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AREA INFLUENCES AND FLOATING POTENTIALS IN LANGMUIR PROBE MEASUREMENTS

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SYMBOLS

A	area
e	magnitude of the charge of an electron
i	electric current (unsubscripted and unsuperscripted it refers specifically to the measured current flowing between the probe and reference electrode)
I_i	dimensionless ion-current, defined by Eq. (5)
j_i	ion-current density collected by an electrode
k	the Boltzmann constant
M	charge-normalized ion mass, m_i/Z^2
m	particle mass
n_e	undisturbed electron density
R	radius
T	temperature
V_a	applied potential normalized to kT_e/e
Z	multiplicity of ionization
α	A_r/A_p
α^*	minimum value of α for which electron temperature measurement is not greater than +2% inaccurate
β	R/λ_D
ϵ	permittivity of free space
λ_D	electron Debye length, $(\epsilon kT_e/n_e e^2)^{1/2}$
ϕ	electric potential
χ	dimensionless potential measured with respect to the plasma, $e(\phi-\phi_o)/kT_e$

$\delta\chi^r$ shift in dimensionless reference potential away from the floating potential necessary to establish $i^r = -i^p$ when the probe is operating anywhere in the transition region of the current-voltage characteristic

$\Delta\chi^r$ total change in dimensionless reference-electrode potential which is necessary to establish $i^r = -i^p$ when the probe is operated from its floating potential to the plasma potential

$\Delta\chi^p$ difference between the plasma potential and the probe's floating potential, $\Delta\chi^p = -\chi_f^p$

SUBSCRIPTS

α for $\alpha < 10^4$

e electron component

f used to designate the dimensionless floating potential

i ion component

o of the plasma or evaluated at the plasma potential

p of or at the probe

r of or at the reference electrode

SUPERSCRIPTS

a measured or apparent

p of or at the probe

r of or at the reference electrode

Area Influences and Floating Potentials in Langmuir Probe Measurements

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ABSTRACT

An analysis has been conducted on the influence of a relatively small reference electrode in a Langmuir probe measurement of plasma density and temperature. It is shown that a ratio α of reference-electrode area to probe area of 10^4 will guarantee no distortion of the measurement as a result of a shifting reference-electrode potential. It is further shown that the constraint on α can be relaxed by approximately two orders of magnitude when the ion mass is decreased from 200 to 1 amu and the ratio of reference-electrode radius to Debye length, R_r/λ_D, is decreased from 100 to 0. An additional result of the analysis is the dependence of a probe's floating potential on its geometry and radius as well as on the properties of the plasma.

I. INTRODUCTION

The experimental methods of plasma diagnostics, together with the corresponding theoretical foundations, have over the years seen considerable treatment in the literature. The technique which seems to have received broadest application is that of the electrostatic probe, better known as a Langmuir probe because of the pioneering work of Irving Langmuir[1] in the first quarter of this century. The Langmuir probe is most simply described as a conductor (generally of planar, cylindrical or spherical geometry) which collects current from a plasma when a voltage is applied. The current drawn by the probe from the plasma is a function of the probe size and geometry, the probe voltage, and the plasma properties of charged-particle number densities, particle distribution functions, and collision frequencies. Consequently, a current-voltage characteristic of a probe imbedded within a plasma is potentially rich with information about that plasma. If one understands the behavior of plasmas in the presence of an electrostatic probe, then in principle the plasma parameters mentioned above can be extracted from a probe characteristic.

The Langmuir and Langmuir-type probe has played an important role in the diagnostics of space plasmas[2] and consequently considerable attention has been directed to the response of probes operating in the collisionless limit. From the theoretical point of view the behavior of probes immersed in this type of plasma is well understood - particularly through the work of Laframboise[3]. The transition from understanding through theory to application involves considerable depth in technique as well as knowledge of secondary influences which tend to distort the Langmuir probe characteristic. The literature has given considerable treatment to the many experimental complications which can yield erroneous results (see Ref. 4) but nothing quantitative and broad in application has been reported which considers the distortion of the Langmuir probe characteristic that results when the electrode with respect to which the probe voltage is measured has a finite area when compared to the area of the probe. It is therefore the object of this work to establish guidelines within which accurate measurements of electron density and temperature can be realistically made when the ratio of reference-electrode area to probe area is finite. (Finite is here considered to be less than approximately 3000.) This is an issue which is of particular importance to rocket- or satellite-borne probe experiments in the ionosphere or in the interplanetary plasma environment since the vehicle itself generally takes on the role of reference electrode. In this case the ratio of reference electrode area to probe area is limited at the reference end by spacecraft size and at the probe end by the sensitivity of the instrumentation for current measurement. Practical considerations in laboratory plasmas can also restrict the area ratio to a value far less than ideal.

II. THEORETICAL CONSIDERATIONS

The Langmuir probe is the smaller electrode of a two-electrode configuration with the ratio of the two areas approaching a value which for all practical purposes should be considered infinite. When the two electrodes are in electrical contact with a plasma a current will pass between them which is a function of an applied voltage difference. When this current is plotted as a function of the applied voltage difference the resulting curve is referred to as the probe characteristic. Figure 1 shows a schematic representation of a Langmuir probe circuit as well as a typical characteristic. (In a laboratory situation the reference electrode can in fact be the container of the plasma volume.) The potential of the reference electrode is here defined as zero and it is of paramount importance to the measurement technique that this potential remain constant (with respect to the plasma potential) for all values of current. When the area of the reference electrode is sufficiently small its potential will shift, resulting in a net distortion of the probe's current-voltage characteristic.

From the considerations to be introduced here the change of potential of the reference electrode is a function of the area ratio $\alpha \equiv A_r/A_p$ and the circuit current i where A_r and A_p are the reference and probe areas respectively. In every case the total current collected by the probe system must equal zero; that is, $i^r = -i^p$ where i^r and i^p are net currents collected from the plasma by the reference electrode and the probe respectively. This constraint yields the identity given by Eq. (1) where the subscripts i and e

$$i_i^r - i_e^r = - i_i^p + i_e^p \qquad (1)$$

are used to designate the ion and electron components to the net current. By assuming that both electrodes are operating at potentials which are less than or equal to the plasma potential and that there are just two charged species - positive ions and negative electrons (the electrodes are therefore ion-attracting) - Eq. (1) can be written in the form shown in Eq. (2a). Rearrangement and appropriate cancellation of terms then yield Eq. (2b).

$$\alpha[n_e e\sqrt{kT_e/2\pi M}\; I_i(\beta_r,\tau,\chi^r) - n_e e\sqrt{kT_e/2\pi m_e}\; \exp(\chi^r)]$$
$$= n_e e\sqrt{kT_e/2\pi m_e}\; \exp(\chi^p) - n_e e\sqrt{kT_e/2\pi M}\; I_i(\beta_p,\tau,\chi^p) \tag{2a}$$

$$\alpha = \frac{\exp(\chi^p) - \sqrt{m_e/M}\; I_i(\beta_p,\tau,\chi^p)}{\sqrt{m_e/M}\; I_i(\beta_r,\tau,\chi^r) - \exp(\chi^r)} \tag{2b}$$

In Eqs. (2), χ^r and χ^p are respectively the probe and reference electrode potentials, ϕ_p and ϕ_r, measured with respect to the plasma potential ϕ_o and normalized to kT_e/e (see Eqs. (3)), while β_r and β_p are the corresponding radii divided by the electron Debye length λ_D (see Eqs.(4)). (Only spherical and cylindrical geometries will be considered explicitly.).

$$\chi^{p} = e(\phi_p - \phi_o)/kT_e, \qquad \chi^{r} = e(\phi_r - \phi_o)/kT_e \tag{3}$$

$$\beta_p = R_p/\lambda_D, \qquad \beta_r = R_r/\lambda_D \tag{4}$$

τ is the ratio of ion-to-electron temperature T_i/T_e, m_e is the mass of an electron, M is the charge-normalized ion mass defined by $M = m_i/Z^2$ where m_i and Z are the ion mass and multipticity of ionization, and I_i is the dimensionless ion current (defined in Eq. 5) which in the collisionless limit is available in numerical form from the calculations of Laframboise[3].

$$j_i = n_e e(kT_e/2\pi M)^{1/2}\, I_i \tag{5}$$

In Eqs. (2a), (3) and (5) the quantities as yet undefined are the undisturbed electron density n_e, the magnitude of the charge of an electron e, the Boltzmann constant k, and the experimentally observed ion-current density collected by an electrode j_i.

