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PLASMA SHEATH

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CONTENTS

INTRODUCTION

There are two general reviews of sheath theory of which the most recent is by Kagan and Perel (ref. 35), but an earlier work by F.F. Chen, 1962 (ref. 15) is generally recognised as the standard work.

Plasma sheath theory has been studied from many points of view and a wide range of literature has been published in recent years. It is the intention of this bibliography to provide those interested in this subject with a handlist of the literature since Chen's review.

References from 1960 onwards have been obtained primarily from indexes kept at Culham Laboratory, supplemented by a scan of the most important journals, and Nuclear Science Abstracts, 1960 to 1964.

Acknowledgements are due to Dr. G. Rowlands for his generous assistance.

1. ALLEN, J.E. and MAGISTRELLI, F.
The plasma-sheath transition in a magnetic field.
Nuovo Cimento, series 10, vol.18, no.6, December 16, 1960, pp.1138-1147.

A criterion for sheath formation is presented which allows for the effect of a weak magnetic field. Relevant measurements have been made using a low pressure mercury arc in which an azimuthal or "pinch-type" magnetic field could be applied.

2. AUER, P.L.
The role of ion currents in the formation of space charge sheaths in a low pressure arc.
Nuovo Cimento, vol.22, no.3, pp.548-564, November 1, 1961.
Fifth Int. Conf. Ionization Phenomena in Gases, Munich, August 28-September 1, 1961. Proceedings, pp.297-305.
Amsterdam, North-Holland Pub. Co., 1962.

It is shown that conditions leading to the establishment of a space charge sheath in the positive column of low pressure arcs provide for a minimal requirement in the positive ion current delivered to the sheath. The minimum required current for a given ion is a function of only the electron density and temperature and is independent of the specific mechanism of ion production for the special case of a plane symmetric discharge. These conclusions are used to shed light on the familiar Bohm criterion which is found to be misleading. The effect of magnetic fields and possible plasma instabilities is briefly examined.

3. BERTOTTI, B.
Fine structure in current sheaths.
Annals of Physics, vol.25, no.3, December, 1963. pp.271-289.

The general, exact theory of a collisionless planar current sheath is developed with the constants of integration method. Every quantity depends on a single space variable x alone; electric field, current, and magnetic field are mutually orthogonal. Appropriate approximation methods can be developed to investigate the structure of the deviations from charge neutrality when the Debye distance d is much smaller than the sheath thickness; they appear either as local spatial electrostatic oscillations whose wavelength is proportional to d as $d \to 0$; or as space-charge regions whose size is comparable to the scale of the magnetic transition itself. The general criterion for the presence of such oscillations is given and the investigation of their structure is reduced to quadratures. In the simple case of two mono-energetic beams turned around by a magnetic field they are discussed in detail. If their amplitude vanishes where the field is nil, we recover Rosenbluth's profile; but the solution deviates slightly from neutrality near the turning points of the particle motions which, in general, are separated. The problem of confinement by an external magnetic field is treated in detail in the case where in the plasma the particles all move only in the x-direction with a Maxwellian distribution: there are no oscillations and the potential jump across the sheath diverges logarithmically as $d \to 0$.

4. BERTOTTI, B.
Stability of collisionless, non-uniform plasma. [In Italian]
Paper presented to Plasma Physics Conference, held by Societa Lombarda di Fisica, Milan, May 6-7, 1963. 6p.

The transition between two plasma regions where the magnetic field has a different intensity occurs through a current sheath whose thickness is not smaller than the Larmor radius of electrons x. We discuss the stability of this system against electrostatic perturbations whose wavelength, proportional to the Debye length, is much smaller than x. When the propagation vector is directed along the density gradient (say, in the x direction), one can state a sufficient criterion of instability in the following way: for a given value of the magnetic potential A and the electrostatic potential, φ. construct the xx- component of the stress tensor

$$P_{xx}(A,\varphi) = \Sigma\ m \int \nu_x^2\ jd^3\nu$$

where the summation runs over all the species present. If $\partial^2 P_{II}/\partial\varphi^2$ is negative, Penrose's criterion [in Phys. Fluids, 2, 258 (1960)] leads to the conclusion that the plasma is unstable. The above inequality means also that the system is not able to screen an external, static electric field. It is stressed that the non-local instability does not follow necessarily from the local one; for a precise connection it is necessary to discuss in detail the general problem and the effect of particles moving at the phase velocity.

5. BERTOTTI, B.
Theory of an electrostatic probe in a strong magnetic field. Pt.1.
Phys. Fluids, vol.4, no.8, August, 1961. pp.1047-1052.

6. BERTOTTI, B.
Theory of an electrostatic probe in a strong magnetic field. Pt.2.
Phys. Fluids, vol.5, no.8, August, 1962. pp.1010-1014.

A probe is considered in a magnetic field so strong as to impair collective transverse drifts. Then the charges supplied to the probe come mainly from a long tube of force, whose radius is about one Larmor radius larger than the probe. Assume that there is acting a diffusion process, more efficient than ordinary drifts, which continuously exchanges particles between the inside of the tube of force and the rest of the plasma. In a previous paper we have proposed a one-dimensional model of this process, leading to an integro-differential Poisson's equation, which has now been fully investigated in the case of slow diffusion. The solution consists of a chargeless, slowly decaying potential which describes the geometrical screening effect of the probe; while in the sheath an approximate boundary-layer solution matches the probe's potential V_p. The asymptotic relation between the current collected and V_p is computed. This model may be suited to the case of diffusion due to random wave fields.

7. BETTINGER, R.T. and WALKER, E.H.
Relationship for plasma sheaths about Langmuir probes.
Phys. Fluids, vol.8, no.4, April, 1965. pp.748-751.
AFCRL - 64 - 429, AD - 603008.

In order to arrive at ion and electron concentrations, temperatures, etc., from Langmuir probe data, one uses the Mott-Smith-Langmuir equations and, in most cases, a rather arbitrary assumption of a fixed value of sheath thickness. This approach has obvious limitations since the sheath's properties are not fixed but must depend on the potential and size of the probe; sheath thickness is clearly zero at zero potential. Walker has treated the nonlinear screening problem for the case of spherical bodies in collisionless moneoenergetic and Maxwellian plasmas. The calculations are elaborate, but results can be displayed graphically or given by approximate analytic expressions. We have extracted from these a relationship for the sheath thickness s in terms of the probe's radius ρ and potential Ψ, for use in the Mott-Smith-Langmuir equations: $s = 0.83\Psi^{1/2}\rho^{1/3}$ where s, ρ are measured in Debye lengths Ψ in terms of kT. For the case of cylindrical symmetry, $s = 1.66\ \Psi^{3/4}$, and depends only weakly on ρ.

