CHAPTER-1
AN OVERVIEW OF COMPLEX ASTRO-SPACE PLASMAS AND DUST CLOUDS

Abstract: This introductory Chapter offers a focal overview of different complex astrospace plasmas from a hydrodynamic viewpoint. The role of the major constituents, which are the solid phases of dust grains mixed in the gaseous phase of plasmas, is specifically enlightened. The excitation of a rich variety of collective waves, instabilities and coherent saturation structures is briefly discussed. It presents a brief highlight on the varied astrocloud categories giving birth to diversified nonhomologous bounded structures, such as stellesimals, planetesimals and other galactic building blocks. The main motivation behind our investigations is summarily outlined alongside the focused objectives and methodologies.

1.1 INTRODUCTION
It is a well familiar fact that the ‘plasma’ is a unique state of matter rich in collective degrees of dynamical freedom usually realizable via a wide class of varied wave-activities of real naturalistic significance. A macroscopic state of the plasma usually consists of statistically large number of free electrons and ionized atoms or molecules together with neutral species in minority [1-3]. It exhibits a global quasi-neutrality condition showing collective behavior due to the presence of long-range forces, such as the Coulomb force, gravitational force, etc.

A good cosmological estimation confirms that 99% of the matter in the Universe is in the plasma state (mostly hydrogen and helium in gaseous phase) and the remaining 1% represents submicron-size dust grains (in solid phase) [1-3]. In other words, in various naturalistic situations, the plasma coexists with the dust particulates in a mixed heterogeneous form. An admixture of these dust particles and plasma particles forms what is popularly called a ‘dusty’, ‘grainy’, ‘colloidal’, or ‘complex’ plasma. However, the plasma with dust particles can be classified into the following two ways [1, 4-5]. These are the ‘dust in plasma’, when \( r_d \ll \lambda_D < a \); and ‘dusty plasma’, when \( r_d < a < \lambda_D \). Here, \( r_d \), \( \lambda_D \) and \( a \) are the dust grain radius, plasma Debye length and average inter-grain separation, respectively. The geometrical size of the dust grains varies from tens of nanometers to hundreds of microns. The grain composition varies in different
laboratory and astrophysical environments. They are compositionally comprised of Silicates, Graphites, Amorphous Carbons and Carbonaceous compounds, Polycyclic Aromatic Hydrocarbon (PAH) molecules, Silicon Carbides and Magnesium Sulfides [6]. The grains are known to be electrically charged, either negatively or positively, depending upon their surrounding plasma background environments. As a result, the grains acquire negative charge by contact electrification mechanisms in the plasma background. In contrast, they are positively charged by virtue of photoemission of electrons in the presence of a flux of ultraviolet (UV) photons, thermionic emission induced by radiative heating, secondary emission of electrons from the surface of the dust grains, and so forth [2-3, 7]. The electric charge on the dust grains varies spatially as a dynamical variable as a result of the random interactions of the dust with the thermal electron-ion currents. The presence of such dust grains in a plasma medium change many of the physical properties of the contaminated plasma, such as its charge distributions, resulting long-range potential distributions, wave-kinetic processes, and so forth [8-9]. The dust grain charge-state may vary in the normal interstellar media in the range of \( q_d = Z_d e = 1e-10^4 e \); where, \( e = 1.6 \times 10^{-19} \) C is the electronic charge unit and \( Z_d \) is the dust charge number. In some especial situations, the dust-charge is treated as a “static” one under the approximation that the dust charging time scale \( (\tau_{d} \sim 10^{-8} \text{s}) \) is much smaller than the massive dust electrodynamic response time scale \( (\tau_{d} \sim 10^{-3} \text{s}) \) [10]. Besides, the grains are dielectric (ices, silicates, etc.) and metallic (graphite, amorphous carbons, etc.) in nature in the interstellar media [3]. The physical parameters of the dust grains vary in a wide range spectrum in such media. The dust number density \( (n_d) \sim 10^{-3} - 10^{-1} \text{ m}^{-3} \), diametric size \( (D = 2r_d) \sim 10^{-9} - 10^{-3} \text{ m} \), mass \( (m_d) \sim 10^{-24} - 10^{-10} \text{ kg} \), material density \( (\rho_d) \sim 10^{-21} - 10^{-9} \text{ kg m}^{-3} \), temperature \( (T_d) \sim 10^{-3} - 10^{-2} \text{ eV} \), and so forth [2-3, 5-13]. We categorically present the grain parametric properties in varied astrocosmic space in a tabular form as in Table 1.1.