The results of the collisionless theory of Laframboise[3] will be employed for values of I_i. Laframboise assumed that each specie of charged particle has a Maxwellian velocity distribution with its own characteristic temperature. His calculations are based on the Boltzmann-Vlasov equation for the two species, coupled with Poisson's equation. He assumed that no magnetic fields are present, that the charged species are totally absorbed at the probe surface (an exception is the zero ion-temperature solution for spherical probes where it was assumed that the repelled species is totally reflected at the probe surface) and that trapped orbits, if any, are unpopulated.

In order to establish a quantitative approach in determining the degree to which a probe characteristic can be distorted by finite values of α, only that region of the probe's characteristic between the floating and plasma potentials (i.e. the transition region) will be investigated. (The floating potential of an electrode immersed in a plasma is defined to be that potential at which no net current flows to the electrode from the plasma.) This is not a serious restriction since it is this region which is normally of prime importance in probe analysis. It is also to be expected that with $\alpha > 1$ there will be no significant distortion of the characteristic for potentials of the probe less than its floating potential.

In moving from the floating potential ($\chi^p = \chi_f^p$), where no net current flows, to the plasma potential ($\chi^p = 0$), where the random thermal flux of electrons is collected, the probe will experience a change in current given by $\Delta^p = +n_e e A_p \sqrt{kT_e/2\pi m_e}$. This change in current corresponds to a change in the probe's dimensionless potential which is given by $\Delta\chi^p = -\chi_f^p$. Since $|\Delta i^p| = |\Delta i^r|$, the reference electrode must also undergo the same absolute change in current and the shift in its potential $\Delta\chi^r$, which is necessary to achieve this Δi^r, is a measure of the distortion in the probe's characteristic. $\Delta\chi^r$ is given by Eq. (6), where χ_α^r is the solution to Eq. (2b) for finite α when $\chi^p = 0$, and χ_f^r is the corresponding solution when $\alpha \to \infty$.

$$\Delta\chi^r = \chi_\alpha^r - \chi_f^r \qquad (6)$$

The analysis of net distortion is herein presented for cylindrical reference-electrodes with $\beta_r \lesssim 3$, $= 10$, $= 100$ while for reference electrodes of spherical geometry the lowest limit is $\beta_r = 2$. (For the calculation of $\Delta\chi^r$ the probe geometry is unimportant.) For both geometries the temperature cases of $\tau = 0$ and 1 were studied for charge-normalized ion masses M [in amu] of 1, 16, 64 and 200. This spans the spectrum of possible cases from the proton plasma of the solar wind to a singly-ionized mercury plasma.

III. RESULTS AND DISCUSSION

A. Cylindrical Reference Electrode

The potential χ_α^r of a reference electrode of cylindrical geometry is shown as a function of α for the cases $\beta_r \lesssim 3$, $= 10$, $= 100$ in Figures 2-a, 2-b and 2-c, respectively. In each figure the running parameter is the charge-normalized ion mass expressed in amu and the results for $\tau = 0$, and 1 are presented. χ_α^r is the value of the dimensionless potential which the reference electrode must assume in order to guarantee that $i^p = -i^r$ when the probe is at the plasma potential. The total shift in χ^r which results when the probe is operated over the entire transition region is given by Eq. (6) for any given $(\beta_r, \tau, M, \alpha)$ and the quantities necessary for calculating $\Delta\chi^r$ are readily obtained from Figs. 2 where χ_f^r can be taken as the value of χ_α^r at $\alpha = 10^4$. As an illustration consider the cylindrical case when $(\beta_r, \tau, M, \alpha) = (100, 0, 16, 200)$. In this situation $\Delta\chi^r = \chi_\alpha^r - \chi_f^r = -6.3 + 5.0 = -1.3$, which would correspond to a voltage shift of -11.2 volts if $T_e = 10^5\ {}^\circ K$.

In Figures 2 it can readily be seen that for a given (β_r, M, α) the value of $-\chi_\alpha^r$ is always smaller when $\tau = 1$ than when $\tau = 0$. This results from the fact that the ion-current response of cylindrical electrodes is an increasing function of τ. The reference electrode can therefore maintain a given ion-current level at a smaller value of $-\chi_\alpha^r$ when $\tau = 1$ than when $\tau = 0$.

The results of Figs. 2 at $\alpha = 10^4$ can be used to generate curves which present the dimensionless floating potential χ_f as a function of M for $\tau = 0$ and 1 and $\beta \lesssim 3$, $= 10$, $= 100$. (Here χ_f is not superscripted nor is β subscripted since the results apply to any electrode.) The results of this approach are presented in Fig. 3 which shows that $-\chi_f$ increases with increasing β for a given (τ, M). This reflects the reduction in the relative sheath size for increasing values of β and consequently a reduction in the dimensionless ion current to the electrode.

Since the general procedure for analyzing a Langmuir probe characteristic in the transition region involves a simple plot of $\ln(i_e^p)$ versus the applied potential[5] an important question concerns the exact manner in which the $\Delta\chi^r$ shift manifests itself. That is, in the presence of a $\Delta\chi^r$ shift is the distortion more dominant in any particular portion of the transition region? This point is of considerable importance since it is possible that a changing reference potential can render inaccurate the determination of T_e or n_e, or both. To answer this question it is necessary to define a potential which is applied between the probe and the reference electrode. This potential will be designated as V_a and in keeping with the use of dimensionless parameters will be considered normalized to kT_e/e. The relationship of V_a to other dimensionless potentials is given in Eq. (7)

$$V_a = + \chi^p - \chi_f^r - \delta\chi^r \qquad (7)$$

where $\delta\chi^r$ is the shift in reference potential necessary to balance the current collected by the probe operating at any point in the transition region The behavior of $\delta\chi^r$ is such that $\delta\chi^r]_{\chi^p=\chi_f^p} = 0$ and $\delta\chi^r]_{\chi^p=0} = \Delta\chi^r$. A representative example of the exact form of the distortion is shown in Fig. 4 as a solid line. Figure 4 is a plot of the logarithm of electron current collected by the probe normalized to its value at plasma potential versus the applied dimensionless potential V_a. The result, which is typical of the response which should be anticipated in the presence of a $\Delta\chi^r$, has been calcuated for a reference electrode and probe of cylindrical geometries with assumed conditions such that (α, β_p, β_r, τ, M) = (150, $\lesssim$ 3, 100, 0, 16). For purposes of easy comparison the case for $\alpha \to \infty$ is shown in Fig. 4 as a dashed line. The latter case points out that the plasma potential is only 4.3 units of dimensionless potential positive with respect to the floating potential of the probe. On the curve for $\alpha = 150$ the probe does not attain plasma potential until $V_a = 8.2$, reflecting a $-\chi^r$ equal to 3.2 and a difference of 0.7 dimensionless units between χ_f^p and χ_f^r.

The bend in the curve in the region $4 \lesssim V_a \lesssim 6$ could easily and erroneously be interpreted in an experimental situation as the "knee" which normally exists near the plasma potential and the portion of the curve for $V_a > 6$ taken as the electron-saturation current response of the probe. It can be seen that a straight line can be drawn through the curve in the region $V_a \lesssim 4$ thus indicating the presence of Boltzmann electrons with a T_e which is approximately 8% higher than the real value.

It is interesting to discuss the possibility of locating the plasma potential on the measured curve. If the point of break-away from the straight line (for discussion of this technique see Ref. 6) is used to locate the measured value of the plasma potential $V_a(0)$, then $3.5 \lesssim V_a(0) \lesssim 4.0$, while it appears that the plasma potential is at $V_a(0) \simeq 5$ if one uses the intersection of the two tangents (the dotted lines in Fig. 4) in the two-tangent technique (see Ref. 3). In this example the latter technique yields no error in locating the plasma potential with respect to χ_f^p whereas the former technique yields a -20 to -30% error or approximately a -9 to -13 volt error in the measurement when $T_e \approx 10^5$ °K.