8. BUTLER, H.S. and KINO, G.S.
Plasma sheath formation by radio-frequency fields.
Phys. Fluids, vol.6, no.9, September, 1963. pp.1346-1355.
Stanford University Report ML-917, AFOSR - 2998, AD - 283839.

It has been observed experimentally that the application of a radio-frequency voltage (10 kc/sec-50 Mc/sec) to any one of several electrode configurations around the outside of a plasma discharge tube results in a constriction of the luminous portion of the plasma away from the inner walls of the glass tube. This investigation has established that the phenomenon is basically a radio-frequency rectification effect, leading to the formation of a thick ion sheath. The interaction is described mathematically in terms of a differential equation which has an approximate solution that fits qualitatively all the observed characteristics of the phenomenon. The differential equation, in its most general form, has also been solved numerically and the solution is shown to fit our experimental observations quantitatively for both radio-frequency sine and square wave signals. An application of this phenomenon as a possible external diagnostic probe technique is proposed.

9. CARUSO, A. and CAVALIERE, A.
The structure of the collisionless plasma-sheath transition.
Nuovo Cimento, series 10, vol.26, no.6, December 16, 1962. pp.1389-1404.

A discussion is given of the transition from the region where the ionization is dominant to the region where the space charge is important, for a collisionless model of a low-pressure arc discharge. As the relevant Poisson equation contains a very small parameter which multiplies the second order derivative, a singular perturbation formalism leads to an unambiguous definition of the plasma and the sheath regions, and to a precise reformulation of the Bohm criterion. The same formalism allows for explicit calculations, on the basis of particular models, of the potential within the sheath and the plasma, and of the ion current to the wall.

10. CASON, C.M. and BARR, T.A.
A general probe theory for measurements in a plasma.
U.S. Army Ordnance Missile Command, Redstone Arsenal, Alabama.
ARGMA-TR-2H-4R, AD-273757, 28p. January, 1962.

The standard model of floating probes in plasmas is reviewed. It is shown that a maximum charge density exists for the application of this model. An explicit expression of voltage applied to the probes in terms of circuit current is obtained. When certain simplifying assumptions are used, this equation is reduced to the Langmuir single probe equation and the Johnson-Malter double probe equation. From measurements of probe current versus applied probe voltage, electron temperature at each respective probe can be determined. One example is given to illustrate the calculation.

11. CHEN, C.J.
Temperature effect on Langmuir probe measurement.
J. Appl. Phys., vol.35, no.4, April, 1964. pp.1130-1133.

A substantial lowering of the work function of a tungsten Langmuir probe immersed in an Argon plasma in a discharge tube is observed. The mechanism is thought to be similar to the Schottky effect. The electron temperature measurement is lowered about 30% in a particular discharge condition, as the probe goes from room temperature to 2000° C. The charge number density measurement by saturation electron current appears to be higher by 15%, and that by ion saturation current appears to be higher by almost one order of magnitude. This phenomenon can also account for the discrepancy of the ratio of ion and electron saturation current obtained by previous authors and this author.

12. CHEN, F.F.
Low-frequency oscillations in gas discharges.
Phys. Fluids, vol.4, no.11, November, 1961. pp.1448-1449.

It is the purpose of this note to suggest that whereas the exact mechanism for sustaining high-frequency oscillations at a sheath is unknown, there may be a natural mechanism for generating very low-frequency oscillations near a sheath when the ion temperature is much lower than the electron temperature.

13. CHEN, F.F.
Saturation ion currents to Langmuir probes.
J. Appl. Phys., vol.36, no.3, pt.1, March, 1965. pp.675-678.
Princeton University. Plasma Physics Laboratory Report. MATT-272.

The parabolic variation of saturation ion current with probe potential observed in dense plasmas is fortuitous and is not directly related to the effects of orbital motion. Agreement between measured and computed saturation ion characteristics is illustrated. The discussion is in the framework of collisionless, magnetic-field-free theories; they apply to the experiments only if the ion Larmor radius is much larger than the probe radius.

14. CHEN, F.F.
Numerical computations for ion probe characteristics in a collionless plasma. Princeton University. Plasma Physics Laboratory. MATT - 252, 18p. February, 1964.

Numerical results in ranges of experimental interest are presented in a graphical form for the potential profile around negatively biased spherical and cylindrical probes in a collisionless plasma and for the saturation ion current-voltage characteristics. The computations were made on the basis of the theories of Allen, Boyd, and Reynolds for zero ion temperature and of Bernstein and Rabinowitz for moneonergetic ions. These theories are useful primarily for small probes. For large probes the theory of Lam is applicable. For completeness we have also included whatever curves are necessary for the use of Lam's theory.

15. CHEN, F.F.
Probe techniques. Notes of a lecture presented at the Summer Institute in Plasma Physics, Princeton University, June 25-August 3, 1962. 144p. June, 1962.

A survey of probe and sheath theory.

16. CHEN, F.F.
The sheath criterion.
Princeton University. Plasma Physics Laboratory.
MATT - 77, 8p. June, 1961.

It was shown that ions arriving at a sheath on a negative electrode or wall must have energy greater than or equal to ½ kTe, however there was doubt as to the validity of this criterion. A discussion is presented to show that this sheath criterion is valid for a wide range of conditions. That the ion velocity near a boundary should be given by the electron, rather than the ion temperature, is physically reasonable when kTe » kTi, since the force driving the ions into the wall is provided by the plasma pressure n_0kTe.

17. CHUNG, P.M.
Langmuir potential associated with Couette flow of viscous plasma.
Phys. Fluids, vol.5, no.8, August, 1962. pp.1015-1016.

Some understanding of a coupled electrical sheath-boundary-layer is obtained by treating a continuum Couette-flow model.

18. CIOBANU, G. and POPESCU, I.
On the movement of positive ions through the positive space-charge sheath.
J. Electronics and Control, vol.16, no.1, January, 1964. pp.59-64.

A kinetic analysis of the movement of positive ions through the positive space-charge sheath is given for the plane, cylindrical and spherical geometries. Expressions are derived for the positive ion relaxation time, concentration, drift velocity, mean kinetic energy and electric field in the sheath.

19. COHEN, I.M.
Asymptotic theory of spherical electrostatic probes in a slightly ionized, collision-dominated gas.
Phys. Fluids, vol.6, no.10, October, 1963. pp.1492-1499.

