Chapter-1

A BRIEF OVERVIEW OF PLASMAS: LABORATORY TO ASTROPHYSICAL SCALES

Abstract: *A brief introduction of diversified plasmas with wide-range existential domains is presented. The different pattern formation and evolutionary morphodynamics are briefed. The laboratory plasma sheath and application in astrophysics are highlighted. The nonlinear fluctuations excitable in the interstellar media are enlightened. A panoptic trailer of the solar plasma equilibrium and perturbation dynamics in the fluid model fabric is finally portrayed.*

1.1 INTRODUCTION

The word '*plasma*' refers to a quasi-neutral macroscopic state consisting of statistically large number of interacting charged particles (electrons and ions) together with neutrals in minority. It exhibits collective behavior due to the long-range Coulomb forces against the other states of matter dominated by the short-range Lennard-Jones [1] forces. The terminology 'plasma', the Greek word which means 'something molded or fabricated', was introduced by Lewi Tongs and Irving Langmuir in 1929 [2]. The terminology was coined to describe the inner region of a glowing ionized gas produced by means of an electrical discharge in a gas-filled tube [3-4]. Plasma is often referred to as the '*fourth state of matter*' from the thermodynamic viewpoint, '*first state*' from the cosmogenic viewpoint and '*unique state*' from the collective dynamical viewpoint sourced by the long-range inter-species interactions. It is ubiquitous (99.99 %) in nature.

Plasma plays an important role in our everyday life everywhere. In the astro-space context, the sparks of lightning and thunderbolts occur due to plasma effects [3-5]. The existence of plasma is well observed in diversified astro-cosmic objects, such as stars, planets, galaxies and so forth [5-6]. It is plasma which originates living species in the biological world via electro-diffusive processes [7-8]. In the field of medical science as well, plasma medicine nowadays occupies the most cost-effective and fruitful means of medical treatment and therapeutics (dental surgery, tumor treatment, etc) [7-9].

In the technological arenas, plasma is applied in industrial and modern plasma processing technologies, such as plasma-wall interactions in thermonuclear fusion devices, plasma processing of materials, Hall thrusters, energy-harvesting reactors, vacuum-arc magnetic filters, and so forth [10-13]. Besides, attempts are in force to solve the long-burning global energy crisis with the help of controlled thermonuclear fusion. In this context, the recent experimental devices are worth mentioning, such as International Thermonuclear Experimental Reactor (ITER), Joint European Torus (JET), Tokamaks, and so forth [3-4, 14-15]. On the other hand, in astrophysical scenarios, plasma provides us an understanding about the origin, evolution and formation of diverse galactic large-scale structures in the Universe. In other words, the naturalistic role of plasmas is realized in molecular clouds, stellesimals, planetesimals, planetary rings, cometary tails, nebulae, magnetospheres, and so forth [3-5]. The thesis compiled here is on the astro-cosmically relevant aspects of the equilibrium and perturbation plasma dynamics prevailing in three different plasma environments. It includes plasma sheath structures (on laboratory scales), DMCs (on astrophysical scales) and solar (stellar) plasmas (on solar scales). Thus, an overview of the different plasma environments and characteristics, starting from the laboratory to astrophysical scales of space and time is worth presenting.

1.2 LABORATORY PLASMA

In all the controlled plasma devices, such as thermonuclear fusion energy reactors, Q-machine and so forth, the plasma is produced in a vacuum chamber of finite size in laboratories. In such a confined plasma case, the plasma always separates itself from the confining wall thereby refraining from being in contact. The coupling of the bulk plasma with the wall gets established through a non-neutral space-charge (positive for normal plasmas) layer (darker than the bulk), termed as '*plasma sheath*' or '*Debye sheath*', which is formed in the vicinity of the wall [3-4, 13]. It is noteworthy that the sheath-associated physical mechanisms considerably differ from the bulk plasma counterparts. An elaborate description of the plasma sheath formation in normal plasmas is presented in the next section.