Another important consideration is of course the determination of n_e from what appears to be $i_e^p(0)$. Using the break-away point[6] one would find $n_e^a \approx 0.2\ n_e$ while the intersection of the two tangents would yield $n_e^a \approx 0.7\ n_e$. Here n_e^a is the measured (i.e. apparent) value of the undisturbed electron density.

B. Spherical Reference Electrode

The results analogous to Figures 2 for a reference electrode of spherical geometry are presented in Figures 5 and as before the value of χ_f^r can be taken as the value of χ_α^r at $\alpha = 10^4$.

In contrast to the results for cylinders it can be seen that the value of $-\chi_\alpha^r$ is larger when $\tau = 1$ than when $\tau = 0$ (at least for $\beta_r < 100$). This is a reversal in the trend of results for cylindrical geometry with the reason for the difference partially lying in the theoretical models employed by Laframboise.

As mentioned earlier Laframboise assumed a totally absorbing probe for all cases except when $\tau = 0$ in the presence of a spherical probe. In the latter case it was assumed that the repelled species (the electrons in the transition region) is totally reflected at the probe surface. The zero collection of the repelled species results in an increase in its density near the probe and decreases the steepness of the electric potential there, allowing more of the attracted particles (ions) to reach it. The net result is an increase of attracted-particle (ion) current above corresponding values calculated for a completely absorbing probe. This difference in collection properties then yields smaller values of $-\chi_\alpha^r$ (and similarly smaller values $-\chi_f$) in the case of a reflecting electrode than those for an absorbing electrode.

It should be pointed out that the difference in theoretical models as discussed above cannot in itself completely explain the trend reversal in the role of τ in determing χ_α^r when comparing the results of spherical and cylindrical geometries. This point bares itself when one considers that the totally-reflecting electrode solution should converge to the totally-absorbing electrode results with increasing values of $-\chi_{\alpha}^{r}$ and $-\chi_f$. In fact it should be expected that at a retarding dimensionless potential of -5 the two solutions should have merged. The role of τ and its relative influence at greater retarding potentials is more easily observed in Figure 6 where $-\chi_f$ is plotted for spheres as a function of M for $\tau = 0$ and $\tau = 1$ and $\beta = 2$, 10 and 100. If for any given value of β the sole reason that $\chi_f(\tau=0) \neq \chi_f(\tau=1)$ was a difference in the assumed theoretical models, it would be expected that the difference $\chi_f(\tau=0) - \chi_f(\tau=1)$ would become smaller for increasing values of $-\chi_f$ and any given value of β. Figure 6 shows clearly that this in fact does not take place.

A larger contribution to the observed difference in the influence of τ on the two geometries lies in the fundamental differences in the ion-current response of cylinders versus that of spheres. The detailed results of Laframboise show that the ion-current to a cylindrical electrode is a monotonically increasing function of τ. This was indirectly observed in the results of Figs. 2 and 3.

In contrast to the results for a cylinder, the nature of the ion-current dependence for spheres on τ is non-monotonic. Laframboise has in fact shown that as τ is decreased from unity, the ion collection to a sphere passes through a small minimum at $\tau \approx 0.25$ and then increases very rapidly as $\tau \rightarrow 0$ He has pointed out that the reason for this behavior is that as τ decreases from unity, the dominant influence is at first the decrease of random ion flux through a decrease of ion thermal motion; as τ decreases further, the absorption boundaries[7] move outward to infinity, slowly at first, then very rapidly, so that the increase in ion-collection volume becomes the dominant influence. This increase in collection volume is such that the current collected at $\tau = 0$ is greater than that at $\tau = 1$. The consequence of this is of course observed in Figures 5 and 6.

Figure 6 is the spherical counterpart of Figure 3 and both figures display the same type of dependence for constant τ on β and M.

IV. COMMENTS AND CONCLUSIONS

A. Relative Probe Size

The results of the analysis presented in Figures 2 and 5 show that a value of $\alpha = 10^4$ will guarantee a fixed reference potential. As evidenced by these Figures the constraint on α can be relaxed with decreasing values of M and β_r. A guideline can be established by requiring $| \Delta\chi^r | \leq 0.1 | \chi_f^r |$. By linearly extrapolating the results of Fig. 4, this constraint implies a worst-case error in electron temperature measurement of +2%. A minimum value of α can be established from Figure 2 and 5 which guarantee the above condition of constraint. This value of α is defined as α^* and is plotted in Fig. 7 as a function of M for both cylindrical and spherical reference electrodes. For all values of β_r except $\beta_r = 2$ in spherical geometry the curves are valid for both $\tau = 0$ and 1 with an accuracy on the value of α^* being $\pm 10\%$. The exception is plotted separately for $\tau = 0$ and 1 since the accuracy of $\pm 10\%$ could not be achieved with a single curve. The values of α^* can therefore be taken as a working lower limit for meaningful Langmuir probe characteristics.

B. Floating Potential

Figures 3 and 6 make it quite clear that the floating potential of a body immersed in a plasma is a function not only of the plasma parameters but also of the body size and geometry. This is a result which should be anticipated in any attempts to determine rocket or satellite potentials as inferred by the floating potential of an on-board Langmuir probe. As an example consider a plasma volume in the limit $\tau \to 0$ with $n_e \approx 10^5/cm^3$, $T_e \approx 2(10^3)$ ^oK and $M = 16$. (This situation would represent conditions that are encountered in the ionosphere at an altitude of approximately 250 km.) If the measurement is made with a cylindrical probe such that $\beta_p \lesssim 3$ and if a 22.9 cm (9.0 in.) diameter rocket ($\beta_r \approx 10$) is employed as a reference electrode the resulting floating potentials would be $\chi_f^p = -4.3$ and $\chi_f^r = -4.6$. The floating potential of the probe would then be 52 mv (= 0.3 kT_e/e) more positive than the rocket potential. (Other possible influences, such as contact potentials and photoemission, have not been included in this example for purposes of simplicity.)

The difference in probe and reference electrode floating potentials can be significantly larger in a laboratory plasma. As an illustration consider an Ar^+(M=40) plasma with $n_e = 10^{11}/cm^3$, $T_e = 10^5\ {}^oK$ and $\tau \to 0$. If a cylindrical probe with $R_p \lesssim .021$ cm(.008 in.) is employed and probe voltages are applied with respect to a large planar electrode in electrical contact with the plasma, the corresponding floating potentials would be $\chi_f^p = -4.7$ and $\chi_f^r = -5.0$ The result for the planar electrode has been approximated by the spherical case with $\beta_r = 100$ and it has been assumed that no density gradients are present in the plasma. In this illustration the floating potential of the probe is approximately 2.6 volts more positive than the corresponding potential of the reference electrode.

C. Other Area Considerations

In addition to the area considerations presented here it must be remembered that the very size of the probe and reference electrode may influence the ambient plasma parameters of density and temperature. The possibility of this type of influence has been studied by Waymouth[9] who has pointed out that the very act of measurement will perturb the undistributed charged-particle energy distribution if the current collected by the probe is large in relation to the processes which maintain the plasma. Consequently both the relative and absolute sizes of a probe are important considerations for the integrity of a Langmuir probe measurement of plasma properties.

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FIGURE CAPTIONS

Fig. 1. Schematic representation of a Langmuir probe circuit and a corresponding theoretical current-voltage characteristic.

Fig. 2. The dimensionless potential χ_{α}^{r} of a cylindrical reference-electrode as a function of $\alpha(\equiv A_r/A_p)$ for $\beta_r(\equiv R_r/\lambda_D) \lesssim 3$ (Fig. 2a), = 10 (Fig. 2b) and = 100 (Fig. 2c). M is the charge-normalized ion mass (in amu), $\tau = T_i/T_e$ and the Langmuir probe is assumed to be operating at the plasma potential.

