB, where the acoustic energy remains trapped within the sheath up to certain threshold value. This similarity prompts for a FB model of magnetars [20].

(e) The gamma-ray bursts (GRBs) noticed in the astrophysical scenario also produce ultra-relativistic FB formation of irregular geometries. The GRBs release energy in the order of $\sim 10^{45}$ J producing peripheral shockwaves. A FB model of GRB is seen reported in the literature [21]. This proves a far stretched application of FB model in the GRBs.

The applications as discussed above are often outcomes of various instabilities and waves formed in the plasma FB system (both laboratory and astrophysical). Hence, a collective study of these applications along with the waves and instabilities are one of the most inquisitive and relevant fields of research. Against this backdrop, the FB model is developed theoretically. The excited instabilities are analysed through both linear, quasilinear, and nonlinear formalisms for the first time, as far as known in the literature. The importance of these various formalisms is illustrated in the respective chapters and distinguished from each other in terms of the results and outcomes.

With a brief overview of the motivation of this thesis work, certain objectives for it are prepared. The individual chapters of this thesis are prepared accordingly to fulfil these objectives. These objectives are enumerated below:

a) Preparation of a theoretical plasma fireball sheath (PFBS) model (both RFB and IFB) for studying the excited instabilities in laboratory plasma systems [10],
b) Analysing the formation of diverse waves and eigenmodes in the PFBS system [11],
c) Understanding the sheath plasma instabilities (SPIs) with the help of linear, quasilinear, and nonlinear formalisms [14, 17],
d) Exploring futuristic practical applicability of the FB systems and fluctuation dynamics in realistic conditions,
e) Developing a PFBS model for astrophysical bodies like magnetars [20], meteoritic radio afterglows [22], etc.

1.4 METHODOLOGY

A bifluidic plasma model approach is constructed to study the realistic FB dynamics and the associated excitable instabilities. Such instabilities are sourced in diversified free energy sources, such as electromagnetic field, density gradient, etc. The different plasma components, i.e., electrons and ions, are postulated to behave as distinct constitutive fluids. The individual dynamics of each plasma constituent particle is thus neglected, and their collective dynamics is studied as two different fluids. The presence of any other plasma component or impurity ion (like dust) is ignored. The individual electronic and ionic dynamics are governed by their respective governing equations coupled via the electrostatic Poisson formalism. The polar and azimuthal variations of the plasma parameters are ignored due to the assumed spherical symmetry and absence of any applied magnetic field. This approach efficaciously holds for the plasma FBs and their instabilities. The efficacy of the bifluidic model is proven with the theoretical outcomes corroborating with the established experimental results discussed in respective chapters individually.

As mentioned before, the plasma FBs are composed of an electrode (anode in this thesis), a sheath where the FB glows, a circumventing double layer, and the ambient plasma. In order to study the excited instability (or stability), the system is assumed to undergo perturbation (from small to comparatively larger scale) in terms of various plasma parameters about their hydrostatic homogeneous equilibria. The ascending scale of the introduced perturbation determines if it may be classified as linear, quasilinear, or nonlinear in nature. The linear perturbation is simpler due to its very small-scale and the associated Fourier transformation (FT) $F = F_o + F_{10}\exp(-i(\omega t - kr))$. Here, F is any dependent plasma parameter. The FT helps in expressing the whole system into a dispersion relation (DR) of various order in terms of the angular frequency (ω), radial distance (r), and wave vector (k). The rest of the plasma parameters are absorbed as the coefficients of the DR. The variation $\omega(r, k)$ denotes the growth ($\omega_i > 0$) or decay ($\omega_i < 0$) of the wave. Also, it gives propagating ($\omega_r > 0$) or evanescent ($\omega_r < 0$) nature of the wave instability. Furthermore, the linear perturbation helps in figuring out the parameters which stabilize (such as charge number density), destabilize (such as temperature or thermal energy), and conditionally stabilize or destabilize (such as electric and magnetic field) the system.

