Plasma and Its Importance

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Abstract— The Universe that we observe is mostly made up of plasma. Plasma is a gas of charged particles which consists of equal nos of free positive and negative charge carriers. Having roughly the same number of charges with different signs in the same volume element, guarantees that the plasma behaves quasineutral in the stationary state. On average of plasma looks electrically neutral to the outside, since the randomly distributed particle electric charge fields mutually cancel. Plasma regimes range from center of stars to attractive pulsars and fill the vacant area in galaxies. There are many unanswered questions about the Universe which can be solved if we know more about space plasma. These questions are like origin of the Universe concerning the Big Bang theory, stellar and planetary formation, pulsars, black holes etc. Space and astrophysical plasma science range from Earth's mesosphere, solar wind, heliosphere till plasma on the scale of whole Universe. So, in this research paper we are going to solve questions which are- "What is the extent of plasma science in understanding the Universe and up to what level we have achieved that knowledge?"

Keywords: Plasma, Solar Wind, Magnetosphere, Ionosphere, Magnetospheric Currents, Future of Plasma

I. Introduction

Knowledge of Plasmas has been an important part of human exploration. It has many practical applications in relation with satellites and humans in space environment. Its knowledge is must for astronaut's safety and health of spacecraft for safety from radiation environment and charging of payload. Centre of sun has temperature -5 million K while solar flares on Earth are -10^5 K and their corresponding densities are -10^6 particles per cubic centimeter to -1 particle per cubic centimeter. For black holes and neutron stars temperature is around -10K while their densities are -10^4 particles per cubic centimeter. So, for plasmas, they have a wide range of temperature and densities, but still it depends upon dimensionless ratios. When researchers study about origin of the Universe, they forget two main things, that is magnetic fields and the fact that this whole Universe is made up of ionized plasma. Magnetic field along with space plasma is dragged in by intergalactic spaces which fill that gap among galaxies – called The Interstellar Medium (ISM). High energy processes related to space plasma are astrophysical systems like pulsar winds, accretion disks/jets, gamma ray bursts, solar flares. These all have high storage of magnetic fields. Recent advances in numerical simulations with like particle-in-cell (PIC) method, magneto hydrodynamic (MHD) method, combined PIC-MHD method and their application to study both microscopic plasma physics and macroscopic astrophysical physics in realistic astrophysical settings have significantly improved our understanding of many longstanding problems and have successfully explained observation. Since the particles in plasma have to overcome the coupling with their neighbors, they must have thermal energies above some electron volts. Thus, typical plasma is a hot and highly ionized gas. While only a few natural plasmas, such as flames or lightning strokes, can be found near the Earth's surface, plasmas are abundant in the Universe. More than 99% of all known matter is in plasma state! Thus, studying magnetic field and particle energization in different systems in astrophysical and space plasmas require a good understanding of fundamental physical processes over a broad range of length scales or particle energies which has been and is a great challenge for all scientists out there. So, in this paper basics of plasma, its relation with magnetic fields based on applications and future of plasma science is discussed.

II. History of Plasma Science

When various corpuscles are removed from blood, the remaining liquid is called "plasma", coined by great Johannes Purkinje (1881-1869). Irving Langmuir (1881-1957) started using this term since 1927 while he was studying electronic devices based on ionized gases. He observed that the way RBCs, WBCs and germs flow in blood plasma, similarly, high velocity electrons, impurities and ions flow in electrified fluid. Further it led to terms "Langmuir waves" and "Langmuir probes". Gradually, researchers on plasma parted I in three directions. Firstly, ionosphere was developed due to radio development, as it either refracts or absorbs radio waves. Thus, a large variety of plasma was known after researches over propagation of radio waves. Secondly, scientists realized that a large part of Universe was made up of plasmas and so, for understanding astrophysical processes like sunspots and solar flares, a wide knowledge of plasma science was needed. Thirdly, formation of nuclear bomb led to the realization that nuclear energy was a great discovery for future. Thermonuclear fusion process, occurring in the core of the Sun, showed that the process needed heavy forms (isotopes) of hydrogen and such intense temperature hat if we produce that energy on Earth, the container would vaporize! Thus, to create plasma at such a temperature, the gas is stored inside a magnetic field. This process of such a "controlled thermonuclear fusion" started with "Project Sherwood in 1950s and still researches are going on it. So, currently fourth growing field is of "space plasma" which consists of all three fields mentioned above including plasma processes occurring in the Universe.