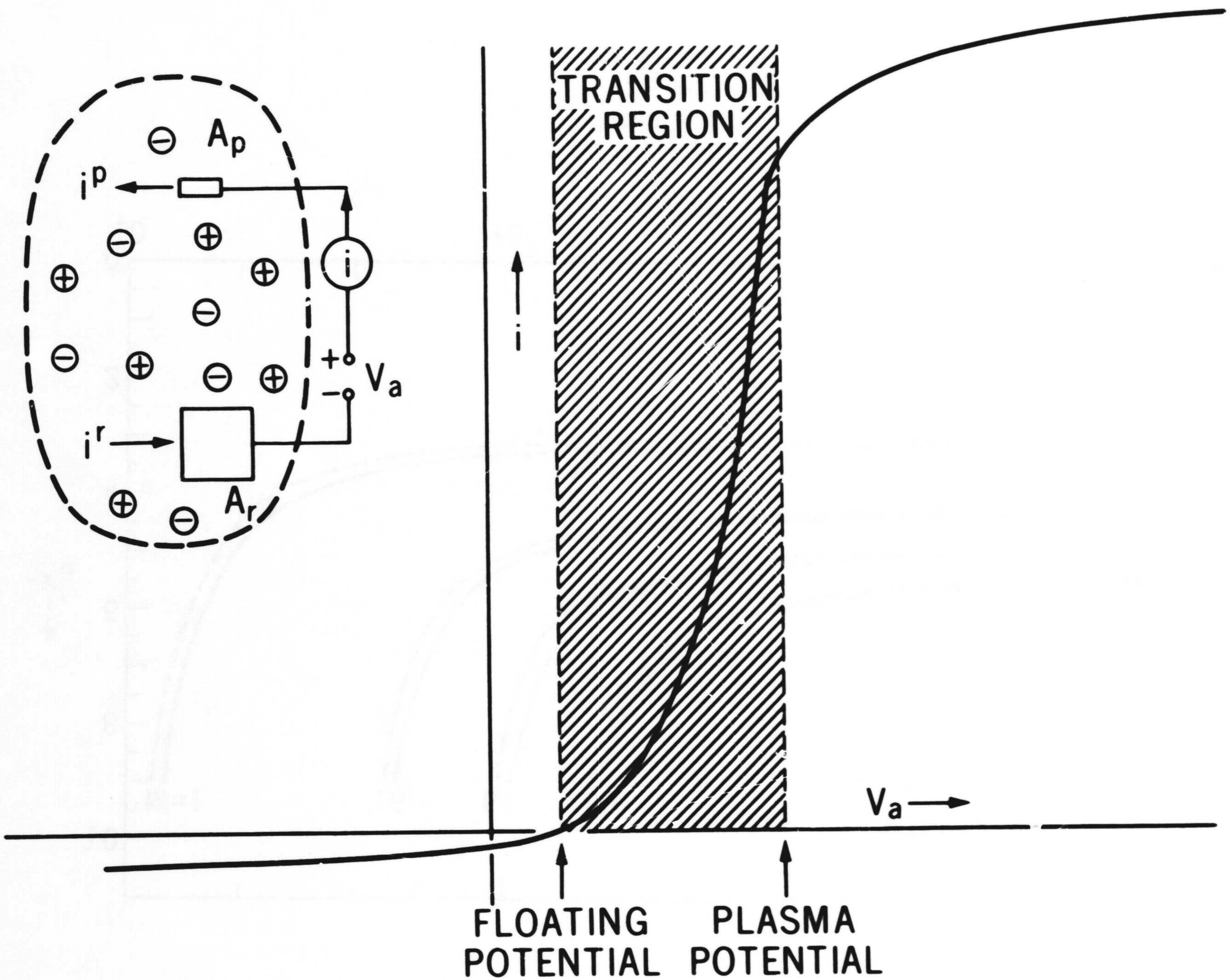
Fig. 3. The dimensionless floating potential χ_f of a cylindrical body immersed in a collisionless, Maxwellian plasma plotted as a function of the charge-normalized ion mass M (in amu) for ratios of ion-to-electron temperature equal to 0 and 1. β is the ratio of body radius-to-Debye length.

Fig. 4. A semi-logarithmic plot of the normalized transition-region electron-current response of a cylindrical Langmuir-probe. The reference electrode is assumed cylindrical and the ratio of its area to that of the probe taken as 150. The dashed line represents the undistorted response when $\alpha(\equiv A_r/A_p) \rightarrow \infty$.

Fig 5. The dimensionless potential χ_α^r of a spherical reference-electron as a function of $\alpha(\equiv A_r/A_p)$ for $\beta_r(\equiv R_r/\lambda_D) = 2$ (Fig. 5a), 10 (Fig. 5b) and 100 (Fig. 5c). M is the charge-normalized ion mass (in amu), $\tau = T_i/T_e$ and the Langmuir probe is assumed to be operating at the plasma potential.

Fig. 6. The dimensionless floating potential χ_f of a spherical body immersed in a collisionless, Maxwellian plasma plotted as a function of the charge-normalized ion mass M (in amu) for ratios of ion-to-electron temperature equal to 0 and 1. β is the ratio of body radius-to-Debye length.

Fig. 7. A guideline on the minimum area ratio $(A_r/A_p)_{min} \equiv \alpha^*$ which will limit errors in T_e measurements, that can result from shifting reference-electrode potentials, to +2%. Except for the spherical case when $\beta_r = 2$ the results apply within a ±10% accuracy in α^* to both $\tau = 0$ and 1.


