Tenth International Conference on

Phenomena in Ionized Gases 1971

Invited Papers

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PREFACE

This volume contains the texts of the Invited Papers presented to the Tenth International Conference on Phenomena in Ionized Gases.

From the list of subjects presented it is apparent that they encompass a wide field which includes chemistry, combustion and clustering in ionized gases.

In order to publish the papers without delay we have kept editing to a bare minimum. Errors in spelling and syntax - inevitable when authors write in a foreign language - have been corrected only where clarity demanded it.

We should like to thank the authors for their co-operation.

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1. Introduction

The cosmical plasma constitutes almost the entire material content of the universe. It reaches to within a hundred kilometers of the Earth's surface and yet has only been accessible to in-situ measurements for a little more than a decade.

During this time a great amount of observational knowledge has been accumulated. As a result there has emerged a very much more refined picture of the distribution and properties of cosmical plasma in those regions of space that are within the reach of space vehicles. However, the observations have also revealed the occurrence in space of numerous plasma phenomena, many of which raise fundamental plasma physical problems.

For example, the cosmical plasma has a great capability for generating energetic particles. The products of the various acceleration processes cover a wide range of energy from that of suprathermal particles in the ionosphere and magnetosphere to the extreme energies of cosmic rays. They include, among many other categories, the auroral primary particles, the geomagnetically trapped particles of the radiation belts and the solar flare particles. For a system lacking features that are essential in earthbound accelerators (such as insulators and tuned frequencies), this prolific particle acceleration is remarkable. This is particularly so for some peculiar acceleration events occurring in connection with auroras and magnetic storms.

Some phenomena that are difficult or impossible to study in the laboratory, e.g. collisionless shocks and collisionless magnetic neutral sheets, exist in space and can be investigated there. However, for phenomena that can more readily be studied in the laboratory, space observations are valuable because they provide experimental information in parameter ranges far beyond those which can ever be realized in the laboratory.

Particular interest is attached to the Earth's magnetosphere. One reason for this is that some of its many different plasma populations are in states which very much resemble the state that will be typical of the fuel in future thermonuclear fusion reactors. For example geomagnetically trapped particles are highly collisionless for binary collisions. Some of them have extremely long trapping times (many years). In contrast, others are rapidly lost due to microscopic electromagnetic fields generated by collective processes. Thus, phenomena that may be of importance in future fusion reactors can now be studied in space. Conversely, the advances made in the fusion research effort can be very important for progress in cosmical plasma physics, and close contacts between these two branches of research is essential.

The measurements in space have so far been mainly exploratory. The exploratory phase of space research is not yet finished. Even as close as in the Earth's magnetosphere, the knowledge of the plasma and field environment is, in some regions, still inadequate. However, at the same time, we are already in the beginning of a second phase, which we may call the fundamental physics phase, which is characterized by conscious attempts to clarify the plasma physics behind some of the phenomena discovered in the exploratory phase. One can also envisage the near regions of space being used as a "laboratory" for active experiments, e.g. the study of certain instabilities by controlled artificial modification of the local plasma state. Experiments of this kind are already being planned.

The observational advances have also made the time ripe in the theory of cosmical plasma for a "second approach" [1], where due account is taken of the complicated behaviour which is exhibited by real plasmas although easily lost in idealized models. It has been emphasized by Alfvén [2] that earlier models of cosmical plasmas have too often neglected important features, e.g. inhomogeneities, especially filamentary structures and magnetic neutral sheets, and electric fields along magnetic field lines, especially electric double layers, leading to violation of the frozen-field condition. By virtue of their importance such phenomena are likely to play a prominent role in the future of cosmical plasma physics. They are complicated phenomena, which need to be attacked coherently by space experiments, laboratory experiments and theoretical efforts.

2. Distribution of Plasma in Space

Different regions of space contain plasmas of greatly different values of density, temperature, composition, degree of ionization etc., and correspondingly different properties. A survey of the main regions will be needed for the subsequent discussion of plasma phenomena.

The ionosphere starts at an altitude of about 50-70 km and extends upward through the D, E and F layers to a not very well defined upper boundary, which is usually defined to be that level above which H^+ is the dominating ionic constituent. The altitude of this level is of the order of 1000 km but varies widely with location and time.