III. Properties of Plasma

A. *Debye Shielding*

It is compulsory for plasma to have about equal number of positive and negative charges per volume for it to have quasineutral behavior in stationary state. Such a volume should be small enough compared with the characteristic length of variations of macroscopic parameters such as density and temperature, but large enough to contain a sufficient number of particles. The microscopic space charge fields of the individual charge carriers must cancel each other to provide macroscopic charge neutrality in each volume element. To let the plasma appear electrically neutral, the electric coulomb potential field of every charge, q, $\phi_c = q/4\pi\epsilon_0 r$ with ϵ_0 being free space permittivity, is shielding by other charges in the plasma and assumes the Debye potential form $\phi_D=q/4\pi\epsilon_0 r \exp(-r/\lambda_D)$ in which the exponential function cuts off the potential as distances $r \gg \lambda_D$. λ_D is the characteristic length , called Debye length. It is a distance, over which a balance is obtained between the thermal particle energy, which tends to perturb the electrical neutrality, and the electrostatic potential energy, which is resulted from any charge separation, which tends to restore charge neutrality. It is to be noted that λ_D is a function of electron and ion temperatures, T_e and T_i, and the plasma density, $\eta_e \simeq \eta_i$ (assuming singly charged ion).

$$\lambda_D = (\epsilon_0 K_B T_e/\eta_e e^2)^{1/2}$$

Assuming that $T_e \simeq T_i$, K_B to be Boltzmann constant and e to be electron charge. It is necessary that the physical dimension of the system, L should be larger than λ_D, for a plasma to be quasineutral, $\lambda_D \ll L$. If this requirement is not fulfilled, then there won't be enough space for collective shielding effect to occur and we are left with just simple ionized gas. Hence, this requirement is likely called first plasma criterion.

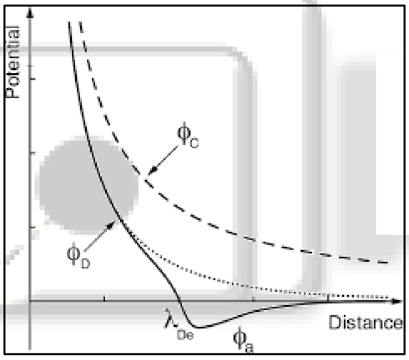

Fig. 1: Comparison of Debye and Coulomb potential

B. Plasma Parameter

It is necessary that the sphere contains enough particles because we know that the shielding effect is the result of the collective behavior inside the Debye sphere of radius λ_D. The number of particles inside a Debye sphere is $4\pi\eta_e\lambda_D^3/3$. The term plasma parameter (Λ) is often represented by $\eta_e\lambda_D^3$ and thus, it is the second plasma criterion, which is

$$\Lambda=\eta_e\lambda_D^3 \gg 1$$

C. Plasma Frequency

Electron plasma frequency, ω_{pe} is the typical oscillation frequency in fully ionized plasma. Suppose, if the quasineutrality of the plasma is being disturbed by some external force, then electrons are accelerated in an attempt to restore the charge neutrality, as they are more mobile than the much heavier ions. The electrons will move back and forth around their equilibrium position due to their own inertia. This results in fast collective oscillations around bigger ions. It is proved that plasma frequency depends upon the square root of plasma density. If we take me to be mass of electron, then

$$\omega_{pe} = (\eta_e e^2/m_e\epsilon_0)^{1/2}$$

Some plasma are not completely ionized as Earth's ionosphere. In these cases, there are considerable numbers of neutral particles. So, if the charged particles collide too often with neutrals, electrons will be forced into equilibrium with the neutrals, and the medium does not behave as plasma anymore, but simply like a neutral gas. To fight this situation, the average time between two electron-neutral collisions, τ_n, must be larger than reciprocal of the plasma frequency. $\omega_{pe}\tau_n \gg 1$

So, this is the third criterion for an ionized medium to behave as plasma.

IV. PLASMAS AND MAGNETIC FIELDS

Interaction between plasma and magnetic field is really fascinating. In any room, you cannot feel Earth's magnetic field around you because interaction between it and gas is negligible. Suppose the room is filled with plasma, then the field exerts Lorentz force on it, which splits it in two parts-magnetic pressure and magnetic tension force. Plasma can be ejected from a curved magnetic field at Alfven speed or can support plasma against gravity. Now, since plasma experiences force due to magnetic field, it can also store energy. Plasma notions that twist and shear magnetic field lines can inject energy in the magnetic field. At times, magnetic field becomes unstable and that energy is released violently. Some of the applications based on this are given below.