A
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POTENTIAL

Figure 1

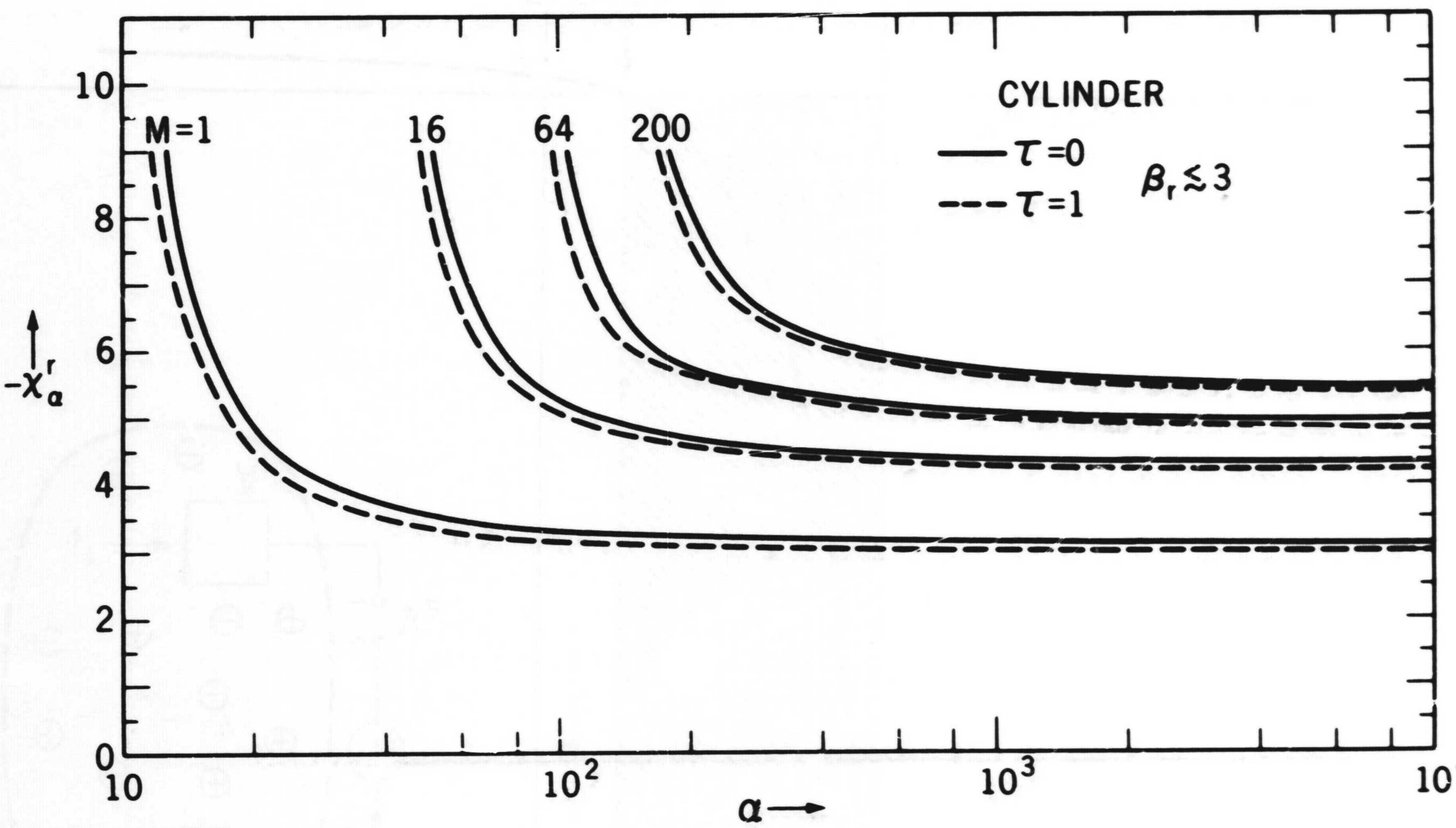


Figure 2a

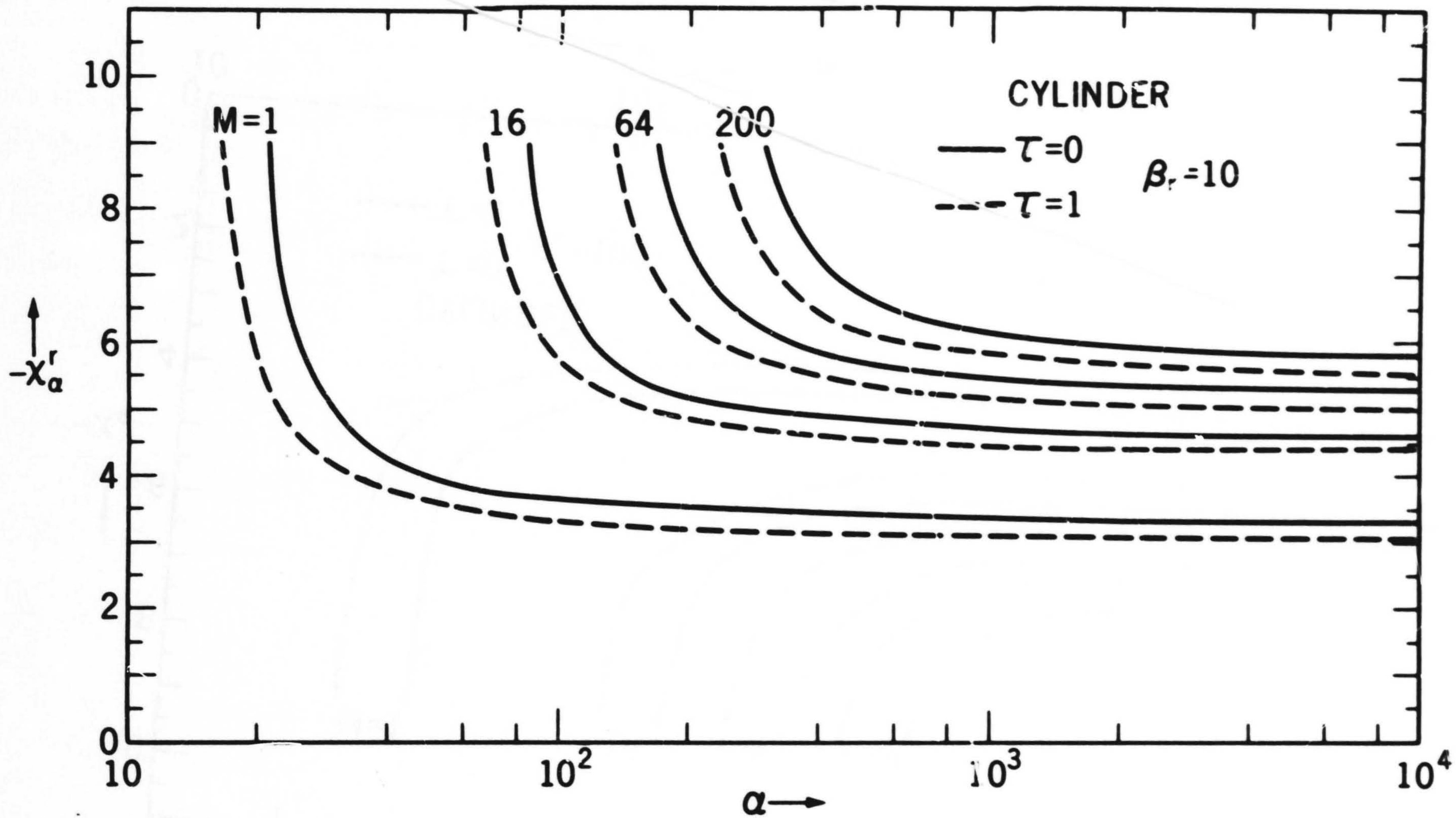