The problem of an electrostatic probe in a dense, slightly ionized gas is treated by techniques of asymptotic analysis. In particular, the asymptotic limits $\rho_p = r_p/\lambda d \rightarrow \infty$ and $\varepsilon = T_+/T_- \rightarrow 0$ are treated in considerable detail (r_p, λ_d, T_-, T_+ are probe radius, Debye length, electron and ion temperature, respectively.) Sample integral curves for electrostatic potential, ion and electron density are given. Probe characteristic curves for three values of ε (finite and small) and ρ_p (large) are also given. It is noted that these characteristics do not saturate for large probe potential because the influence of the probe is felt to very great distances from the probe; the shielding due to the space-charge sheath is incomplete

20. CRAWFORD, F.W. and FREESTON, I.L.
The double-sheath at a discharge constriction.
Sixth International Conference on Ionization Phenomena in Gases, Paris, July, 1963. Proceedings, vol.1, pp.461–464.

For a given discharge current and neutral gas pressure, the electron temperature and number density in a low-pressure discharge column are dependent on the cross-sectional area of the tube. If there is an abrupt change of section, a thin double-sheath forms there and serves to substantially equalize the random currents flowing between the sections. Studies of this sheath have been made with a movable Langmuir probe. Application of the Druyvesteyn method allows observations of the decay of the high-velocity group entering the smaller section to be made. An expression is given for the approximate volt-drop across the sheath, and some comments are made on the role of the sheath in exciting fluctuations in the tube.

21. D'ANGELO, N.
Low-frequency oscillations in cesium thermionic converters.
Phys. Fluids, vol.4, no.8, August, 1961. pp.1054–1055.

Oscillations were observed when cathode temperatures were in the region 1350° to 1450° K. It is considered that these oscillations were due to a positive ion sheath near the cathode.

22. DOTE, T., TAKAYAMA, K. AND ICHIMIYA, T.
Analysis of probe characteristics in drifting plasma.
J. Phys. Soc. Japan, vol.17, no.1, January, 1962. pp.174–183.

A new method is proposed to calculate the altitude profiles of positive ion density in the ionosphere from the ion current obtained by a rocket-borne Langmuir probe.

For a spherical probe, moving relatively to a plasma, the form of ion sheath is deformed from the spherical one. It is assumed that the radius of the ion sheath perpendicular to the moving direction is equal to that of the probe at rest, for the forward sheath a rotating ellipsoid is applied, and in the backward the ordinary relation between the total current and the current density at the surface of sheath is used.

Positive ion densities of the ionosphere are determined by using the above relations and observed total current. Good accordance of the calculated values with the simultaneous observations of the electron density at E-layer from h'-f curves will suggest the validity of the method.

23. ECKER, G., MASTERSON, K.S. and McCLURE, J.J.
Probe theory in a dense plasma.
UCRL-10128, 33p. March, 1962.

A dense plasma is defined as one in which the effective mean free path of one particle component is small in comparison with the probe dimensions; thus Langmuir's theory is not applicable in such a plasma. The presence of the probe causes marked changes of density and potential distributions in the probe environment. These effects were calculated for insulated probes of various geometries. An exact solution is given for a concentric cylindrical probe. For more general geometries, an appropriate approximation procedure, the composition method, was developed from variational principles. The effect of probe disturbances on the measurements can be accounted for in terms of an effective probe position and a potential correction. Introduction of the probe also causes changes in the eigenvalue and electron temperature. The results allow one to unfold experimental data to find the true plasma qualities. Consideration of the inertia-limited region shows that Bohm's criterion is not suitable to judge either the stability or stationarity of the sheath. A stationary inertia-limited region can exist only under certain restricted circumstances.

24. FRANKLIN, R.N.
The plasma-sheath boundary at low pressures.
Proc. Phys. Soc., vol.79, no.510, April, 1962. pp.885-887.

The plasma-sheath boundary regions of the positive columns of an electric discharge at low pressures are calculated and discussed. The correction factor for locating the sheath boundary is derived and explained. The criterion $Mv^2 > kT$ for the formation of a sheath of a monoenergetic beam of ions of velocity v_0 leaving the plasma is translated into an inequality involving the ion current for the case of uniform ion generation in space. Limiting values of the fractional space charge as functions of the ratio of the Debye length to the size of the system are given for the correction factor (relating the current at the sheath boundary).

25. FRENCH, J.B.
Langmuir probes in a flowing low density plasma.
Toronto University. Institute of Aerophysics.
Report no. AFOSR-2159, AD-273698. UTIA-79, 75p. August, 1961.

Two aspects of the use of Langmuir probes were investigated. First, a Langmuir probe free-molecular with respect to all species, and in a plasma in which the ion temperature is higher than the electron temperature, is considered. Theoretical predictions are that both the ion current and the electron current outside the retarding field region are controlled by ion energy instead of electron energy. Hence, directed ion energy in the form of plasma mass motion is expected to influence collection. The retarding field method of measuring electron temperature is uninfluenced. Experiments in the form of comparisons between ion collecting cylindrical probes parallel and transverse to the supersonic plasma stream agree quantitatively with these predictions. Second, the situation is considered in which the electrons have much higher thermal energy than the ions, and in which the probe is free-molecular with respect to neutral particles but in continuum flow with respect to the ions and electrons. The smaller electron and ion mean free paths are calculated to have little effect on the current collected by the probe, unless mass motion is present. In this case experiments indicate that a region of increased ion density exists in front of a probe biased to reflect ions back into the oncoming stream.

26. GENERALOV, N.P.
The theory of probes. [In Russian]
Atomnaya Energiya, vol.4, 1958. pp.183-185.
Trans. in J. Nucl. Energy, vol.9, pt.2, Soviet J. At. Energy, 1959. pp.148-151.

Existing theories all make some kind of assumption concerning the distribution of the electric field in the boundary layer and the thickness of the layer is then estimated.

In this work the plasma is described in terms of the diffusion approximation which is applicable at sufficiently high densities. It is possible in this case to find a description for the build up of the electric field in the boundary layer.

27. GILLEO, M.A.
Low-density plasma flow at a magnetic barrier.
Phys. Fluids, vol.4, no.2, February, 1961. pp.210-214.

Rosenbluth-Garwin sheath model used for case in which the barrier rises so rapidly that the moment of the ions is not adiabatically invariant.