1.2.1 PLASMA SHEATH FORMATION MECHANISM

As already mentioned above, the term '*sheath*' refers to a thin non-neutral space-charge layer of strong electric field formed due to electrostatic polarization developed in scale-transition between the bulk plasma and confining wall [16-18]. In normal plasmas (hydrogenic), the sheath develops because of mobility difference of lighter electrons (hot) and less light ions (cold). Since, electrons have much higher thermal velocities than ions, they are lost faster in the wall via collisions, thereby leaving the plasma with a net positive charge. It makes the wall potential negative relative to the bulk plasma. As a result, the negative wall repels the electrons, while the ions are attracted towards the wall. Thus, there arises a thin positive space charge layer formed in the vicinity of the wall in the form of '*sheath*'. It may be noted that an ion-rich sheath (positive) is formed in normal electron-proton plasma in the presence of boundary effects. The electron population density goes to a minimum value thereby rendering the ion population density maximum in the sheath-existence zone [16-19].

It is worth mentioning here that the typical spatial extension of the plasma sheath is on the order of the electron plasma Debye length (λ_{De}); whereas, the scale-length of the bulk plasma quasi-neutrality existence is on the order of the plasma system scale-length (L).

1.2.2 BOHM CRITERION

In 1949, David Bohm derived a threshold condition, known as the Bohm criterion [10], for the evolutionary existence of plasma sheath at the boundary. This condition physically states that the ion flow speed at the sheath entrance region must be at least as great as the ion sound phase speed in order for a sheath to form at the boundary, i.e. $M_{i0} \geq 1$ [16-18]. The plasma sheath formation in the vicinity of confining wall, even after a dynamic equilibrium is established, is strongly influenced by particle loss and recombination processes. It is widely seen that such nonlinear structures in the form of positive space charge sheath shielding a negative wall are normally possible only when the Bohm local criterion is fulfilled.

1.2.3 SHEATHS IN ASTROPHYSICAL DOMAIN

In addition to laboratory plasma sheaths as already highlighted above, the basic insight of the plasma-wall interaction physics so long known on the laboratory scales of space and time, has already been applied in the solar plasma system to formulate the gravito-electrostatic sheath (GES) model addressing the fundamental solar plasma issues [20]. In this model, unlike the laboratory plasma sheath, the Sun does not have any physical wall, but the solar self-gravity acts as a non-rigid potential wall to restrain the outward plasma flow relative to the solar plasma center. The GES model enables us to see that the entire solar plasma system is divided into two concentric plasma layers, known as the solar interior plasma (SIP) on the bounded scale and the solar wind plasma (SWP) on the unbounded scale. They are dynamically inter-coupled via a thin diffused concentric interfacial layer, known as the solar surface boundary (SSB), determined by the field extremization principle [20-22]. As the sheath is formed due to the nonlinear coupling of the gravito-electrostatic force fields, it is termed as the *gravito-electrostatic sheath* (GES), which demonstrates the invariant physics of experimental plasmas. The GES model throws light into the surface subsonic origin of the out-of-surface supersonic solar wind. It, in turn, implies that the origin of the supersonic SWP lies in the subsonic SIP dynamics itself. Thus, the GES formulation model provides a deep physical insight on the interrelation between the Sun (SIP) and its atmosphere (SWP) from a purely new viewpoint of plasma-wall effects.

1.3 ASTROPHYSICAL PLASMA

The term ‘astrophysical plasma’ refers to a wide-range class of plasmas existing in different astrophysical objects, their surroundings and the space among them collectively [5-6, 23]. The study of astrophysical plasma is very useful in understanding the origin, evolution and structure of the celestial bodies constituting the Universe as a whole. A few examples in this context are stars, DMCs, nebulae, supernova explosion, accretion discs, galaxies and their arms; and so forth [24-25].

It may be quite interesting to see that dusty plasmas play an important dynamical role in the space and astrophysical environments. Dust is a ubiquitous component in interstellar clouds, circumstellar media, nebulae, solar system, cometary tails, etc. [6, 24, 26]. An interesting point to be noted here is that such dust-contaminated plasmas support a great variety of collective waves, fluctuations and coherent structures, such as solitons, shocks, double layers, etc. [6, 26-27]. In the present compilation, we are focusing mainly on two different types of astrophysical plasmas, viz. DMCs and solar (stellar) plasmas.