A number of forces act on the dust grains in diversified astrophysical media. It includes electromagnetic forces, thermal forces, vorticity-driven forces, ion-neutral drag forces, radiation pressure forces, frictional forces, and so on. The action of such forces governs the wave fluctuation dynamics in such complex plasma environments [2-3]. Such situations are naturalistically exist in different astro-cosmo-plasmic circumstances, such as stars, circumstellar rings, planetary atmospheres, planetary rings, dust molecular clouds
Dusty plasma pigments for paints applications (cathode) of materials dust grains fusion devices large scale the industrial plasma rocket and space shuttle exhausts, thermonuclear fireballs, and so forth [3]. A few important examples of such dust-laden plasmas are rocket and space shuttle exhausts, thermonuclear fireballs, and so forth [3].

Apart from the above, the dust grains are present almost in all the categories of industrial plasmas in the form of plasma-assisted engineering and technology [2-3, 26-32]. The dust grains are known to significantly affect the nature and performance of both the macro-electro-mechanical [2-3] and micro-electro-mechanical [26-32] devices on a large scale. In a broader sense, such dust grains are present in microelectronics [26-27], fusion devices [28], direct current and radio-frequency discharges [3], and so forth. The dust grains get produce in such devices by a number of processes, such as surface coating of materials, etching processes, sputtering, evaporation and sublimation of wall material (cathode), etc. Besides, the dust dynamics are involved in many useful technological applications as well, such as solar cells [29], memory devices [29-30], production of color pigments for paints [31], production of hard wear-resistant coatings [32], etc. Thus, the dusty plasma is ubiquitous due to its various wide-range applications featuring from

<table>
<thead>
<tr>
<th>Grain type (Source)</th>
<th>Structure (Formula)</th>
<th>Mass (kg)</th>
<th>Concentration (m$^3$)</th>
<th>Density (kg m$^{-3}$)</th>
<th>Charge ($Z_d e$)</th>
<th>$T_d$ (eV)</th>
<th>Size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstellar [2-3, 5-13]</td>
<td>CO, CS, etc</td>
<td>$10^{-24}$</td>
<td>$10^{-3} - 10^{-1}$</td>
<td>$10^{-21}$</td>
<td>$\pm 1.6 \times 10^{19}$</td>
<td>$-10^3$</td>
<td>$10^9$</td>
</tr>
<tr>
<td>Interplanetary [3, 5, 14-17]</td>
<td>$S_2^2$, $CO_2^{-3}$, etc</td>
<td>$10^{-21}$</td>
<td>$10^{-8} - 10^{-12}$</td>
<td>$2 \times 10^{-9}$</td>
<td>$\geq 1.8 \times 10^{13}$</td>
<td>$10^{-2}$</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>Jovian [18-21]</td>
<td>NaCl, $H_2SO_3$, etc</td>
<td>$10^{-16}$</td>
<td>$10^{-5} - 10^{-4}$</td>
<td>$10^{-20}$</td>
<td>$\pm 1.6 \times 10^{18}$</td>
<td>$10^{-3}$</td>
<td>$3 \times 10^7$</td>
</tr>
<tr>
<td>Dwarf star atmospheres [22-25]</td>
<td>Amorphous $Al_2O_3$, Carbon, etc</td>
<td>$10^{-6}$</td>
<td>$10^4 - 10^7$</td>
<td>$10^{-5}$</td>
<td>$\pm 1.6 \times 10^{15}$</td>
<td>$10^{-3}$</td>
<td>$10^9$</td>
</tr>
</tbody>
</table>

Table 1.1: Dust grain features in varied astrocosmic environs
micro-to-macro domains of naturalistic importance. We are mainly concerned here only with the instability dynamics of self-gravitating complex astroplasmas in different conditions. It covers molecular clouds, stellar and circumstellar atmospheres, planetary environments, cometary tails, and so on [2-3, 5]. In this direction, the wave excitation and propagation kinetics of gravito-electrostatic origin in such partially ionized plasmas provide microphysical insights to understand the mechanisms responsible for diversified bounded astrostructures to form, grow and evolve.

1.2 DUST MOLECULAR CLOUDS

The dense sites of giant interstellar media, which act as stellar nurseries, are known as the dust molecular clouds (DMCs; also, astroclouds). They are magnetized, turbulent and complex fluids in nature [33-35]. The structural behavior of the molecular clouds is highly dynamic in nature featuring many transient transitional phases (longevity \( \sim 10^7 \) years without any noticeable major change) still remaining not completely well understood [36-37].

The DMCs are classified into different morphodynamical categories based on their bulk physical properties, like mass, size, material density, temperature, and so forth. The classification includes globular clouds, dark clouds, giant molecular clouds, dense molecular clouds, diffusive dust molecular clouds, and so forth. We enlist their important physical properties alongside examples extracted from existing sources [6, 24, 35, 36-48] as in Table 1.2.