28. GOLD, L.
On the plasma sheath.
J. Electronics and Control, vol.16, no.5, May, 1964. pp.493-496.

A formalism has been devised for the boundary-valued, on dimensional sheath problem which admits series solutions that automatically yield the Bohm stability criterion. An advantage of the present theory is the embodiment of natural boundary conditions associated with the region where the sheath and ambient plasma potentials merge. In this manner the Bohm sheath criterion becomes clearer and recognised to be the low energy limit for the sheath formation. Relativistic modification of the criterion for high energy plasmas is indicated.

29. GOLDSTEIN, A.W.
Sheath near a plane electrode bounding a collisionless plasma in a magnetic field.
N.A.S.A. Lewis Research Center, Cleveland.
NASA-TN-D-1992, 37p. October, 1963.

The entire transition region is treated as a unit by velocity-distribution functions. Self-consistent fields, currents and charges are determined as well as all components of the nonisotropic pressure tensors of ions and electrons. Numerical results are shown for hydrogen plasma.

30. GRAD, H.
Boundary layer between a plasma and a magnetic field.
Phys. Fluids, vol.4, no.11, November, 1961. pp.1366-1378.

The problem of a steady boundary layer or sheath between a plasma and a magnetic field is considered. A self-consistent transition layer is found which joins a uniform magnetic field at plus infinity with a collisionless field-free plasma region with arbitrary velocity distribution at minus infinity; i.e., a magnetic field profile is found such that the exact particle orbits in this field produce a current which gives rise to the field.

An interesting mathematical feature of the "thinnest" such solution is that, with any non-singular velocity distribution at minus infinity, the magnetic field penetrates only a finite distance into the plasma although the plasma extends to infinity, exponentially attenuated, into the magnetic field region. The scale of length is the ratio of the speed of light to the plasma frequency or, equivalently, the Larmor radius of a representative particle. Electric fields arising from charge separation in the case of particles of different mass are ignored.

31. HALL, L.S.
Application of Bohm's criterion for the formation of a sheath.
Phys. Fluids, vol.4, no.3, March, 1961. pp.388-389.

Criticises the paper by Hoh (ref.33) claiming that in the case under discussion where the wall potential can never be more than $kT_e/2e$ no sheath will appear.

32. HALL, L.S.
Harrison-Thompson generalization of Bohm's sheath condition.
Proc. Phys. Soc. vol.80, no.513, July, 1962. pp.309-311.
UCRL-6868.

Harrison and Thompson (1959) generalized Bohm's condition for the formation of a sheath in an electrical discharge. One point of their generalization which restricts the claim that their analysis is applicable to an arbitrary incident ion velocity distribution is discussed. The restriction lies in the divergence of their expansion of the integral for the ion density. A corrected analysis is suggested, and the physical interpretation of the results is described briefly.

33. HOH, F.C.
Plasma stability and boundary condition.
Physical Review Letters, vol.4, no.11, June 1, 1960. pp.559-561.

The validity of the classical theory of charged particle diffusion across a magnetic field is discussed. Lehnert found agreement with classical theory for fields weaker than a certain critical value B_c, beyond which this theory was observed to be invalid. It is shown that this phenomenon can be explained by an instability of the wall sheath. It is postulated that the plasma becomes unstable when the boundary conditions are not satisfied because the ion velocity normal to the wall on entering the sheath can be reduced by a magnetic field. The discussions are valid for partially ionized gases; the corresponding situation for fully ionized plasma remains to be investigated. The present theory appears to connect the classical diffusion theory and the ion wave theory in a natural way.

34. JONES, J.E.
A refinement of the Langmuir probe theory for the investigation of a gas conduction plasma.
Direct Current, vol.7, no.1, January, 1962. pp.6-18.

A model of the low pressure arc is taken where the plasma is created by a mono-energetic beam of primary electrons from the cathode, making elastic and inelastic collisions with the neutral vapour. The beam increases in energy along the positive column.

A detailed analysis of the probe characteristic provides an explanation for the observations reported by other workers who detected deviations from the simple probe theory given by Langmuir. The primary electrons which make inelastic collisions are said to become subsidiaries and are divided into energy groups defined by the energy involved in the inelastic collision. The arrival of each of these groups at the probe gives a discontinuity in the current-voltage characteristic.

Equations are derived for the energies of electrons in the subsidiary groups and the current contributions which these groups make to the total probe current.

A Langmuir probe characteristic taken in a low voltage, low pressure, mercury pool cathode rectifier direct current discharge is analysed in detail. The main arc parameters are deduced from the characteristic together with electron concentrations in the various electron energy groups present using the revised probe theory developed.

The values obtained are in fair agreement with those generally accepted for low voltage low pressure discharges.

35. KAGAN, Yu.M. and PEREL'. V.I.
Probe methods in plasma research. [In Russian]
Usp. Fiz. Nauk, vol.81, December, 1963. pp.409-452.
Trans. in Soviet Physics - Uspekhi, vol.6, May-June, 1964. pp.767-793.

Review of status of probe techniques. 112 references.

36. KAGAN, Yu.M. and PEREL', V.I.
Theory of ion current in a probe. [In Russian]
Zh. Tekh. Fiz., vol.32, no.12, December, 1962. pp.1479-1482.
Trans. in Soviet Physics-Tech. Phys., vol.7, no.12, June, 1963. pp.1093-1095.

Simple aspects of ion current theory are based on separation of plasma around a probe into quasilinear and space-charge regions, resulting in 2 equations for the current on a spherical probe. One formula was developed for the surface current postulating that a potential exists at the boundary layer of the order of (kT_e/e) and that ions wave a normal incidence to the surface. The other formula represents the 3/2 law for determining the radius of an r_0 layer, assuming the electron concentration could be neglected when compared to the ion concentration. A simplified verification is given for the ion current theory.

37. KANAL, M.
Theory of current collection on moving cylindrical probes.
J. Appl. Phys., vol.35, no.6, June, 1964. pp.1697-1703.

The theory of current collection of a moving cylindrical probe is investigated. Volt-ampere relations are derived for two distinct cases: (i) The general-ion current for accelerating collector potential and its special cases, including general-ion current to the stationary probe, orbital-motion-limited current to the moving and the stationary probes, and sheath-area-limited current to the moving and the stationary probes; (ii) the general-electron current for the retarding collector potential and its special cases, including the general-electron current to the stationary probe and random-electron current to the moving and the stationary probes.

Orientation of the cylinder with respect to the drift velocity vector is taken into account. Volt-ampere characteristics are included for illustrating the functional behaviour of the current relations.