1.3.1 DUST MOLECULAR CLOUD

The dense cold regions in the vast dust-gas mixed volume (DMCs) in the space between stars (Inter-Stellar Medium, ISM) in the galaxies are the nurseries of stars and other bounded structures. The massive dust grains, both electrically charged and neutral, form the most important and abundant ingredient of the ISM thereby strengthening gravitational instability phenomena. The grains are mainly composed of graphites, silicates, carbon and other metallic compounds. The grain-size in the ISM varies from micron to sub-micron scales [28-30]. The DMCs are sufficiently so dense that they are well-shielded against the dissociating factors of interstellar ultraviolet radiation. As a result, the constituent hydrogen atoms bind to form hydrogen and other molecules; and hence, the nomenclature 'DMC'. The formation of stars, planets and other galactic objects is initiated exclusively within such molecular phase regions via self-gravitational collapse dynamics [26-29].

1.3.2 TYPES OF MOLECULAR CLOUDS

The collective dynamics of Interstellar Molecular Clouds (IMCs) is well known to play a crucial role in material transport processes initiating the formation mechanisms of stellesimals, planetesimals and other galactic objects. The IMCs, in fact, are spatially inhomogeneous and non-uniform in nature. The physical IMC properties keep on changing dynamically from point to point in the clouds. The most pronounced properties of astronomical relevance refer to density, temperature, mass, size, extinction, star-formation rate, and so forth. On the basis of such characteristic properties, the IMCs can be macroscopically categorized into the following main classes.

(1) Globular Clouds (GCs): The globular clouds (GCs), also referred to as the Bok globules (BGs) form a special type of interstellar clouds. They are so named after the famous astronomer Bart Bok in 1940 [31]. The macro-state of such clouds is quite simplistic in nature. They are the potential sites for star-formation together with other like bounded structures. The GCs have a simple round appearance in terms of geometric shape, attracting researchers for exploration of interest, which may be handled analytically. Their mass falls in the range $M_{GC} \sim 10-100\ M_{\Theta}$, population density $n_{GC} \sim 10^9 - 10^{10}$ cm^{-3}, temperature $T_{GC} \sim 10$ K, and their scale-size $L_{GC} \sim 3.08 \times 10^{15}$ m, and visual extinction goes as $A_{V_{GC}} \sim 10$ mag [31].

Here, M_{Θ} is the mass of the Sun, a reference mass unit in astronomical observations. It may, for instant convenience, be reproduced that the interstellar (visible) extinction (measured in magnitude) refers to the obscurational behavior of the constituent dust grains as a result of the summative effects contributed jointly by absorption and scattering of starlight by the grains [31-33]. The star-formation rate in such clouds is estimated as small as R_{GC}^{*} ~ $2.5\times10^{-2}-2.5\times10^{-1}$ M_{Θ} yr^{-1}. A well-known example of such BGs is B335.

(2) Dark Clouds (DCs): The dark clouds (DCs) are similar to the globules, except in the geometrical size, being relatively larger. The DCs have a typical mass $M_{DC}\sim10^{4}$ M_{Θ}, average population density $n_{DC}\sim10^{9}$ m^{-3}, temperature $T_{DC}\sim10$ K, scale-size $L_{DC}\sim1.54\times10^{17}-3.08\times10^{17}$ m, and visual extinction $A_{V_{DC}}\sim5-10$ mag [31-33]. The star-formation rate here is calculated as $R_{DC}^{*}\sim$ 25 M_{Θ} yr^{-1}. The actual geometrical size of such clouds is not precisely known because of many sub-cloud-like structures existing inside the DCs. The examples include Taurus-Auriga, B1, Spitzer dark cloud 335, etc.