Figure 2b

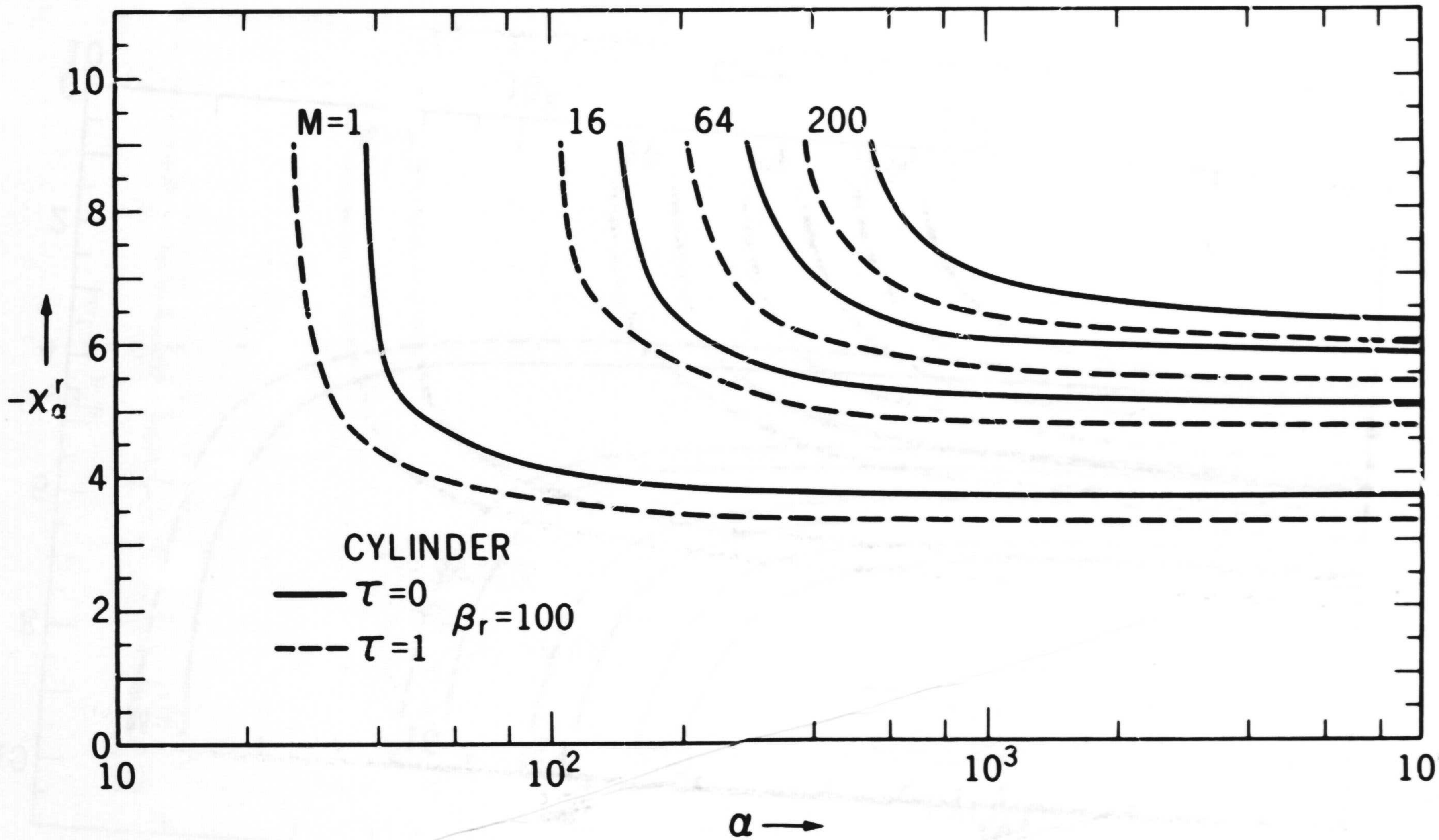


Figure 2c

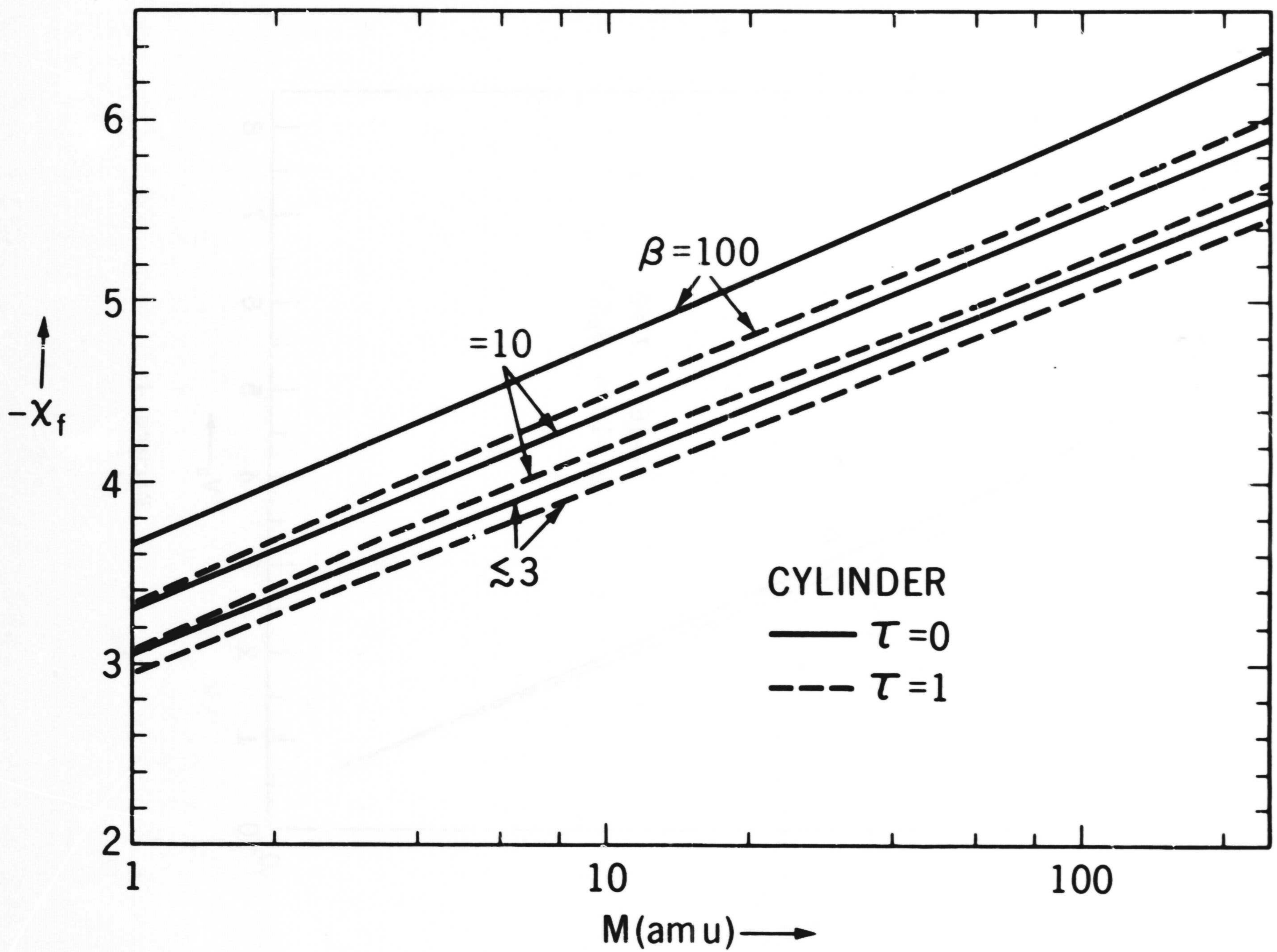
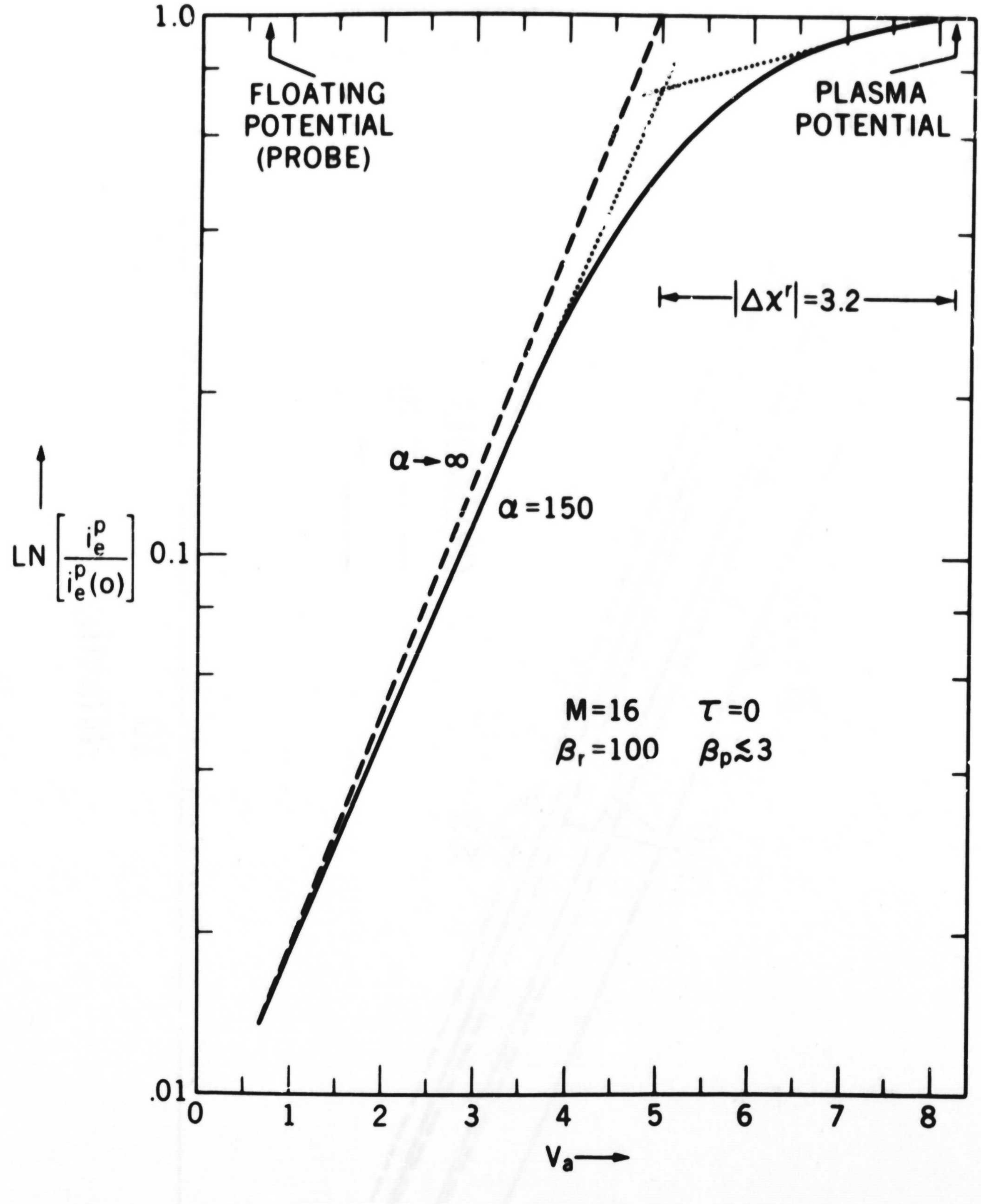