A. The Sun and Solar Wind

The Sun has such a large amount of heat content that if we stop reactions in its core anyway, its affects will be solar surface after 10^7 years. The Sun is a hot sphere of plasma made by its own self-gravitation and has heat energy due to nuclear reactions. Over the whole of the solar photosphere the magnetic field is concentrated by turbulent convective motions into intense magnetic flux tubes of strength 1500 Gauss at the boundaries of convective elements. Going up above the photosphere of the Sun these flux tubes spread out in the chromosphere and fill the whole space in the upper chromosphere and corona with beautiful magnetic loop structures where the magnetic field is strong enough. Elsewhere, the plasma stretches the magnetic field out into open structures leaving the Sun. Sun's atmosphere is the greatest known plasma physics laboratory for humans ever where we can do experiments which cannot be done on Earth. Highly conducting tenuous plasma is being emitted by Sun called Solar wind into the interplanetary space as a consequence of Sun's corona (due to its magnetic field). The Earth is just like a little pebble in a stream of plasma flowing supersonically out from the Sun. The solar wind does not flow steadily. The sunspot cycle causes the solar activity to manifest itself through it; it causes the plasma from a particular solar region to expand at a much greater speed setting up a shock that accelerates ions in situ to large energies. Solar wind is being emitted by Sun at supersonic speed of about 500km/s into the interplanetary space as a consequence of the supersonic expansion of the solar wind.

It contains mainly electrons and protons with a small mixture of 5% Helium ions. Because of the high conductivity, the solar magnetic field is frozen in the plasma (like a superconductor) drawn outward by the expanding solar wind. The interplanetary magnetic field is of order 5nT. Earth's dipolar magnetic field is strong enough to face solar wind when it hits it. The solar wind cannot simply penetrate and pass through it but it slows down to a large extent and is deflected around the magnetic field. A bow shock wave is generated where plasma is slowed down due to hitting of solar wind to obstacle with supersonic speed. More than that, considerable fraction particles' kinetic energy is converted to thermal energy. The region of thermalized subsonic plasma behind the bow shock is called the magneto sheath. Its magnetic field has higher values in this region and also its plasma is hotter and denser than solar wind plasma.

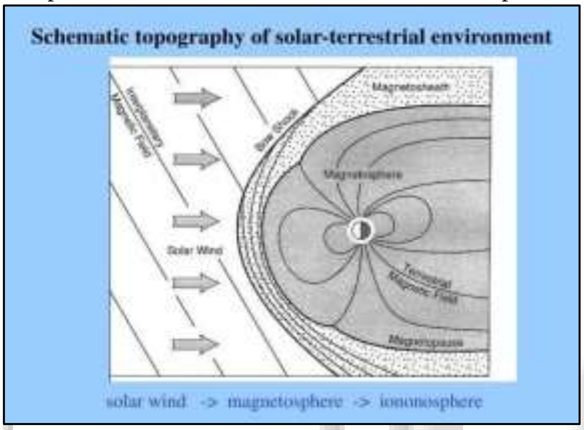

Fig. 2: Topography of solar terrestrial environment

B. The Magnetosphere

The shocked solar wind plasma in the magneto sheath cannot easily penetrate the terrestrial magnetic field but mostly deflected around it. This is the result of the fact that the solar wind particles cannot leave the interplanetary field lines and the interplanetary magnetic field line cannot penetrate the terrestrial field lines due to the aforementioned frozen-in characteristic of highly conducting plasma. The boundary separating the two different regions is called magnetopause and the cavity generated by terrestrial field is called magnetosphere. The kinetic pressure of the solar wind compressed at the front side and the night side magnetic field is stretched out in a long magneto tail, reaching beyond lunar orbit. The sources of electrons and protons in plasma of magnetosphere are terrestrial ionosphere and the solar wind. Other than these, here are also He^{+}, O^{+} and He^{++} ions. So, plasma in magnetosphere is grouped into different regions with quite different densities and temperatures.

Most of the magneto tail plasma is concentrated around the tail midplane in about 10RE thick *plasma sheet.* Near the Earth, it reaches down the high latitude *auroral ionosphere* along the field lines. Average electron densities and temperature in plasma sheet are $\eta e \approx 0.5\ cm^{-3}$ and $Te \approx 5.10^{6}$ K with $B \approx 10nT$. The outer part of magneto tail, magneto tail lobe, contain highly rarified plasma with typical valves for the electron density, temperature and magnetic field strength of $\eta e \approx 10^{-2}\ cm^{-3}$, $Te \approx 5.15$ K and $B \approx 30nT$, respectively. The Sun has its own magnetosphere called the heliosphere; it is the region within the galactic medium where the solar plasma digs out, and fills a cavity. A hot corona must expand as it cannot be in static equilibrium with the interstellar medium. There is a surface surrounding the Sun at which he pressure of the solar wind balances pressure of the interstellar gas, once the solar wind is introduced there. The global solar magnetic field organizes the heliosphere. The morphology of the heliosphere, its evolution over space and time, and the location of its boundaries are determined by the globalsolar magnetic field and by the properties of the local interstellar medium. The position of the boundary is probably of order 100 AU, but not so accurately. Excluding most distant comets, the heliosphere contains most of the solar system.