38. LAM, S.H.
A general theory for the flow of weakly ionized gases.
Amer. Inst. Aeronautics and Astronautics, J. vol.2, no.2, February, 1964. pp.256-262.

A general theory is developed for the flow of a weakly ionized gas about an arbitrary solid body with absorbing surfaces. The main interest lies in the prediction of the electrical responses of the body as a function of the pertinent properties of the flow. The theory is based on continuum formulation, and is valid when 1, the mean-free-path of the charged particles is much smaller than the thickness of the sheath, and 2, the Debye length is much smaller than the thickness of the boundary layer adjacent to the body surface. The entire range of flow velocity in terms of an electric Reynolds number R is investigated, but the detailed analysis is devoted to the case $R^{\frac{1}{2}} \gg 1$. It is found that the electrical disturbances can be divided into three physically distinct and mathematically uncoupled regions, namely the outer region, the ambipolar diffusion region, and the sheath region. Closed-form analytical results are obtained for the floating potential and the current-voltage characteristic. These are useful in the interpretations of Langmuir probe data. Detailed structures of the solutions are given in terms of explicit universal functions.

39. LAM, S.H.
The Langmuir probe in a collisionless plasma.
Princeton University. Gas Dynamics Laboratory Report 581, AFOSR-64-0353, NASA-N64-18566, AD-434842, 71p. March, 1964.

This paper presents as asymptotic analysis of the Langmuir probe problem in a quiescent, collisionless plasma in the limit of large body dimension to Debye-length ratio. The structures of the electric potential distribution about spheres and cylinders are analysed and discussed in detail. It is shown that when the probe potential is smaller than approximately $\frac{1}{2}$ kT, where T is the undisturbed temperature of the repelled particles, there exists no sheath adjacent to the solid surface. At large body potentials, for which a sheath is present, the electric potential distribution is given in terms of several universal functions. Master current-voltage characteristic diagrams are given that exhibit clearly the effects of all the pertinent parameters in the problem. An explicit trapped-ion criterion is presented. The general problem with an arbitrary body dimension to Debye-length ratio is qualitatively discussed.

40. LAM, S.H.
Unified theory for the Langmuir probe in a collisionless plasma.
Phys. Fluids, vol.8, no.1, January, 1965. pp.73-87.

An asymptotic analysis is presented of the Langmuir-probe problem in a quiescent, collisionless plasma in the limit of large body dimension to Debye length ratio. The structures of the electric potential distribution about spheres and cylinders are analysed and discussed in detail. It is shown that when the probe potential is smaller than a certain well defined value, there exists no sheath adjacent to the solid surface. At large body potentials, for which a sheath is present, the electric potential distribution is given in terms of several universal functions. Master current-voltage characteristic diagrams are given which exhibit clearly the effects of all the pertinent parameters in the problem. An explicit trapped-ion criterion is presented. The general problem with an arbitrary body dimension to Debye length ratio is qualitatively discussed.

41. LEE, T.H. and GREENWOOD, A.N.
Motion of ions in the cathode sheath of an arc.
Sixth International Conference on Ionization Phenomena in Gases, Paris, July, 1963. Proceedings, vol.1, pp.469-474.

It is shown that to account for the ion current in the cathode sheath, one must consider the diffusion of ions due to a very strong gradient. This gradient is set up to neutralize the space charge of electrons diffusing toward the cathode against the electric field. By treating the gas in the sheath as a multicomponent mixture in the presence of an electric field and a concentration gradient, an effective mobility can be defined for the ions which includes the effect of concentration gradient. It is then shown that the electric field required to calculate the ion current is quite reasonable.

42. LEFFERT, C.B.
A plasma-sheath theory for noble gas thermionic converters.
Advanced Energy Conversion, vol.2, July-December, 1962. pp.417-436.

A plasma-sheath theory is described for computing the V-I characteristics of noble gas thermionic converters. Application of this theory in the form of IBM computer code to laboratory and inpile experimental data is presented. The assumptions in the theory are twofold: 1, a spatially uniform ion density is assumed in the interelectrode plasma between the emitter and collector sheaths; and 2, the ion loss rate is taken to be independent of the diode voltage. The basic plasma sheath equations are presented and the operation of the computer code to produce the theoretical voltage-current characteristics is outlined. The experimental data from the operation of laboratory and inpile thermionic converters are analysed by adjusting plasma parameters to fit the theoretical to the experimental voltage-current characteristics. A reasonable fit of the theoretical curves to the experimental curves is obtained. It was found that the ion density in the plasma varies considerably with the diode voltage. The effects of such variables as volume recombination of ions, plasma resistivity and tube geometry on the voltage-current characteristics are discussed. The general V-I characteristics obtained from the code for a Gabor-type triode are described. The results show a significant increase in the ratio of the output current to the ion source rate for a large collector to emitter area ratio not only for the plasma limited case but also for the power producing region of the emission limited case.

43. MEDICUS, G.
Theory of probes with non-uniform work function.
Fifth International Conference on Ionization Phenomena in Gases, Munich. September, 1961. Proceedings, vol.2, pp.1397-1405.

Langmuir's theory for the plane and for the infinitely small spherical probe is extended to "microscopic patchines" of the work function of the probe. The case of a Maxwellian electron energy distribution and a Gaussian work function distribution is treated. The normalized probe currents and their second derivatives are plotted, with the width of the Gaussian as parameter. Breaks in the curves, such as the "knee" in the probe curve for the plane probe, are "smeared out", however, the exponential character in the electron retarding region is maintained for high enough probe voltages. The exact location of space potentials results.

44. MJOLSNESS, R.C., RIBE, F.L. and RIESENFELD, W.B.
Self-consistent reversed field sheath.
Phys. Fluids, vol.4, no.6, June, 1961. pp.730-735.

An analytic solution is obtained for the structure of a proto-type reversed field sheath. The configuration is a region of uniform (direct) magnetic field separated from a second region of uniform (reversed) field of equal magnitude but opposite sign by a current sheath of finite width composed of zero temperature plasma. Growth rates of certain instabilities of the system are calculated. It is found that the modes considered do not grow as rapidly as the plasma frequency, but the growth rates may still be quite large. Finally, a qualitative discussion is given of the results to be expected when the reversed field is opposed by a direct field of larger magnitude.

45. MODESITT, G.E.
Idealized sheath theory and satellite charge-up in the Van Allen region.
Rand Corporation, Santa Monica, California.
RM-3096-PR, AD-274599, 32p. April, 1962.