(3) Giant Molecular Clouds (GMCs): The giant molecular clouds (GMCs) are the largest inhabitants of the galaxies. The GMCs are composed mainly of helium and hydrogen along with small fraction of heavier gases. Most of the stars, planets and other galactic structures are formed in the GMCs. They are generally elongated in shape. Their net mass is $M_{GMC}\sim10^{5}$ M_{Θ}, average number density $n_{GMC}>3\times10^{8}$ m^{-3} (lower than GCs or DCs), average temperature $T_{GMC}\sim15-40$ K, scale-size $L_{GMC}\sim1.54\times10^{18}-3.08\times10^{18}$ m, and visual extinction $A_{V_{GMC}}\sim$ 2 mag [31-33]. The star-formation rate here is estimated as R_{GMC}^{*} ~ 250 M_{Θ} yr^{-1} [34]. The most common example of such GMCs is the Orion molecular cloud.

(4) Dense Dust Clouds (DDCs): The dense compact molecular cloud cores residing within the GMCs are known as the dense dust clouds (DDCs). They are denser and warmer than the surrounding clouds [31-33]. The DDCs have a net mass $M_{DDC}\sim10^{3}$ M_{Θ}, population density $n_{DDC}\sim10^{11}-10^{12}$ m^{-3}, temperature $T_{DDC}>50$ K, scale-size $L_{DDC}\sim3.08\times10^{15}$ m, and visual extinction $A_{V_{DDC}}\sim100$ mag [31-33]. These DDCs are the places in the GMCs where the star formation takes place. A simple calculation based on the above cloud mass gives the star-formation rate as $R^{*}_{DDC} \sim 2.5\ M_{\Theta}$ yr^{-1}. Here, TMC-1 is a known example of this category.

(5) Diffuse Dust Molecular Clouds (DDMCs): The diffuse dust molecular clouds (DDMCs) represent a minor fraction of the interstellar gaseous fluid existing in the ISM. The DDMCs have a net mass $M_{DDMC} \sim 50\ M_{\Theta}$, population density $n_{DDMC} > 10^{7}$ m^{-3}, temperature $T_{DDMC} \sim 50 - 100$ K, scale-size $L_{DDMC} \sim 9.24 \times 10^{16}$ m, and visual extinction $A_{V_{DDMC}} \sim 1$ mag [31-33]. The star-formation rate for such clouds is determined as $R^{*}_{DDMC} \sim 1.25 \times 10^{-1}\ M_{\Theta}$ yr^{-1}. A familiar example of the DDMCs is ς-Ophiuchi.

(6) Cirrus Clouds (CCs): The cirrus clouds (CCs) are the smallest clouds in the ISM. As their mass is very small, so their star-formation rate is too small. They have low visual extinction (indeterminable), and hence, cannot be easily observed. The CCs appearing at high galactic altitudes can only be clearly visible. Their nomenclature stems from their appearance in the infrared region, as observed by the Infrared Astronomical Society (IRAS) [33]. The CCs mostly contain cold HI gas. However, only about 10 % of the CCs have molecular (H_2) cores. Their density is $n_{CC} \sim 10^{7} - 10^{10}$ m^{-3}, and temperature $T_{CC} \sim 10 - 100$ K [31-33].

1.3.3 JEANS INSTABILITY

The mechanical instability caused due to the self-gravitational interactions of the fluid-elements in a large-scale gravitating fluid of extremely large size (than the Jeans length) is known as the Jeans instability, named after the British physicist, Sir James Jeans [35]. The instability appears, alternatively speaking, when the cloud mass exceeds the Jeans critical mass; otherwise, stable. Jeans was the first to predict this instability for self-gravitating spherical gaseous nebula leading to the condensation and structure formation.

Massive partially ionized dust grains in the DMCs are well-known to develop significant self-gravitational instability effects on the Jeans scales of space and time. The coupling of the self-gravitational attraction (inward) developed by the grain mass (Newtonian) and the electrostatic repulsion (outward) sourced by the grain charge (Coulombic) with partial ionization leads to an interesting phenomenology ‘the pulsational mode instability' [36-38]. The unstable DMCs undergo condensation processes, leading to bounded equilibrium structures, when both these counteracting forces become comparable. In other words, the self-gravitational collapse towards structure formation takes place when the self-gravitational force overcomes the electrostatic repulsive force. This indeed happens if and when the grain charge-to-mass ratio (dust specific charge) becomes $(q_d/m_d) \sim \sqrt{G}$, where $G = 6.673 \times 10^{-11}$ N m^2 kg^{-2} is the universal gravitational coupling constant through which gravitational interaction is realized [39]. The initiation of stars and other galactic unit formation in such DMCs is attributable to the self-gravitational collapse according to the Jeans criterion under the condition of such dust specific charge values. Thus, the different nonlinear evolutionary wave patterns resulting from such instabilities play a crucial role in understanding the basic physics of the formation-evolution processes of diverse galactic structures in the Universe via wave-induced fluid material transport processes [26-29]. Figure 1.1 shows a schematic diagram of a typical DMC in spherically symmetric configuration.