If the assumed perturbation has a larger scale, then it may be termed as quasilinear or nonlinear in nature. The perturbation formalism in this case is given as $F = F_o + \sum_{i=1}^{n} \epsilon^i F_i$. For $i = 1$, the perturbation is quasilinear and for $i \geq 2$, the perturbation is nonlinear in nature. It may be added that unlike the linear perturbation scheme, there is no pre-assigned form of perturbation in quasilinear and nonlinear formalisms. Instead, the quasilinear and nonlinear expressions of the dependent plasma parameters are to be derived in terms of the independent plasma parameters and associated system specific constants. A tabulated comparison of linear and quasilinear perturbation formalisms in terms of relevant items is presented in Table 1.2.

The fundamental difference between the linear and nonlinear perturbation scheme is that in case of an instability excitation, the former shows an exponential growth of the scale of perturbation, whereas the latter signifies a sign of saturation with the increase in nonlinearity. Thus, it may be stated that linear theory is a special case which holds at the beginning of the instability and nonlinear theory is a general case which holds throughout the successive stages. However, the linear formalism has the benefit that it clearly figures out the stabilizing and destabilizing plasma parameters. The procedure adopted during the quasilinear and nonlinear formalism are discussed henceforth.

The governing equations, such as the electron (ion) continuity and the momentum equations are perturbed by substituting the perturbed expressions of the dependent parameters. The order-by-order substitution yields perturbed equations of the relevant order. The simplified expressions of continuity equation when substituted into the momentum equation, yields solutions for velocity and density expressed in terms of the electrostatic potential. The density-potential relation eventually substituted in the Poisson equation generates the final partial differential equation (PDE) of the corresponding order. The solution of the final PDE with applied boundary condition offers the expected plasma parameters in terms of different constants and independent plasma parameters.

This perturbative process is similarly repeated for higher-order nonlinear terms and the relevant expressions of the corresponding nonlinear terms are derived. It is observed that the difference between the successive orders of perturbations gradually minimize, proving saturation occurring with respect to the increasing order of nonlinearity.

Table 1.2: Linear vs. quasilinear formalisms

S. No.	Item	Linear	Quasilinear	Remark
1	Adopted space	Wave space	Coordination space	Depends on the space of interest and relevance
2	Perturbation formalism	Fourier-type	Lowest order but moderated with ϵ	Difference is due to fluid nonlinearity
3	Order of perturbation	Lowest order (with no ϵ)	Lowest order (with ϵ)	ϵ-moderation is in the quasilinear case
4	Outcome	Generalized linear DR	Multi-order PDE	Multi-order harmonics excite in the quasilinear case
5	Solution nature	Linear in wave space	Quasilinear in coordination space	Weak nonlinearity is in the quasilinear case
6	Superposition principle	Applicable	Not applicable	Linear transformations obey superposition
7	Fluid convection	Forbidden	Allowed	Convective dynamics is in the quasilinear case
8	Fluid dispersion	Allowed	Allowed but dictated by nonlinearity	Dispersive and nonlinear fluid nature prevails in quasilinearity

9	Parametric interaction	Forbidden	Allowed	It ignores the parametric excitation of other modes in linearity
10	Boundary condition	System dependent	$F_1(r \to \infty) = 0$, $F_1(t \to \infty) = 0$	Important for feasible results
11	Number of modes	Multiple	Normal acoustic mode	Each DR root is mathematically a possible mode
12	Mode saturation	Simple	Complex	Multi-order convective interactions are in the quasilinear case
13	FT	Applied	Not applied	FT helps to see stabilizing and destabilizing parameters

1.5 CONCLUDING REMARKS

A brief overview of the plasma medium is presented herein. It covers the basic properties, existential environs, production mechanisms, excitable instabilities, etc. The applied fluid model is justified. The main area of research, i.e., plasma FB is elaborated with schematics (Fig. 1.1). The formation mechanism, various classes of laboratory and astroplasmic FBs are also discussed. The motivation and objectives of the current work is highlighted as well. The differences between the various applied formalisms are briefly contrasted (Table 1.2).

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