As an aid in the determination of the electric potential of naturally charged satellites, the concept of the idealised sheath introduced by Langmuir and Mott-Smith is studied in some detail through the use of distribution functions. It is shown that the functions are discontinuous in velocity variables and lead to the same results as particle trajectory theory. The limitations of the sheath theory and its connection with space-charge-limited diode theory are discussed. It is shown that, under certain assumptions, the potential on a satellite whose diameter is smaller than the local Debye length will reach 3500 volts negative in the more intense regions of the Van Allen electron belt. The equilibrium potential decreases with increasing size of the satellite, with a limiting value of -35,000 volts for satellites much greater than the Debye length in diameter.

46. MORSE, R.L.
Adiabatic time development of plasma sheaths.
Phys. Fluids, vol.8, no.2, February, 1965. pp.308-314.

The formation of the electromagnetic sheath separating a field free Maxwellian plasma from a confining field is treated by an adiabatic approximation. It is found that the condition imposed by the approximation is not severe. Solutions are shown for several values of the ion-electron temperature ratio. The problem is done in plane symmetry and with the collisionless approximation. The question of stability is not considered.

47. MORSE, R.L.
Collisionless plasma sheaths without trapped particles.
Paper given at the American Physical Society, Plasma Physics Division, San Diego Meeting, November, 1963.
CONF-471-34, 34p. [1963] microfiche.

The sheath of a collisionless field free plasma is treated by an extension of the charge neutral approximation and by numerical integration of the exact equations. It is doubtful that physically acceptable solutions exist without trapped particles in the sheath, if the distribution of particle velocities is isotropic or near isotropic. Acceptable solutions are, however, found where the relative velocity of the sheath and plasma is large compared to the thermal spread of particle velocities in the plasma rest frame. These solutions are shown. It is also shown that these solutions go over smoothly to the Rosenbluth case as the thermal spread goes to zero.

48. NICHOLSON, R.B.
Solution of the Vlasov equations for a plasma in an externally uniform magnetic field.
Phys. Fluids, vol.6, no.11, November, 1963. pp.1581-1586.

An exact solution of the collisionless Boltzmann equation is presented that describes a slab of plasma contained in a magnetic field that is uniform external to the slab. The magnetic field dips in the plasma due to the diamagnetic currents in the plasma sheath separating the region of nearly constant density from the vacuum region. The currents are given by the distribution functions for ions and electrons and the fields obey Maxwell's equations. The solution has the qualitative features of real collisionless laboratory plasma distributions. The problem of a cylindrical plasma with axial magnetic field is also treated, and a solution presented for a limiting case. The solution to the slab problem is charge neutral. The limiting case in the cylindrical problem is also charge neutral, but the general cylindrical problem is not, and contains radial electric fields. The solutions have the merit of being substantially more simple than others that have previously been found for the plasma sheath problem.

49. OKUDA, T.
Collection of charged particles on probe in high pressure plasma.
Memoirs of the Faculty of Engineering, Nagoya University, vol.15, no.1, May, 1963. pp.122-134.

An experimental and theoretical investigation. The depletion of charged particles is characteristic in high pressure plasma in which the mean free path of charged particles is small compared to the probe radius. The mechanism responsible for the depletion is that the density in the vicinity of the probe is decreased by virtue of scattering, according to a simple theory.

To obtain a reasonable explanation for the observed depletion, a consideration of another process leading to an additional depletion is needed in addition to the simple theory. The former process is the formation of a disturbed region which has been discussed extensively in an earlier paper. The existence of a space charge sheath results in a reduction of the depletion.

50. OKUDA, T. and YAMAMOTO, K.
Penetration of ion sheath into plasma.
Memoirs of the Faculty of Engineering, Nagoya University, vol.14, no.1-2, November, 1962. pp.179-181.

An estimation of penetrating voltage is made for a negative probe in high pressure plasma with the aid of the sheath criterion. This penetrating voltage may be a major source of errors appearing in the probe measurement.

51. PAK, T.S.
A method of approximation for Langmuir probes.
J. Sci. Instrum., vol.41, no.3, March, 1964. pp.180-181.

The use of a Langmuir probe in the study of an electric plasma is restricted to probes with a flat collecting area. For probes with other shapes a saturation of the ion current is not obtained, since the electron probe current is made up, in part, of an electron equivalent of the saturated ion current, a knowledge of its value is necessary for probe analysis. A method of approximation is proposed by which this difficulty can be surmounted. In this method log i + log $(1 + i'/i)$ is substituted for log i_e. Experimental results show that the method can be used and is applicable to all shapes of probes.

52. PARKER, J.V.
Collisionless plasma sheath in cylindrical geometry.
Phys. Fluids, vol.6, no.11, November, 1963. pp.1657-1658.
AD - 296287.

Numerical solutions to the problem of electron density and potential valid throughout the sheath region in a low density plasma with cylindrical geometry.

53. PAVKOVICH, J. and KINO, G.S.
R.F. theory of the plasma sheath.
Sixth International Conference on Ionization Phenomena in Gases. Paris, July, 1963. Proceedings, vol.3, pp.39-44.

A theoretical treatment for the variation of rf fields within the sheath is given. The analysis is based on an integration of the collisionless Boltzmann equation, with the assumption that the static potential varies parabolically in the sheath. It is shown that an effective impedance for the sheath can be defined, and that over the range in which the numerical results have been calculated, this impedance always has a real positive part. The real part of this impedance is associated with Landau damping. A set of curves is given of the field through the sheath.

54. PEALE, S.J.
Plasma sheaths and their effects on antennas.
Cornell University. Center for Radiophysics and Space Research.
CRSR-116, 67p. May, 1962.

An investigation of particle losses from plasma by neutralization at the solid boundary was conducted. It was found that the lack of conservation of particles does not allow the establishment of Maxwell density distribution for either electrons or ions in a plasma sheath. Thus, in situations where a finite body is moving at a velocity comparable to ion thermal velocities, the ion density will be approximately constant and equal to that in the undisturbed plasma, while the electrons can be approximated by a Maxwell density distribution with only small error. Plasma sheaths are known to hamper some techniques for measuring plasma parameters. An example of this is the effect on the impedance measurements of an antenna embedded in plasma. To investigate situations where the sheath might be ignored with the subsequent realization of reliable plasma data from antenna impedance measurements, a long thin wire in plasma and photon streams is considered.

55. ROSE, D.J. and ESTERLING, R.J.
Calculation of distributions in one-dimensional plasma sheaths.
J. Appl. Phys., vol.33, no.11, November, 1962. pp.3317-3318.