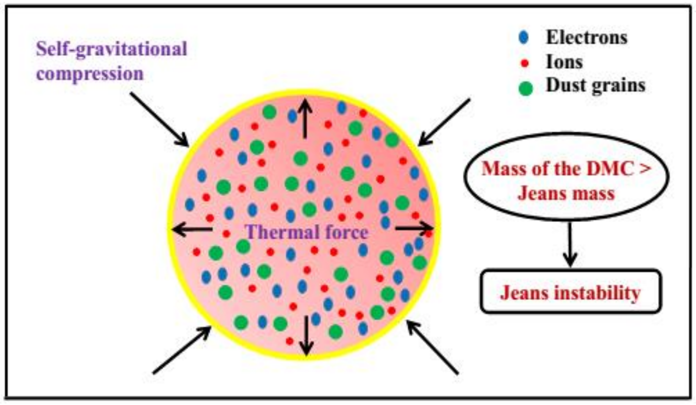

***Figure 1.1:** Schematic diagram of a typical spherically symmetric gravito-thermally bounded dust molecular cloud (DMC).*

1.3.4 SOLAR (STELLAR) PLASMA

The Sun is an astrophysical plasma object of great beauty and fascination, born via the Jeans collapse dynamics, which has been widely studied with great interest for decades. It came into existence from a contracting, rotating, interstellar cloud that spun up during the collapse. It is a self-gravitating hot plasma ball held together by the dynamical equilibrium of gravitational, thermal and electromagnetic forces. It influences the Earth's climate and space weather, and plays a crucial role in understanding the behavior of stars and cosmic plasmas in general. It provides a naturalistic route for learning different fundamental cosmic processes such as magnetic turbulence, solar dynamos, sunspots, solar cycles, coronal mass ejections, solar wind, flares, and so and so forth [40-41]. Thus, the Sun and its atmosphere constitutes a dynamic complex laboratory full of mysteries yet to be explored.

The solar plasma phenomena are usually classified into two categories: quiet and active. The *quiet Sun* is static, spherically symmetric ball of plasma, whose properties depend on the radial distance from the center with negligible effect of magnetic field. On the other hand, the *active Sun* comprises of transient phenomena, such as sunspots, prominences, coronal mass ejections, overlying on the quiet atmosphere having a strong dependency on magnetic field [40-42]. The Sun is an ordinary main-sequence star of spectral type G2V and has a stellar magnitude of 4.8 on standard scale. It is mostly composed of the natural elements, such as hydrogen (~ 98 %) and helium (~ 8 %), along with a very minute percentage (~ 0.01 %) of some other heavier elements and neutrals, such as carbon, oxygen, and nitrogen [40-42]. The main physical properties of the Sun according to the standard solar model (SSM) based on radial variation assumption are enlisted in Table 1.1.

Table 1.1: Physical properties of the Sun

S No.	Physical parameters	Typical value
1	Age	4.6×10^{9} years
2	Mass (M_Θ)	2×10^{30} kg
3	Radius (R_Θ)	6.95×10^{8} m
4	Mean Density	1.4×10^{3} kg m^{-3}
5	Mean distance from Earth	1.49×10^{11} m
6	Surface gravity (g_Θ)	274 m s^{-2}
7	Radiation (luminosity, L_Θ)	3.86×10^{26} J s^{-1}
8	Core temperature	1.5×10^{7} K
9	Surface temperature	5700 K
10	Coronal temperature	6×10^{6} K

1.3.5 SOLAR STRUCTURE

The solar interior as per the SSM can be classified into three parts based on the different energy transfer processes radially outwards as follows: (a) *Core*: Energy is generated here by the thermonuclear reaction. Almost 99 % of the solar energy is produced in this region; (b) *Radiative zone*: The originated energy is transported here by means of radiation; and (c) *Convective zone*: The mode of energy transportation occurs here through mass convection and circulation phenomena. The transition region of the Sun between the radiative interior and the differentially rotating outer convective zone is known as the *tachocline* [40-42].