The magnetosphere, is defined as that region of space through which the geomagnetic field extends. It includes several different regions of plasma. Far from being spherical, it has an extension toward the sun of about ten earth radii (varying by as much as several earth radii), but is stretched out in the antisolar direction to distances of more than a thousand earth radii. The structure of its near parts is shown in Fig. 1. It must be remembered,

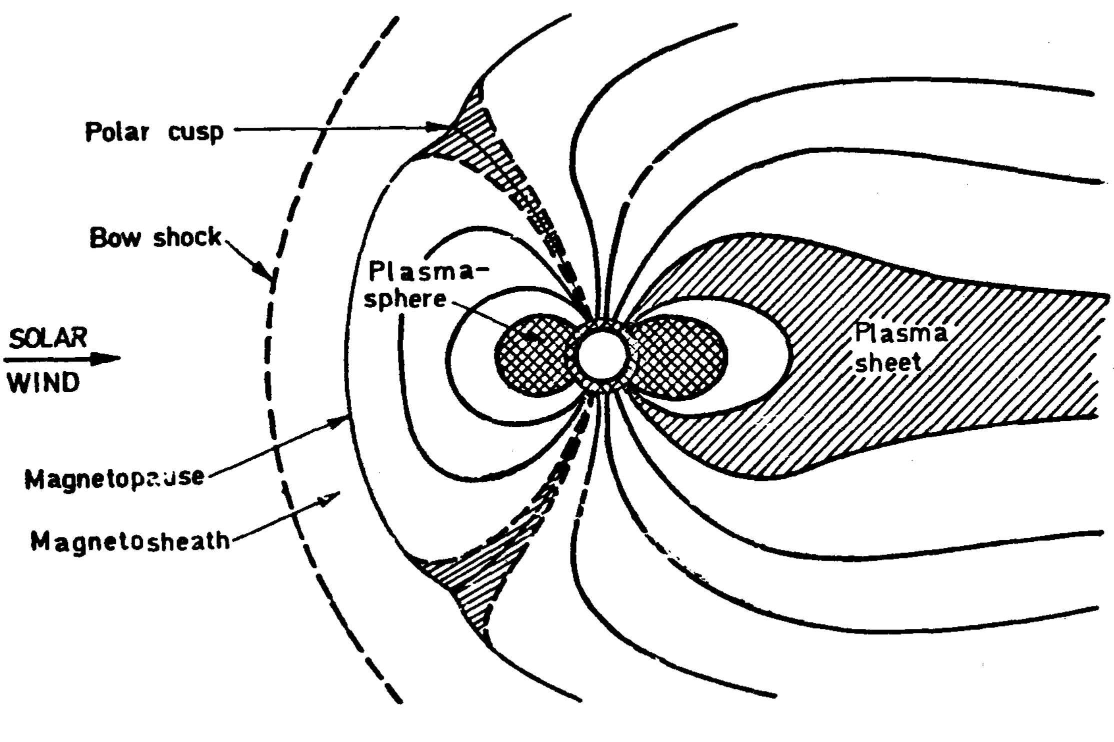

FIG 1
Qualitative outline of the structure of the magnetosphere.

however, that the shapes and extents of the various regions shown are highly variable.

Overlapping some of the regions shown in Fig. 1. are regions with magnetically trapped particles of relatively high energy (from tens of keV up to beyond 100 MeV). These form the radiation belts.

The magnetosphere is immersed in an interplanetary plasma, which also contains a magnetic field, although one that is much weaker, (of the order of a few gammas; 1 gamma = 10^{-5} gauss) and much more irregular than the geomagnetic field. This plasma is of solar origin. As it is continually streaming past the Earth's orbit, at supersonic and superalfvénic speed, it is also called the solar wind. At its encounter with the magnetosphere it forms a standing shock front of the bow shock type.

The interplanetary plasma can be considered a direct extension of the solar corona, The corona is maintained at a much higher temperature (over 10^6 °K) than that of the solar surface (about 4000°K). Immediately below the maximum temperature gradient is the chromosphere (thickness of the order of 10^7m) where the absorption lines in the solar spectrum are formed. The temperature minimum is situated in the photosphere (thickness of the order of 10^5m). This is the layer, where the material density becomes small enough to allow the photons to escape into free space. For a recent model of the physical conditions in the solar atmosphere, the reader is referred to the Harvard-Smithsonian reference atmosphere [3].