In collisionless plasma acceleration and sheath problems, where the potential and one of the fluxes are known, the distribution in energy of flux of the other species can be computed as a solution of Abel's equation. This technique is illustrated, and self-consistent sample solutions are given for ion and electron beams crossing a potential drop, with a concomitant-trapped electron flux.

56. SCHULZ, G.

Electron and ion saturation currents in weakly ionized gases at high pressures (an expansion of the Langmuir probe theory at high pressures).
Zeitschrift fur Physik, vol.167, no.2, 1962. pp.205-228. [In German]

The electron saturation currents measured with the help of fine cylindrical probes at high pressures in the intermediate gas volume of methane-hydrogen-air flames can be described neither by the Langmuir equations nor the Borgnis probe theory. It was shown that the electrons in the space charge, which at high pressures and low carrier densities completely shield the field of the probe, do not have a constant motion but one dependent on the field and therefore on the position in the space charge layer. It was also shown that in the divergent field of the space charge layer a relaxation of the electron energies occurs which may be neglected at infinitely high pressures. From this viewpoint, a characteristic current-voltage relationship was derived for the electron current at high pressures which permits an exact evaluation of the measurements for determination of the electron densities. The ion saturation currents can be described and evaluated with an equation by Borgnis.

57. SCHULZ, G.

Probe theory at medium and low pressures. [In German]
Zeitschrift fur Physik, vol.17, no.2, 1962. pp.196-211.

At medium and low pressures (100-35 mm Hg) the charge transport in the space charge zone is determined by the density gradient of the charge carrier as well as by the electric field strength. It is shown that in the combination of the space charge and transport equations, consideration of the diffusion of the oppositely charged particles is indispensible at low pressures and potentials and as a consequence, in the stationary state, no relative potential minimum can exist in the space charge sheath. Simple analytic expressions in plane as well as cylindrical geometry are obtained for the current-potential probe characteristic and are discussed for the methane-hydrogen-air flame.

58. SELF, A.S.

Asymptotic plasma and sheath representations for low-pressure discharges.
J. Appl. Phys., vol.36, no.2, February, 1965. pp.456-459.

The collisionless plasma-sheath equation is discussed in the limit that the ratio of Debye length to discharge dimension is vanishingly small, for the cases of planar, cylindrical, and spherical symmetric discharges. Separate representations for the plasma and sheath regions are found and numerical results given for the potential profiles, ion current, energy distributions, and floating wall potentials for two different assumptions regarding the ion generation function in each case.

59. SELF, S.A.

Exact solution of the collisionless plasma-sheath equation.
Phys. Fluids, vol.6, no.12, December, 1963. pp.1762-1768.
ARL-64-13, AD-431860, NASA-N64-16794.

The plasma-sheath problem for the low-pressure discharge in plane geometry is treated exactly, that is, with no arbitrary division into plasma and sheath regions. Numerical solutions are presented for various values of the parameter α, which is of the order of the ratio of the Debye length to the discharge width for $10^{-3} \leqslant \alpha \leqslant 10^{-1}$; and for three assumptions regarding the ion generation rate, namely generation uniform, proportional to electron density, and proportional to the square of electron density.

For the higher values of α, corresponding to weak laboratory discharges, there is a smooth transition from a quasi-neutral plasma region to a thick sheath. At the smaller values of α, the conventional model of a quasi-neutral plasma region passing rather abruptly into a narrow sheath region is substantiated. In all cases, accurate values for the potential profile throughout the plasma and sheath regions are given and compared with the separate asymptotic plasma and sheath solutions for $\alpha = 0$. The ion current density, wall potential, space-charge density, mean ion energy, and sheath thickness are discussed.

60. SESTERO, A.
Charge separation effects in the Ferraro-Rosenbluth cold plasma sheath model.
Phys. Fluids, vol.8, no.4, April, 1965. pp.739-744.

An exact treatment is given of the Ferraro-Rosenbluth cold plasma sheath model, to improve on the charge neutral approximation considered previously in the literature. It is found that the turning points of the ion stream and of the electron stream are actually separated in space. It is found also, somewhat unexpectedly, that there exists a certain range of parameters for which the ions are turned back sooner than the electrons, due to the combined effect of the electric and magnetic forces in the sheath. The change of behaviour in the solution occurs discontinuously allowing for no intermediate case with the two species of particles turning together. Finally, it is found that the sheath is not, in general, overall charge-neutral, and that the excess charge can actually be of either sign, depending on the values of the parameters.

61. SESTERO, A.
Structure of plasma sheaths.
Phys. Fluids, vol.7, no.1, January, 1964. pp.44-51.

A model is given to provide a microscopic description of plasma sheaths, using the Vlasov equation for ions and electrons coupled with Maxwell's equations for the fields. The sheaths considered connect two different constant states of a plasma in a magnetic field. In the charge-neutral approximation a solution is obtained in closed form in terms of quadratures. The solution depends essentially on three free parameters, related to the differences in density and electric potential between the two end states, and to the value of β, the ratio of the plasma pressure to the magnetic pressure, on one side of the sheath. The scaling law changes considerably from one solution to another. Solutions are obtained which scale according to some representative electron Larmor radius, or ion Larmor radius, or piecewise according to both. As a limiting case, when the density is allowed to go to zero on one side of the sheath, one obtains the boundary layer between a plasma and a containing vacuum magnetic field. As a peculiar feature in this limiting situation, the curve for the electric potential appears to be very sensitive to the slightest changes in the distribution functions, in the asymptotic region where the plasma density becomes vanishingly small.

62. SIMON, A. and ROSENBLUTH, M.N.
Single-particle cyclotron radiation near walls and sheaths.
Phys. Fluids, vol.6, no.1, November, 1963. pp.1566-1573.
GA-4029.

A particle which moves perpendicular to a magnetic field while undergoing periodic elastic collisions with a rigid wall emits radiation which is rich in higher harmonics. Collisions with a sheath instead of a wall, also produces radiation of this sort. The resulting radiation is calculated utilizing a simplified model of a sheath and also assuming an exponential plasma density distribution, and is then compared with experiment. One can fit either the observed spectral shape or the observed intensity, separately, but a simultaneous fit is rather difficult. The best results are obtained for a sheath thickness of the order of a Debye length.

A comment by J. Slepian on this paper can be found in:
National Academy of Sciences, Proceedings, vol.51, no.4,
April, 1964. pp.592-593.