Similarly, the outer solar atmosphere can also be divided into different concentric spherical zones with different physical properties, viz., the photosphere (solar surface), chromosphere, transition region and corona radially outwards [40-42]. The different concentric layers of the solar interior and the solar exterior is shown in figure 1.2.

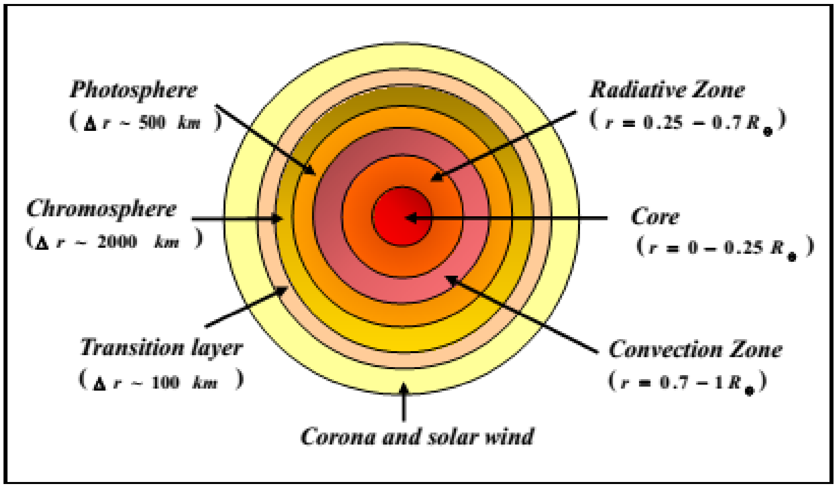

Figure 1.2: *Schematic diagram of the Sun and its ambient atmosphere according to the standard solar model (SSM).*

1.3.6 GES MODEL OF SOLAR WIND

The standard solar model (SSM), as already mentioned, has been successful in providing a good understanding of various canonical properties of the Sun, such as solar mass, radius, luminosity, etc [40-41]. The most prominent outcome based on the hydrostatic equilibrium-based SSM is the Parker model of solar wind flow dynamics [43]. The acceleration of the solar wind is based on the physics of the *de Laval nozzle* mechanism. An apparent drawback of this model under hydrostatic equilibrium is that it fails to explain the interconnection between the solar interior and the exterior. Moreover, the other major drawbacks have been addressed in the gravito-electrostatic (GES) model based on the physics of the collective plasma-wall interaction mechanism [20-21]. This model has successfully predicted that the origin of the supersonic SWP lies in the subsonic SIP dynamics itself via the SSB mechanism. The physical mechanisms associated with the GES model formulation has already been discussed in the past. A schematic diagram of the Sun and atmosphere as per the GES model is shown in figure 1.3.

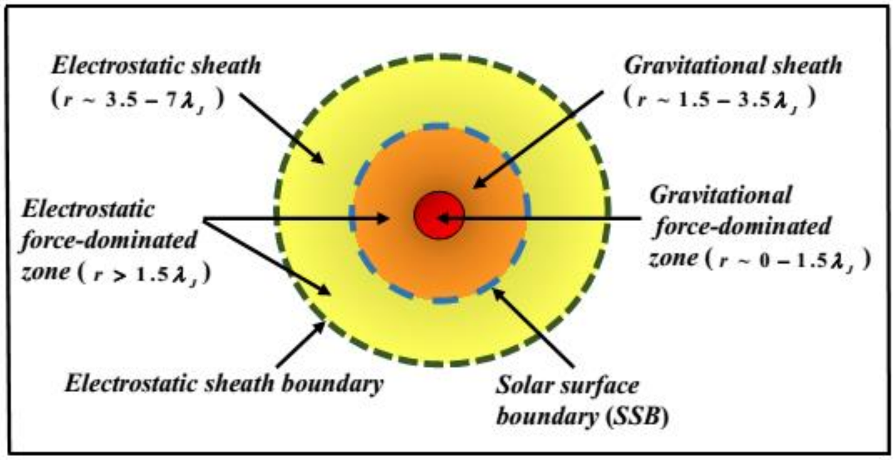

Figure 1.3: *Schematic diagram of the Sun and its ambient atmosphere according to the gravito-electrostatic sheath (GES) model.*