The sun itself is a sphere of plasma, of which the central parts are hot enough to sustain thermonuclear fusion (hydrogen to helium via a chain of reactions). However, these proceed at a very slow rate. The power density (<1mW/kg of total solar mass) is much less than what will be required in earthbound thermonuclear reactors.

The radial extent of the solar wind is not known, but may be one or two powers of ten larger than the Earth's orbital radius. Where the solar wind has been thermalized, presumably by a standing shock, charge-exchange reactions with interstellar hydrogen are expected to produce a return flux of neutral hydrogen atoms [4].

Many other stars, like the sun, probably emit their own plasma flows, stellar winds [5]. These stars too, will be surrounded by plasma bubbles which they create within the larger body of interstellar plasma.

Beyond the relatively small stellar wind regions there is an interstellar plasma. Its properties depend very much on the temperature of and distance to the nearest stars [6, 7]. Interstellar plasma is usually subdivided into two different types of regions. HII regions consist of those neighbourhoods of hot stars where the radiation is sufficient to ionize the dominating constituent hydrogen. Beyond the reach of intense stellar radiation are the HI regions, where the hydrogen is in its neutral state, but the matter is still a plasma because of partial ionization of certain minor constituents such as metals.

3. Classification of Plasma

A typical feature of cosmical plasmas is that they are magnetized. For magnetized plasmas it is often convenient to use a classification [8] with three main categories based on the mean free path λ, gyroradius ρ and characteristic length l_c:

1. High-density plasmas:	$\lambda \ll \rho$
2. Medium-density plasmas:	$\rho \ll \lambda \ll l_c$
3. Low-density plasmas:	$l_c \ll \lambda$

Each category is different in physical properties, and the mathematical models that can be used to describe it.

In space, high-density plasmas constitute the sun and the stars (with the exception of their upper atmospheres), and also the lower ionosphere of the Earth. (In the ionosphere, $\lambda/\rho \ll 1$ for both electrons and ions up to an altitude of about 70 km. Beyond that there is a transition region, where $\lambda/\rho \ll 1$ for electrons but $\lambda/\rho > 1$ for ions. Above about 120 km $\lambda/\rho \gg 1$ for both ions and electrons, and the plasma is of medium density.) Above the ionosphere a low density plasma fills the magnetic flux tubes emerging at low and medium magnetic latitudes, forming the plasmasphere (cf. Fig. 1). At high latitudes there is a transition region of medium density plasma in which medium density conditions prevail. Outside the crosshatched region in Fig. 1 the plasma of the magnetosphere (and interplanetary space beyond it) belongs to the low-density category.

4. Ionospheric Plasma Processes

The ionosphere is a complicated plasma system containing numerous ionic constituents and subject to ionization, loss and transport processes that vary greatly with altitude, geographical location, local and universal time.

Elementary Model of the Production Function

Consider ionizing radiation (intensity I) incident under an angle θ with the vertical direction onto a single-gas atmosphere. Let z be the vertical coordinate (positive upward) and the neutral-gas density be n(z). If the absorption coefficient for the radiation is σ, the radiation intensity is attenuated according to

$$\frac{dI}{dz} = I\sigma n(z)/\cos\theta \qquad (1)$$

If the ionization efficiency is η, it produces ion-electron pairs at a rate, q, given by

$$q = \eta\sigma I n(z) \qquad (2)$$

From these equations q can be computed for any given functional form of n.

If, in particular, n is exponential, with a scale height H, the production function, q, expressed in term of the normalized height ξ takes the form [9].

$$q = \text{const.}\ \exp\{1-\xi-\exp\frac{-\xi}{\cos\theta}\} \qquad (3)$$

This formula is known as Chapman's production function. It has a maximum where the downward increase of neutral-gas concentration just compensates the radiation-intensity decrease due to attenuation.