Figure 3



1.0
0.1
.01
0
1
2
3
4
5
6
7
8
FLOATING
POTENTIAL
(PROBE)
PLASMA
POTENTIAL
|ΔX'|=3.2
α→∞
α=150
LN [i_e^p / i_e^p(o)]
M=16 τ=0
β_r=100 β_p≲3
V_a

Figure 4

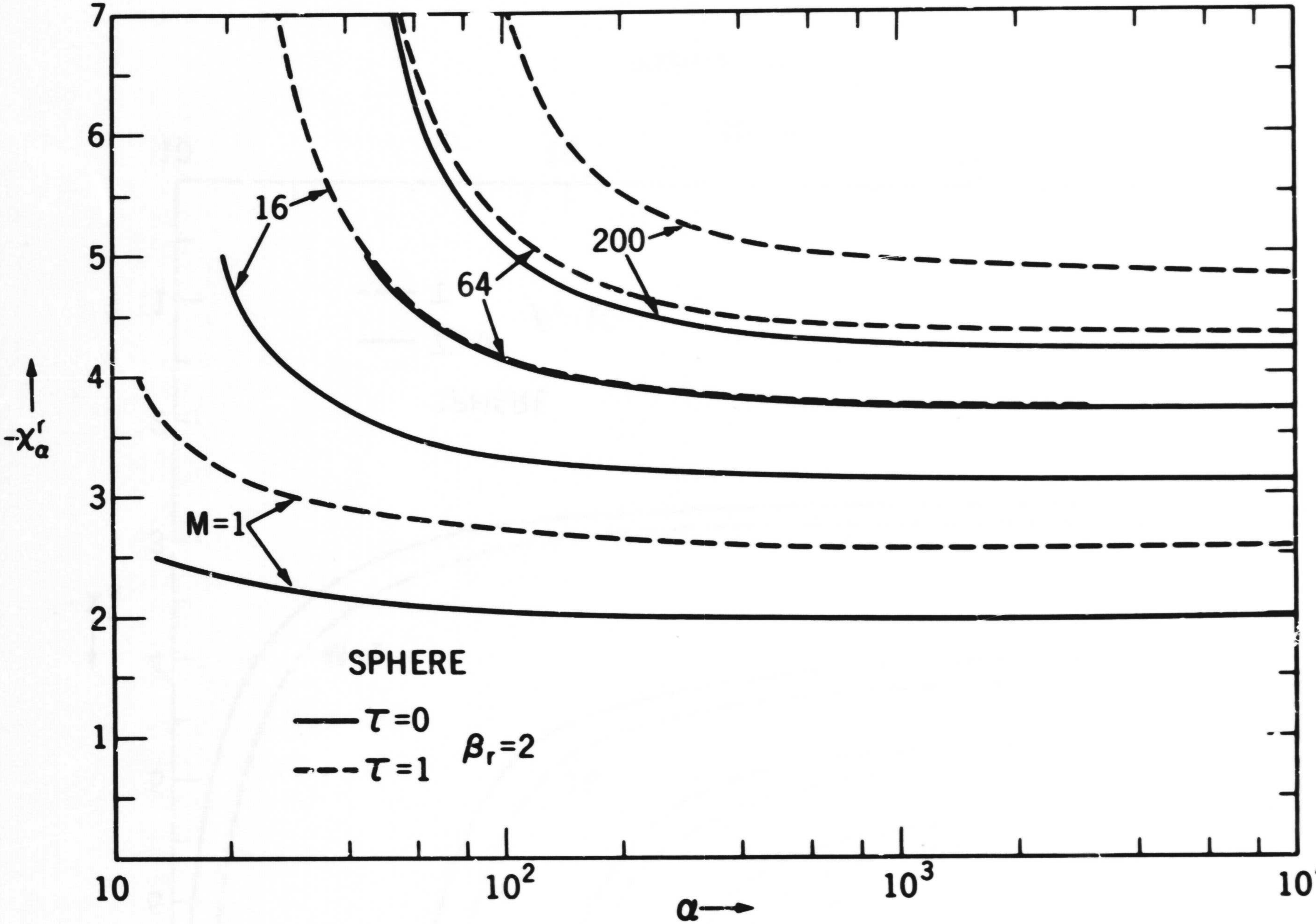
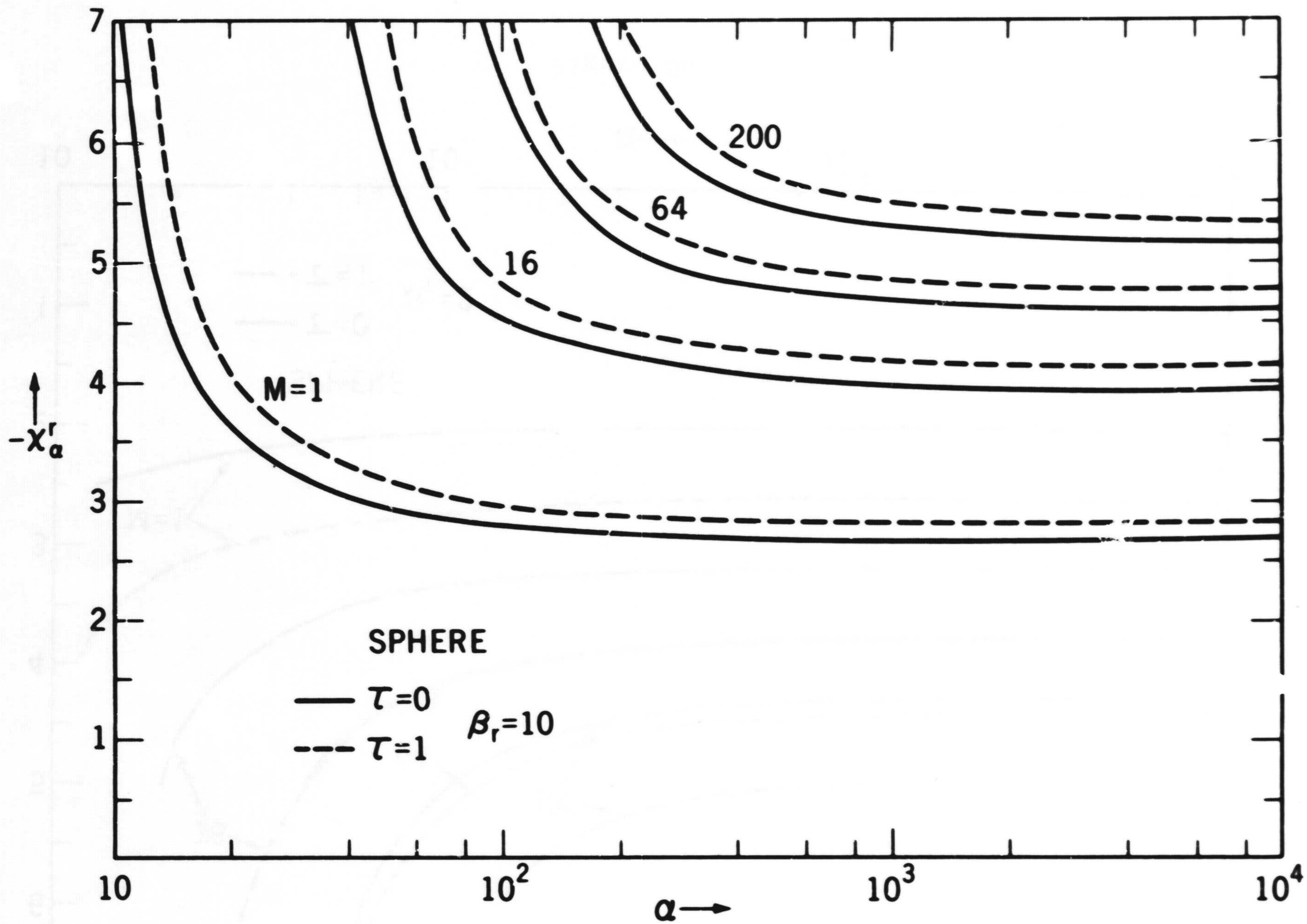