C. Ionosphere

A fraction of neutral atmosphere is being ionized by the solar ultraviolet light impinging on Earth's atmosphere. At about 80km altitude, these collisions occur more rapidly and result in permanent ionized population called, ionosphere. Typical electron densities and temperatures in the mid latitude ionosphere are $\eta e \approx 10^{5}\ cm^{-3}$ and $T \approx 10^{3}$ K. The magnetic field strength is of order 10^{4}nT. The ionosphere gradually merges into the plasma sphere. It is a torus-shaped volume inside the radiation belt. It contains a cool but dense plasma of ionospheric origin ($\eta e \approx 5.10^{2}\ cm^{-3}$, $Te \approx 5.10^{3}$ K), which corotates with the Earth. In the equatorial plane, at a boundary called plasmapause, where density drops sharply to about 1 cm^{-3}, the plasma sphere extends out to a radius of about 4RE. At high latitudes, plasma sheet electrons can precipitate along magnetic field lines down to ionospheric altitudes where they collide with it and ionize neutral atmospheric particles. As a by- product, the polar light *aurora* is observed, created by photons emitted by this process, inside the *auroral oval*. This oval has traits of field lines which thread plasma shut. Field lines connected to the trait lobe thread *polar cap* inside this auroral oval.

D. Magnetospheric currents

The plasmas discussed above are usually not stationary but move under the influence of external forces. Sometimes ions and electrons move together, like in the solar wind. But sometimes in other plasma regions, electrons and ions create an electric current by moving in different directions. They transport charge, momentum, mass and energy to Earth's plasma environment. More than that, the currents create magnetic fields, which may distort or alter any pre-existing fields badly. Actually, electrical currents accompany the distortion of the terrestrial dipole field into the typical shape of the magnetosphere. The comparison of terrestrial magnetic field on the dayside is associated with current flow across the magnetopause surface, the *magnetopause current.* As shown in figure, the *tail current* flowing on tail surface and the neutral sheet current in the central plasma heet accompany the tail-like field of the night side magnetosphere. The *ring current* which is another large-scale system and influences the configuration of the inner magnetosphere is carried by radiation belt particles and flows around the Earth in a westward direction at radial distances of several Earth radii. These particles drift slowly around the Earth in addition to their bounce. It constitutes a net charge transport because the electrons move in the eastward and the protons drift in westward direction.

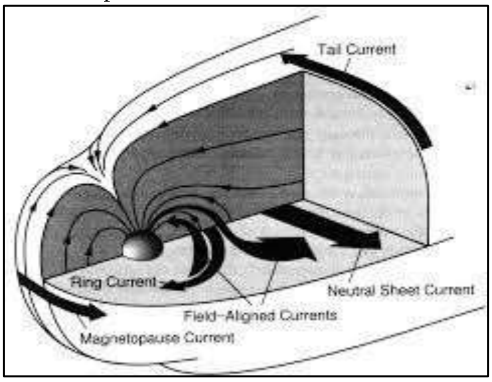

Fig. 3: Synopsis of Magnetospheric currents

Among number of current systems existing in the conducting layers of Earth's ionosphere, at 100-150km altitudes, most noticeable are the *equatorial electro jet* near the magnetic equator, *auroral electro jets* inside the auroral oval and the *Sq currents* in the dayside mid- latitude ionosphere. Other than perpendicular currents, there are also current which flow parallel to magnetic field lines. The Magnetospheric current systems flowing in the polar ionosphere and those in the magnetosphere are connected by the *field-aligned currents* as shown in figure. The field aligned currents are mainly carried by electrons and are essential for the exchange of energy and momentum between these regions.