The interstellar magnetic field is very weak (\( B_0 = 3 \times 10^{-10} \) T) [49]. For dust charge, \( \sim 100e \) and dust mass, \( m_d \sim 10^{-13} \) kg, the gyro-rotation period of the charged dust is estimated \( \tau_{cd} \sim 10^6 \) years. It is too small to influence the dust-charge fluctuation dynamics felt via plasma constituents coupled with the magnetic field [50]. It validates the consideration of unmagnetized clouds in normal situations. The clouds exhibit macroscopically quasi-neutral condition in the absence of external force field [1-5]. The equilibrium electrical neutrality is defined by the bipolar charge balancing condition as

\[
q_i n_{io} = (en_{eo} - q_d n_{do})
\]

in customary notations [3]. Here, \( n_{eo} \), \( n_{io} \) and \( n_{do} \) are the equilibrium concentrations of the electrons, ions and dust grains, respectively. The ionic (dust) charge is denoted as \( q_i = Z_i e \) (\( q_d = \pm Z_d e \)).
Table 1.2: Interstellar clouds and major properties

<table>
<thead>
<tr>
<th>Serial No</th>
<th>Cloud (type)</th>
<th>Region (space)</th>
<th>Density ( (\text{m}^{-3}) )</th>
<th>Mass ( (\text{M}_0) )</th>
<th>Temperature ( T_p ) (eV)</th>
<th>SFR ( (\text{M}_0 \text{yr}^{-1}) )</th>
<th>Example (standard)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Globular</td>
<td>HII</td>
<td>( 10^9 - 10^{10} )</td>
<td>( 10^2 - 10^3 )</td>
<td>( 10^{-3} )</td>
<td>( 2.47 \times 10^{-1} )</td>
<td>NGC6388, B335, etc</td>
</tr>
<tr>
<td>2</td>
<td>Dark</td>
<td>HII</td>
<td>( 10^9 )</td>
<td>( 10^4 )</td>
<td>( 10^{-3} )</td>
<td>4.50</td>
<td>B5, Taurus-Auriga, etc</td>
</tr>
<tr>
<td>3</td>
<td>Giant</td>
<td>HI</td>
<td>( 10^9 - 10^{10} )</td>
<td>( 10^4 - 10^6 )</td>
<td>( 1.4 \times 10^{-3} )</td>
<td>( 5.0 \times 10^{-3} )</td>
<td>250</td>
</tr>
<tr>
<td>4</td>
<td>Dense dust</td>
<td>HI</td>
<td>( 10^{11} )</td>
<td>( 10^{12} )</td>
<td>( 10^3 )</td>
<td>( 3.0 \times 10^{-3} )</td>
<td>( 1.0 \times 10^{-2} )</td>
</tr>
<tr>
<td>5</td>
<td>Diffuse dust</td>
<td>HI, HII</td>
<td>( 10^7 )</td>
<td>( 3 - 10^2 )</td>
<td>( 5.0 \times 10^{-3} )</td>
<td>( 1.0 \times 10^{-2} )</td>
<td>( 4.50 \times 10^{-2} )</td>
</tr>
<tr>
<td>6</td>
<td>Cirrus</td>
<td>Cold HI</td>
<td>( 10^7 - 10^9 )</td>
<td>24</td>
<td>( 10^{-3} - 10^{-2} )</td>
<td>( 1.08 \times 10^{-2} )</td>
<td>Polaris</td>
</tr>
<tr>
<td>7</td>
<td>Supernova remnant</td>
<td>HII</td>
<td>( 10^6 )</td>
<td>8</td>
<td>( 1 - 10^3 )</td>
<td>( 5.00 \times 10^{-1} )</td>
<td>SNR 3C 58</td>
</tr>
</tbody>
</table>

1.3 WAVES AND INSTABILITIES IN MOLECULAR CLOUDS

It is well known that the DMCs are the birth sites of stars and other astrophysical bounded objects. The microscopic constituent particles in them exhibit collective correlative behaviors in an extremely complex fashion yet to be well understood [2-5, 49]. They are susceptible to various types of forces, such as electromagnetic forces, thermal forces, vorticity-driven forces, ion-neutral drag forces, radiation pressure forces, self-gravitational forces, frictional forces, etc. However, due to the presence of constitutive massive partially ionized dust grains in majority, the gravito-electrostatic forces play an active role in their evolution. As a result, the DMC wave fluctuation dynamics is mostly of gravito-electrostatic origin.