Elementary Theory of Diffusive Equilibrium

In the presence of several ionic species the height distribution of any one species will be influenced by the presence of the others via the ambipolar electric field (Pannekoek-Rosseland field) that is established to maintain quasineutrality. The direction of the ambipolar electric field is upward so as to restrain the electrons and lift the positive ions. Its magnitude is given by

$$E = \frac{\bar{m}_i g}{e} \frac{T_e}{T_e + T_i} \qquad (4)$$

where $\bar{m}_i$ is the local mean ionic mass, g is the gravitational acceleration, e the electron charge and T_e and T_i the temperatures of ions and electrons. Under the influence of this field, and of gravitation, the density n_{ik} of the k:th ion species assumes a distribution determined by the following equation [8] (written here for singly charged particles)

$$\frac{1}{n_{ik}} \frac{dn_{ik}}{dz} = - \frac{m_{ik} g}{kT_i} + \frac{\bar{m}_i g}{k(T_e + T_i)} ; k = 1,2, \ldots \qquad (5)$$

(all ions are assumed to have the same temperature). Notice that the density of any given species increases with height up to the level where the mean ionic mass is about twice the mass of the species in question.

In realistic models of the upper ionosphere, account must of course also be taken of the net downward mass motion that results because of the difference in spatial distribution between sources and losses. Generally speaking, the latter are located lower, and slow downward motion results. However, the influence on the electron density distribution is not very great [11].

Processes Determining Ionospheric Composition

The establishment of different ionospheric layers is due to the fact that the neutral atmosphere gas, containing several differently distributed constituents, is ionized by radiation that covers a wide spectrum of electromagnetic energy including certain emission lines of special importance and furthermore influenced by impact ionization due to precipitating electrons.

For example, the spectral range that is adequate to ionize N_2 is that of wavelengths below 796Å, including the strong HeI line at 584Å. The penetration of this spectral range determines the extent of the F regions (situated above about 150 km). Ionization of O requires wavelengths below 911Å and of O_2 below 1027Å. This range includes the Lyman β line at 1026Å. The Lyman lines and the Lyman continuum provide most of the ultraviolet-light ionization that maintains the E region altitude (about 90-150 km). There is, however, also a contribution due to ionization by X-rays in the range 8-140Å, which is about equally important (and extends somewhat deeper).

Still greater wavelengths in the ultraviolet penetrate deeper, but are not energetic enough to ionize any of the major atmospheric constituents. However, Lyman α radiation (1216Å) ionizes the minor constituent NO, and this is considered an important source of electrons for the D region (altitude about 60-90 km). Another contribution is due to X-rays. The relative importance of these two is not known, and may vary with the solar cycle.

In the very lowest part of the ionosphere (50-60 km, sometimes called the C region) cosmic rays are important for causing some ionization.

Corpuscular radiation of more moderate energy may play some role in the quiet ionosphere too, but is primarily important in connection with auroral disturbances (cf. § 6).

The only part of the ionosphere that contains an appreciable amount of negative ions, is the D region, where O_2^- is formed by electron attachment.

The loss processes with which the ionization competes to maintain the equilibrium include ion-ion recombination (in the D layer) and electron-ion recombination of three body type (important in the D region) and the dissociative type (dominates in the F region). They are summarized in TABLE 1.

The complicated interplay of the ionospheric processes leads to a distribution of ion species, and of electrons, which is shown in Fig. 2. Also shown in the figure is the density distribution of the constituents of the neutral atmosphere. Notice that the degree of ionization is very low in most of the ionosphere. Yet, above about 250 km the electron-ion collisions dominate over the electron-neutral collisions. In the topside ionosphere (above the F layer maximum) the coupling between the charged-particle gas and the neutral gas becomes very weak.

TABLE 1

Production and Loss Processes in the Ionosphere [9]

	D Region	E Region	F Region
Main sources of photo-ionization	Ly α 1216Å X-rays 1-10Å	EUV 911-1027Å Ly β 1026Å X-rays 10-170Å	EUV 170-911Å
Main sources of impact ionization	Electrons >30keV Protons >1MEV	Electrons 1-30keV (sporadically)	Electrons <1keV (may be important in nighttime)
Recombination processes	Ion-Ion Three body dissociative	Dissociative	Dissociative
Other processes	Three-body attachment Collisional detachment Photo-detachment	Charge exchange Three-body attachment Collisional detachment Photo-detachment	Charge exchange