1.3.7 POLYTROPIC MODEL OF SOLAR WIND

The continuous radially outflowing stream of high energetic particles (electrons, ions, minor neutrals) emanating from the Sun is known as the *solar wind* [44-45]. Parker (1958) was the first to predict a transonic outflow from the hot corona into the cold interplanetary space. The unequivocal existence of the solar wind has been established by the Mariner-2 spacecraft launched in 1962 [44]. Based on the conventional flow dynamics, there are mainly two types of solar wind: a fast, tenuous and almost uniform stream component; and a slow, dense, non-uniform component. The fast solar wind originates from the inactive, quiet part of the Sun, whereas, the slow from the active regions, which is more turbulent in nature than the fast one. The fast component has average speed exceeding 700 km s^{-1}; while, that of the slow one is around 300 km s^{-1} [44-45].

It may be mentioned here that various solar spacecraft missions for probing the Sun and its ambient atmosphere has already been existent for years [41, 46-47]. The probe mission includes the Ultraviolet Coronagraph Spectrometer (UVCS) on board the Solar and Heliospheric Observatory (SOHO), Transition Region and Coronal Explorer (TRACE), Helioseismic Magnetic Imager (HMI) on board Solar Dynamics Observatory (SDO), Ulysses, Solar Terrestrial Relations Observatory (STEREO), Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), the Solar Optical Telescope (SOT) on board the Hinode, Advanced Composition Explorer (ACE), and so forth [41, 46-47]. With the help of these spacecraft missions, the direct observation of the different solar wave activities and their primary characteristics becomes accurately possible.

The origin of solar wind has been a great research problem since the detection of a supersonic character of the material flow from the Sun through ground-based observations of cometary tails, cosmic-ray variations, geomagnetic disturbances, and so forth [48]. The problem of dynamical stability and the energization mechanism responsible for the solar wind acceleration from the slow to fast components are yet to be well understood [48-49]. It may however be appreciated that many researchers in the past have made bold efforts to see the solar wind flow dynamics and stability from different perspectives, like hydrodynamic model [45, 48], magnetohydrodynamic (MHD) framework [44, 49], kinetic approach [50-51], and so forth. In addition, there exists another class of models, involving a reduced or spatially variable adiabatic index, known as the '*polytropic model*' [44-45].

As the central theme of this subsection is the polytropic model of the solar wind, we stress on it elaborately. A 'polytrope' refers to a hydrostatic equilibrium structure obeying the pressure-density law of thermodynamic origin as $P = K\rho^{(n+1/n)}$, with P as the pressure, K the polytropic index, ρ the material density and n is the polytropic index [44-45, 52]. In a simplistic sense, a polytropic state qualitatively implies a structural configuration with a maximized density at the structural core with asymptotically decreasing value outwards. This governing equation of state is called the polytropic equation of state, or polytropic pressure equation, or polytropic energy equation due to the fulfilment of the universal law of conservation of energy. This is a simplified model in the sense that it excludes the need for solving the energy equation throughout the stellar structure to manipulate the full rigorous solutions characterizing the structures. The polytropic index is often assumed to have a value close to unity in order to represent the nearly 'isothermal state' of the solar corona and to obtain the acceleration of the solar wind [44]. Moreover, a polytropic process can be defined as a 'quasi-static change' of state in which the specific heat is held constant [52-53]. It furthermore describes the internal structure of astrophysical objects, molecular clouds, galactic matter distribution, and so forth. A polytropic model formalism can be widely employed to see the equilibrium and stability behaviors of the solar wind flow dynamics.

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