V. ASTROPHYSICAL PLASMA

If a solar-like star is defined as a star which has a turbulent magnetic field sufficiently strong to control the dynamics and energetics in its outer atmospheric regions, it then turns out that (1) dwarf stars of spectral type GM and rapidly rotating sub giants and giants of spectral type A7- F7 in spectroscopic binary systems are definitely solar- like, (2) dwarf stars of spectral type A7-F7 are almost certainly solar-like, (3) T Tauri stars and other pre-Main- Sequence stars are probably solar-like, (4) slowly rotating single giants of spectral type F to early K are probably solar-like. As a consequence, plasma physics is important for astrophysics as a whole. The interactions of magnetic field with plasma play an important role in star formation. The self-gravitating molecular cloud where star formation is taking place is being provided with a very efficient mechanism of support by the magnetic fields. They affect the conditions for collapse of a self gravitating cloud and thus, help in regulating star formation. The relatively slow rotation of non-degenerate stars are also explained by magnetic fields and plasma physics. Stars would be spinning much faster than they actually do, if in the process of star formation angular momentum would be conserved. Without braking the Sun would not be a slow rotator with a speed of 27d but would rotate turbulently with a rotational speed 10^8 times faster than its actual speed. Thus, it is a fact that all stars undergo braking during their formation; else they would be spinning much faster than they actually do.

VI. FUTURE OF PLASMA PHYSICS

1) One interesting application is the use of plasma thrusters for Spacecraft-plasma-debris removal. Finding an external means of applying the decelerating force is not trivial once the space asset runs out of fuel. One possible solution is to use another satellite capable of producing a sufficiently powerful plasma beam that it can direct at the debris to decelerate it, and another plasma beam that it can use to ensure a safe distance is maintained between itself and debris.
2) The existing classical platforms can also be replaced by hybrid systems incorporating several different schematic solutions. There are many options on how the tested systems and already known systems can be combined into novel platform to ensure their capabilities and characteristics [4].
3) There are many other concepts which can be implemented practically in near future. One of them includes "laser-plasma systems", which can be very important. It is possible to design thrust systems that take advantage of photonic propulsion to propel spacecraft in space. These can employ laser radiation generated by a power station based on board, on the ground or on a space base. Hence, the light can be used to drive the acceleration of a propellant, whether solid or liquid [4].

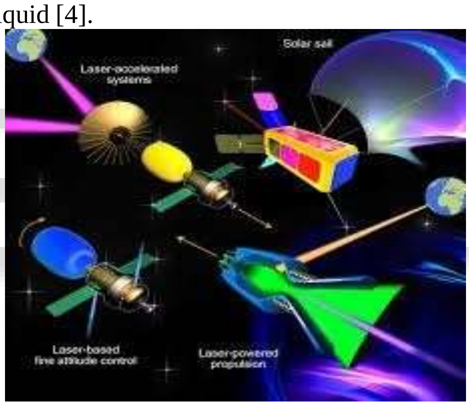

Fig. 4: Artistic presentation of several types of photonic space thrust platform, where laser beams may be used to power plasma based thrusters

4) Complex optical system for ion thrusters- The complex multigrid system is one of the recently emerged promising techniques that could in principle drastically enhance the surface thrust density without compromising their specific impulse and grid sputtering-determined service life [4].

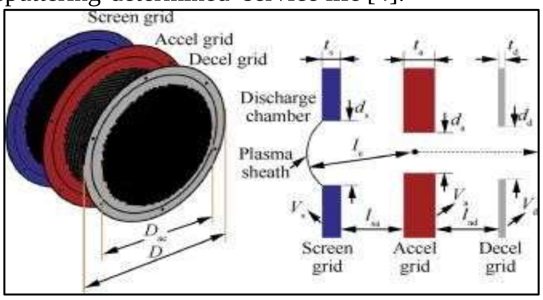

Fig. 5: Ion engine grids

5) Future Beam Experiments in the magnetosphere with plasma- In a low-density magnetosphere, the spacecraft charges to a very high potential that prevents beam

emission. On the other hand, the ion emission route(with the contactor current larger than the beam current), relies only on the contactor cloud which reaches an area where ion emission is not space charge limited and it is independent of the background density. However, the transient of the spacecraft potential relative to the case where contactor is emitted in vacuum is being reduced by the presence of the background plasma, and therefore it favors beam emission. So conclusively, the ion emission route offers a pathway to perform beam experiments in the low-density magnetosphere [5].

6) Outlook for future performance in Wendelstein 7- X- A triple product of $1\times10^{13}m^{-3}$ was achieved in OP1.1 [3], and is expected to increase by an order of magnitude, perhaps as much as a factor of 40, in future operation phases, primarily as a result of the higher density and higher heating power expected.

VII. Conclusion

Plasma science holds promise for further progress in the future, including advanced methods of processing materials, new methods of accelerating particles and producing electromagnetic radiation, progress towards fusion energy, better methods of cleaning up environmental hazards and mitigating the effects of deleterious chemicals, and improved understanding of our space environment and the astrophysical media of the universe. Thus, plasma science can have an important impact on many disciplines and technologies, including those directly linked to industrial growth.

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