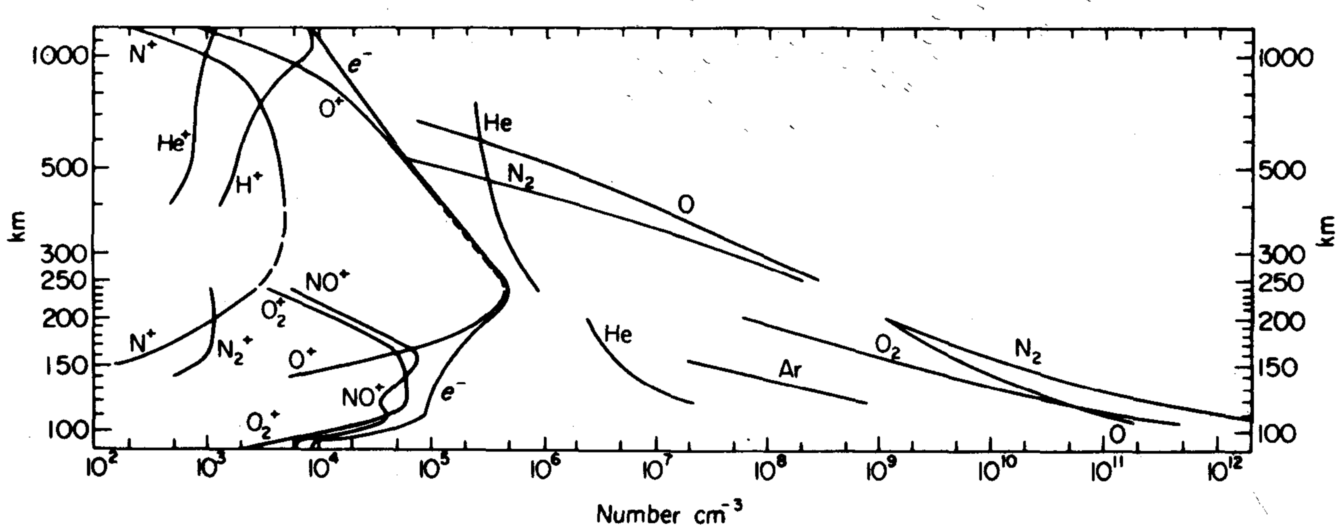

FIG 2

Measured height distributions of various atomic, molecular and ionic species and of electrons [9].

Thermal Conditions

In the D and E region collisions are frequent enough to ensure a good thermal contact between electrons, ions and neutrals. In the F region the newly created electrons share their excess energy relatively rapidly with the bulk of the electron population but only much more slowly with the heavier particles. In outline the situation is that the electron temperature T_e is higher than the ion temperature T_i, which in turn is nearly equal to the neutral gas temperature T_n up to about 250km. At higher altitudes, T_i becomes larger than T_n and may approach T_e at heights toward 1000 km.

Comprehensive theoretical models for calculating upper ionospheric density and temperature on the basis of the coupled equations of continuity, momentum and heat transport for electron, ion and neutral gases have recently been developed [12, 13].

Ionospheric Disturbances

Transient surges of the sun's ionizing radiation occur during solar flares. Although the Lyman α radiation increases by only a few percent, the total X-ray emission can rise by orders of magnitude. With very short delay the ionosphere is affected by this enhanced irradiation.

The main consequence is a greatly enhanced low altitude ionization, which affects radio-wave propagation so as to produce a whole complex of phenomena, referred to as SID (for "sudden ionospheric disturbances"). Examples of SID phenomena are shortwave fade out, cosmic noise absorption and enhancement of atmospherics.

After a delay of a few hours another category of ionospheric disturbances set in. They are due to the energetic protons (1-10 MeV) that are also emitted by the flare but travel at a speed considerably less than that of light. As the solar protons follow paths determined by the geomagnetic field, they can reach the ionosphere only in certain regions, the polar caps. There they cause an intense low-altitude ionization that leads to absorption of radio-waves (polar cap absorption, PCA) which can black out high-latitude radio communication for days. Although the flare particles are emitted within less than hour, they remain trapped in the interplanetary magnetic field for an extended time during which they continuatly leak into the polar caps.)

A third kind of ionospheric disturbances appear still later, when the flare plasma reaches the earth after a day or two, and are associated with the magnetic and auroral phenomena caused by such plasma (cf. §6).