The gravitational instability dynamics in astrophysical fluids (gaseous nebulae) have been studied for the first time by J. H. Jeans [51], and hence, accordingly named as the ‘Jeans instability’ after him. This mechanical instability naturally arises due to a perturbation in the gravitating astrocloud media relative to equilibrium thereby causing
the astroclouds to contract under its own self-gravity until counterbalanced by the outward thermal agency. As a consequence of self-gravitational contraction, the clouds become denser, making the thermal pressure enhanced. If the gravitational pressure force (inward) counterbalances the thermal pressure force (outward), the clouds remain stable in hydrostatic equilibrium configurations. When the mass of the cloud exceeds the Jeans mass (a critical mass limit for the onset of the Jeans instability), the gravitational pressure force overcomes the thermal pressure force. It results in gravitational condensation thereby initiating formation of bounded equilibrium structures, such as stars, planets, comets, nebulae, and so forth. If the global cloud mass is much larger than this Jeans limit, the cloud fragments into cloudlets, which, in turn, get transform into protostellar or protoplanetary structures. It may be recapitulated that the clouds consist mainly of heavier heteropolar dust grains in a gaseous background. It hereby implicates an important inference to be drawn that the heavier dust grains in the astroclouds play a crucial role in the formation initiation mechanism of astrophysical bounded structures via the so-called canonical Jeans instability [2, 4-5].

The wave fluctuation dynamics excitable in the diversified astrophysical fluid media are studied via various sophisticated mathematical tools, such as the standard Fourier perturbation techniques (FPTs) [2-5], reductive perturbation techniques (RPTs) [52], Sagdeev pseudo-potential methods (SPMs) [53], gas dynamic methods (GDMs) [54], etc. The FPTs are applied to see the linear stability of the astrophysical fluid system [2-5], RPTs to study weakly nonlinear perturbations [52], SPMs to see strongly nonlinear perturbations [53], GDMs (adiabatic) to see highly nonlinear wave propagation dynamics without any real gaseous medium perturbation on the basis of existential condition of the Bernoulli invariants [54], and so forth. We are, herein, interested in using the FPTs [2-5], RPTs [52], and SPMs [53] to see the stability dynamics of diversified astrofluids of real astronomical relevancy.

It is seen that, in the presence of the dust grains, a plethora of collectively modified or entirely new type of wave excitations exists in the DMCs [2-5]. Such waves undergo both linear and nonlinear evolutionary dynamics with many interesting characteristic features yet to be well understood. In most of the cases, the cloud dynamical systems are nonlinear and dispersive in nature thereby exhibiting a rich variety of nonlinear structures, such as solitary waves, shocks, vortices, double layers, chaos, and so forth [1, 3, 55]. The nonlinearity in such fluid media arises due to fluidity, dispersion due to the Poisson gravity and dissipation due to internal molecular friction [2, 3]. It may
be noted that the soliton-like nonlinear coherent structures are developed due to the balance between the nonlinearity and the linear dispersion effects [2-5]. The shock-like structures are formed due to the balance of the nonlinearity and dissipative effects in the presence of dispersion, and so forth [3, 5].

It is seen further in the literature that the dynamics of the modified waves, together with its nonlinear coherent structures, have been reported theoretically by many authors in the past [3, 4, 55-62]. A few examples of such modified waves are dust-acoustic wave (DAW), dust ion-acoustic wave (DIAW), dust-lattice wave (DLW), dust-acoustic soliton/shock (DAS), dust ion-acoustic soliton/shock (DIAS), and so forth. It is seen that the existence of the low-frequency linear and nonlinear DAWs has been first predicted theoretically with the help of local RPTs in an unmagnetized dusty plasma in 1990 [56]. The Boltzmannian electrons and ions; and heavy negatively charged dust grains have been considered in the studies. In the weakly nonlinear regime, authors have derived a generalized Korteweg-de Vries (KdV) equation by using the RPTs [52]. It has been mainly pointed out that the nonlinear DAW propagation results in supersonic solitary wave structures [56-57]. Authors have also explored various wave-kinetic features in the strongly nonlinear regime in the SPM-fabric [53]. The propagation of nonlinear dust-acoustic shock-like waves in varied dusty plasmas has been found to be significantly modified by the dust-charge fluctuations [42, 60], nonplanar geometry [61-62], dust density and temperature [42], and so forth.

A number of researchers have found a new type of hybrid mode, called the pulsational mode of gravitational collapse in the partially ionized self-gravitating DMCs, developed due to gravito-electrostatic interplay [50]. Such instabilities are formed only in an admixture of charged and neutral grains along with the constitutive plasma species. Many authors have studied such modes in varied plasma configurations of astronomical importance [10, 42, 63]. The wave structures play important roles towards particle acceleration, material transportation and self-gravitational collapse mechanisms responsible for different bounded structure formation and evolution [63-65].