63. STOVER, H.L. and KINO, G.S.
Landau damping in the plasma sheath.
Stanford University. Microwave Laboratory.
ML Report 1105, CONF-471-24, 7p. October, 1963.

The dispersion characteristics and attenuation of slow waves propagating along a finite plasma column are measured. The loss is found to be considerably higher at high frequencies than would be expected from collisions of electrons with neutrals or ions. A detailed propagation theory is presented that takes account of the radial variation of density in a Hg-vapour discharge plasma. Attenuation resulting from sheath impedance and elastic collisions with neutrals is calculated. Experimental and theoretical results are compared, and the results are bound to be compatible with the hypothesis of Landau damping in the sheath.

64. SU, C.H. and LAM, S.H.
Continuum theory of spherical electrostatic probes.
Physics of Fluids, vol.6, no.10, October, 1963. pp.1479-1491.
AFOSR-3067.

A continuum theory for spherical electrostatic probes in a slightly ionized plasma is developed. The density of the plasma is taken to be sufficiently high such that both ions and electrons suffer numerous collisions with the neutrals before being collected by an absorbing probe. A general discussion of probes at an arbitrary potential is given. It is found that for very negative probe potentials the sheath thickness can be comparable to the probe radius. Two explicit forms of current-voltage characteristics are given; one for very negative probes, the other for probes at nearly plasma potential. Both of these are based on the assumption that the probe radius is large compared with the Debye length. Numerical computation is also given for negative probes of a wider range of probe sizes.

65. SWIFT, J.D.
Effects of finite probe size in the determination of electron energy distribution functions.
Proc. Phys. Soc., vol.79, no.510, April, 1962. pp.697-701.

The corrections which are necessary in the measurement by means of a spherical Langmuir probe, of the energy distribution function $f_0(U)$ of the electrons in a plasma are analysed. The principal effect considered here is the disturbance of the plasma produced by the drain of electrons to the probe. This disturbance becomes increasingly serious as the gas pressure p and the probe radius a increase and as U decreases. It is shown that the true value of $f_0(U)$ differs by less than 25% from that determined from the simple theory neglecting the disturbance provided $U > \frac{1}{2}U$ and $a < \frac{1}{2}l_e$ where l_e is the electron mean free path.

66. TALBOT, L.
Note on the stagnation-point Langmuir probe.
Phys. Fluids, vol.5, no.5, May, 1962. pp.629-630.
AD-271646; HE-150-195.

A simplification of the theory of the stagnation-point Langmuir probe in a supersonic stream with completely frozen ionization.

67. TALBOT, L.
Theory of the stagnation-point Langmuir probe.
Phys. Fluids, vol.3, no.2, March-April, 1960. pp.289-298.

A theory is developed for a Langmuir-type probe consisting of a collecting electrode placed at the stagnation point of a blunt body immersed in a supersonic partially ionized stream. It is shown that under certain conditions, the stagnation-point boundary layer equations and the probe sheath equations can be solved together to yield potential vs current relationships which permit the free stream ion and electron densities and temperatures to be measured by such a probe.

68. TURCOTTE, D.L. and GILLESPIE, J.
Electrical resistance and sheath potential associated with a cold electrode.
Amer. Inst. Aeronautics and Astronautics, J., vol.1, no.10, pp.2293-2299, October, 1963.

The boundary-layer resistance and the difference in sheath potentials between a pair of electrodes have been measured in a shock tube. Using a small, square electrode and a strip electrode flush with the wall of the shock tube, the electric current that could be drawn across the shock tube was measured as a function of the shock wave position for several applied voltages and load resistances. All measurements were made in air at a shock speed of 4.35 mm/μsec and an initial pressure of 1 mm Hg. In the range of applied voltages considered, the boundary-layer resistance was not a function of the current level. The change in the sheath potential was of the order of several volts. A continuum theory is developed to predict the boundary-layer resistance for small current levels and the sheath potential. The sheath solution is separated from the convective compressible boundary-layer problem where ambipolar diffusion dominates. In the sheath, the transport equations for ions and electrons in an electric field are solved numerically. Resulting integrals for the dimensionless boundary-layer resistance and sheath potential are evaluated, both in the sheath and in the compressible boundary layer, to obtain results that can be compared with experiment. Values of the resistance obtained, assuming the ionization reaction to be frozen, are not in agreement with experiment. Reasonable agreement between theory and experiment is obtained for the magnitude of the sheath potential.

69. WAYMOUTH, J.F.
Perturbation of a plasma by a probe.
Phys. Fluids, vol.7, no.11, November, 1964. pp.1843-1854.

The theory of the electrostatic probe immersed in a plasma is discussed under the assumptions that particle mean free paths are comparable with or smaller than probe radius. The range of validity of the results is for $\lambda_c/r_p < 10$, $r_p/100\ \lambda_D > 1$, $\lambda_c/\lambda_D > 10$, where r_p is probe radius, λ_c is particle mean free path, and λ_D is the Debye length. In the limit of λ_c/r_p approaching infinity, the results converge toward the Langmuir result for the same probe. The probe-current vs voltage characteristic obtained when mean free paths are short is distorted because the degree of perturbation of plasma density and potential vary with probe voltage. An unexpected result is that the shape of the probe characteristic in the vicinity of the "knee" is sensitive to ion temperature, and may possibly be used to determine the ion temperature.

70. WASSERSTROM, E., SU, C.H. and PROBSTEIN, R.F.
Kinetic theory approach to electrostatic probes.
Phys. Fluids, vol.8, no.1, January, 1965. pp.56-72.

A spherical electrostatic probe in a slightly ionized plasma is studied from a kinetic theory point of view. The two-sided distribution function method of Lees, which embodies the Mott-Smith approach, is used. The velocity space is divided into two regions along the straight cone tangent to the spherical probe and different distribution functions are defined in the two regions. On satisfying the two relevant moments of the distribution function (continuity and number density flux) three simultaneous ordinary nonlinear differential equations, which are appropriate to all values of the Debye length, collision mean free path and probe potential are obtained for determining the ion and electron number densities, and the potential. These equations reduce to the usual linear flux equations when the mean free path is much shorter than the probe radius and the Debye length. The equations are first linearized and solved for the case of small probe potential. Explicit solutions are given for the current-voltage characteristics and the distributions of the number densities and the potential. The general case of arbitrary probe potential is also studied. Results for the characteristics and for the potential drop in the sheath are presented for some representative cases. Many of the results which are obtained do not appear in the original simplified Langmuir model. The modifications required to take into account the curvilinear orbits of the charged particles are discussed.

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