5. Wave Phenomena in the Magnetosphere

The various plasma regions in the magnetosphere allow propagation of waves of a many types. Excitation of waves is provided both by fields and motions imposed from the outside and by instabilities within the plasma itself. It can therefore be expected that the Earth's wave environment should be rich and varied. So it is, as observations have confirmed, but still it remains rather incompletely explored. Only a couple of examples of wave phenomena will be given here.

Ducted Whistlers

Wave energy in the audio-frequency range, generated by a lightening discharge occasionally escapes through the ionosphere and propagates along the magnetic field of the Earth in a circularly polarized mode, the so-called whistler mode [14].

The reason for the strictly field-aligned propagation is that the waves are guided by field-aligned plasma ducts of a density slightly different from that of the surrounding. The origin of these ducts and the conditions that allow escape through the ionosphere at certain places are not known.

The whistler is usually reflected at the conjugate ionosphere and propagates back and forth between the hemispheres large number of times. At each bounce some energy leaks back through the ionosphere and can be recorded at ground level. The damping between successive bounces is often small, sometimes even negative. The probable explanation is that in transit along the field line the whistler is resupplied with energy by a wave-particle interaction mechanism, which feeds energy from an anisotropic particle distribution into the whistler's wave field.

The propagation is greatly dispersive. The transit time, as determined by the group velocity varies with the frequency f according to the expression

$$T(f) = \frac{1}{2c} \int \frac{f_g f_{pl} ds}{\sqrt{f(f_g - f)^3}} \qquad (6)$$

when f_g is the local gyro frequency and f_{pl} is the local plasma frequency. A graph of this relation is given in Fig. 3, which also shows an example of a whistler recording in the form of sonagram i.e. a display of signal intensity as a function of frequency and time.

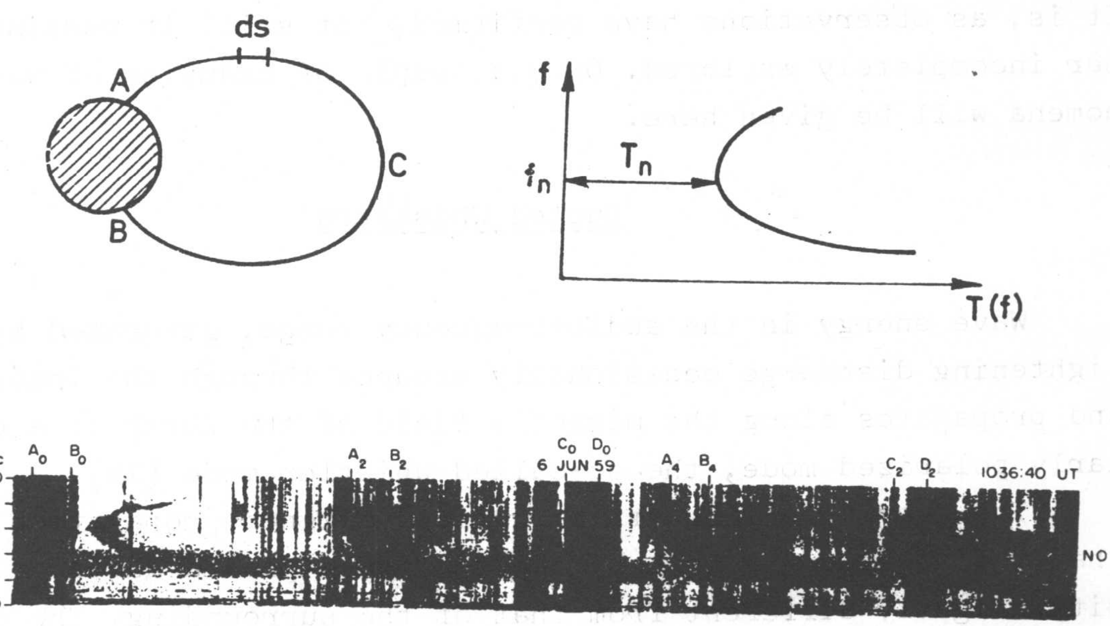

FIG 3

Ducted whistlers. Drawings above show examples of propagation path (left) and graph of group delay time as a function of frequency (right). Photograph below shows sonagram with ducted whistlers ([14], p.106).

Given the <u>path</u> of the whistler and the <u>shape</u> of the plasma density distribution along that field line (i.e. given variation of f_{pl} along the path), the <u>magnitude</u> of the density can be obtained.