It is noticed that several authors have investigated the instability and fluctuation dynamics in the DMCs by considering the effects of fluid turbulence [33, 37, 49, 66] and magnetic field [49, 67-69]. The turbulence arises due to the existence of multiple randomized erratic motions of the constitutive fluid species. It shows a chaotic type of change in fluid pressure and flow velocity, which is incorporated with the help of a nonlinear Larson logatropic barotropic equation of state [37, 70]. In this direction, many
authors have investigated the various properties of linear [67] and nonlinear [49, 67] waves contributing to the global cloud collapse dynamics into bounded local substructures. Such nonlinear waves have also been confirmed by many authors experimentally [71-73] as well as by satellite (Viking, FISRT, Freja, Polar, etc) observations [74-77] in various astrospace environments.

It is interesting to know that a good number of researchers have confirmed the existence of bipolar dust grains (positively and negatively charged) in the different regions of space and astrophysical environments, viz., Earth’s mesosphere [78], cometary tails [79-80], Jupiter’s magnetosphere [80-81], etc. It has been found that the larger (massive) dust grains are positively charged [82], whereas the smaller (lighter) are negatively charged [83], or vice-versa. Such correlations between dust charge and size have been initially reported to exist in laboratory devices [82-83]. Later, several authors have investigated the wave-kinetic features by considering different dusty plasma configurations [84-86]. It may, therefore, be conjectured that the study of waves and instabilities in diversified complex astrosplasmas is obviously an important area of research extensively useful to enlighten understanding the basic physical mechanism related to star formation and galactic block evolution.

1.4 MOTIVATION
The study on the collective dynamics of diversified waves, oscillations and fluctuations in varied multifluidic complex astrosplasmas has been an importantly emerging area of great explorative interest for many years. The growing research interest on such fluid media is mainly due to the active roles played by the excited collective fluctuations and the wave dynamic processes. These instabilities trigger the formation mechanism of varied bounded equilibrium structures via various wave-kinetic transport processes sourced in re-distribution of mass, energy and angular momentum in star-forming environs. Such structures include stellesimals, stars, stellar rings, planetesimals, planets, and so forth.

It is well known that the stars and planets are the fundamental structural objects full of mysteries in Astronomy. They are formed due to the gravitational collapse mechanism of the DMCs. The study of the wave-instability excitations herein is of immense importance to know the origin, evolution and structure of the celestial bodies constituting the universe as a whole. The linear and nonlinear wave-instability analyses of complex turbo-magnetic unbounded inhomogeneous astroclouds, alongside various heterogeneous collisional and grain-charge dynamics triggering star formation processes,
still constitute an open problematic challenge to be well explored. The instability dynamics of the gravito-electrostatic waves in a self-gravitating complex plasma in the presence of ion-drag effects is yet to be well understood in the strongly nonlinear regime. The nonlocal nonlinear stability analysis of gravity-driven modes with the entire equilibrium gradient forces in bipolar gravoviscous grainy plasmas amid dynamic neutral dust background as yet remains unexplored and unanswered in both the weakly and strongly nonlinear regimes. All these scenarios highlighted above throw light into the fact that there still exist a good number of important burning problems towards gravitational collapse theory. It summarily provides the basic foundation of the driving momentum responsible behind the proposed compiled thesis.

1.5 OBJECTIVE
It is seen that the astrospace clouds are highly inhomogeneous and nonuniform in nature. As a result, various types of waves and instabilities may be excited and driven therein. The objective of this thesis work is to focus on the stability analysis of such mysterious astrospace plasma fluid environs in the framework of theoretical, graphical and numerical strategies. The underlying objectives in the compiled thesis can be summarily entitled as:

a. Study of “Pulsational mode dynamics in turbo-magnetized complex astrofluids”,
b. Exploration on “Bimodal conjugational pair f-kdv dynamics in complex astroclouds”,
c. Analysis of “Nonlinear waves in dust molecular clouds with ion-drag effects”,
d. Study of “Nonlocal nonlinear stability analysis of gravoviscous astroclouds”, and
e. Investigation of “Dynamics of strongly nonlinear waves in gravoviscous astroclouds”.

It is worthwhile that each of the above objectives constitutes a separate Chapter in the compiled thesis. Thus, this thesis, as a whole, contains a rich plethora of collective excitation of diversified waves and instabilities of gravito-electrostatic origin in varied astroclouds bearing pivotal structure formation relevancy.