Figure 5a



7
6
5
4
3
2
1
$-\chi_\alpha^r$
10
10^2
10^3
10^4
α
M=1
16
64
200
SPHERE
τ=0
τ=1
β_r=10

Figure 5b

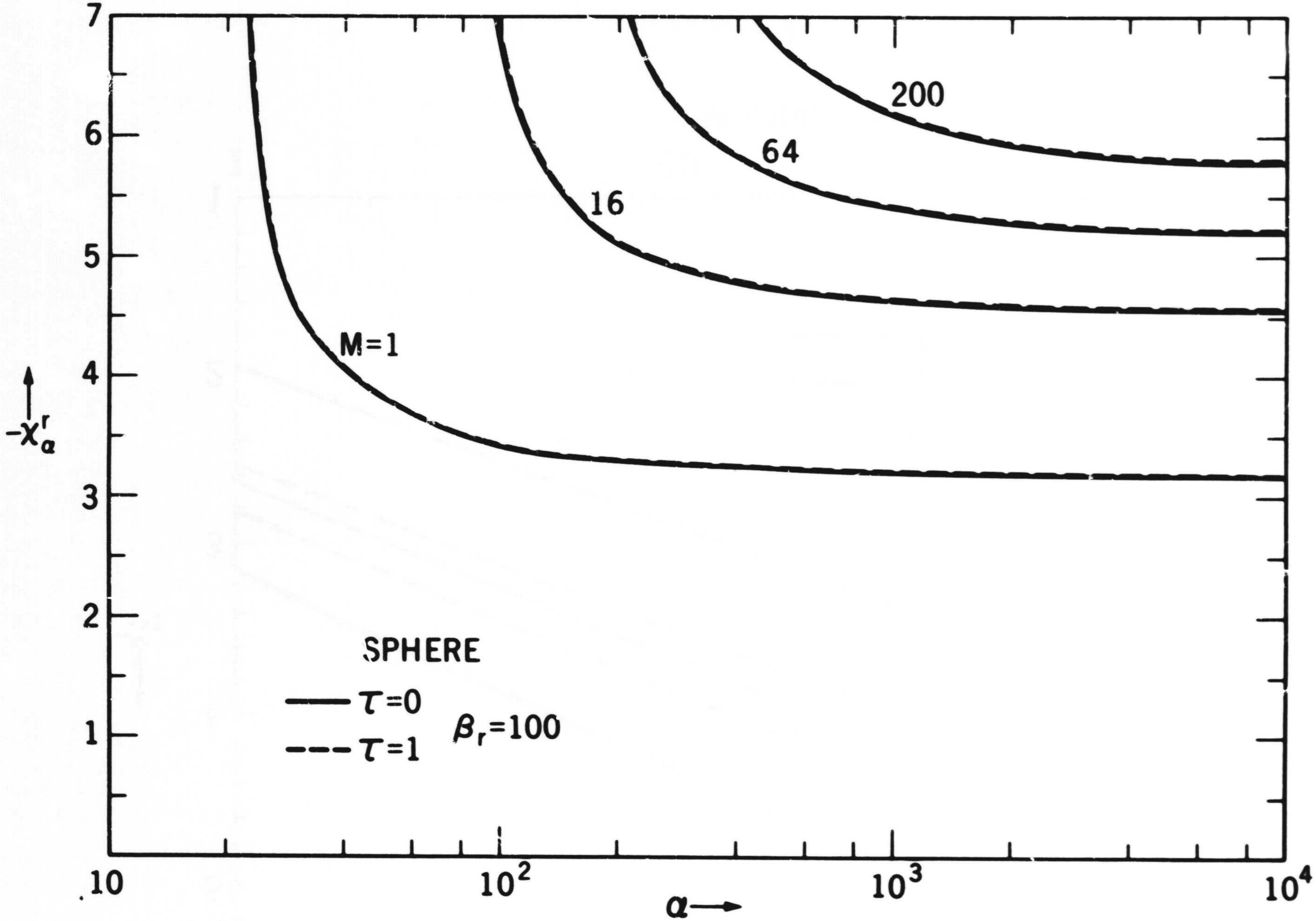

7
6
5
4
3
2
1
$-\chi_a^r$
.10
10^2
10^3
10^4
a
M=1
16
64
200
SPHERE
τ=0
τ=1
β_r=100

Figure 5c

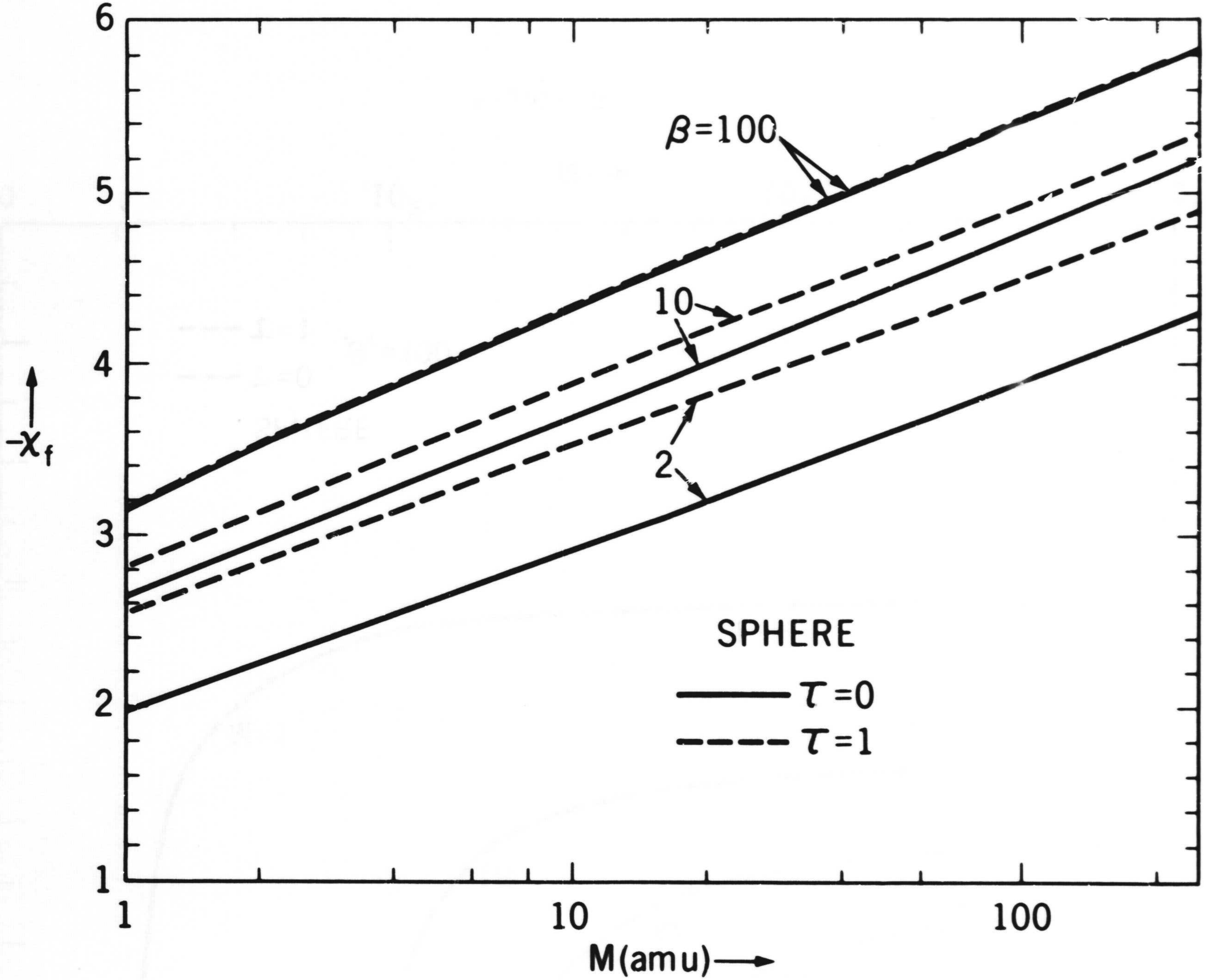


Figure 6

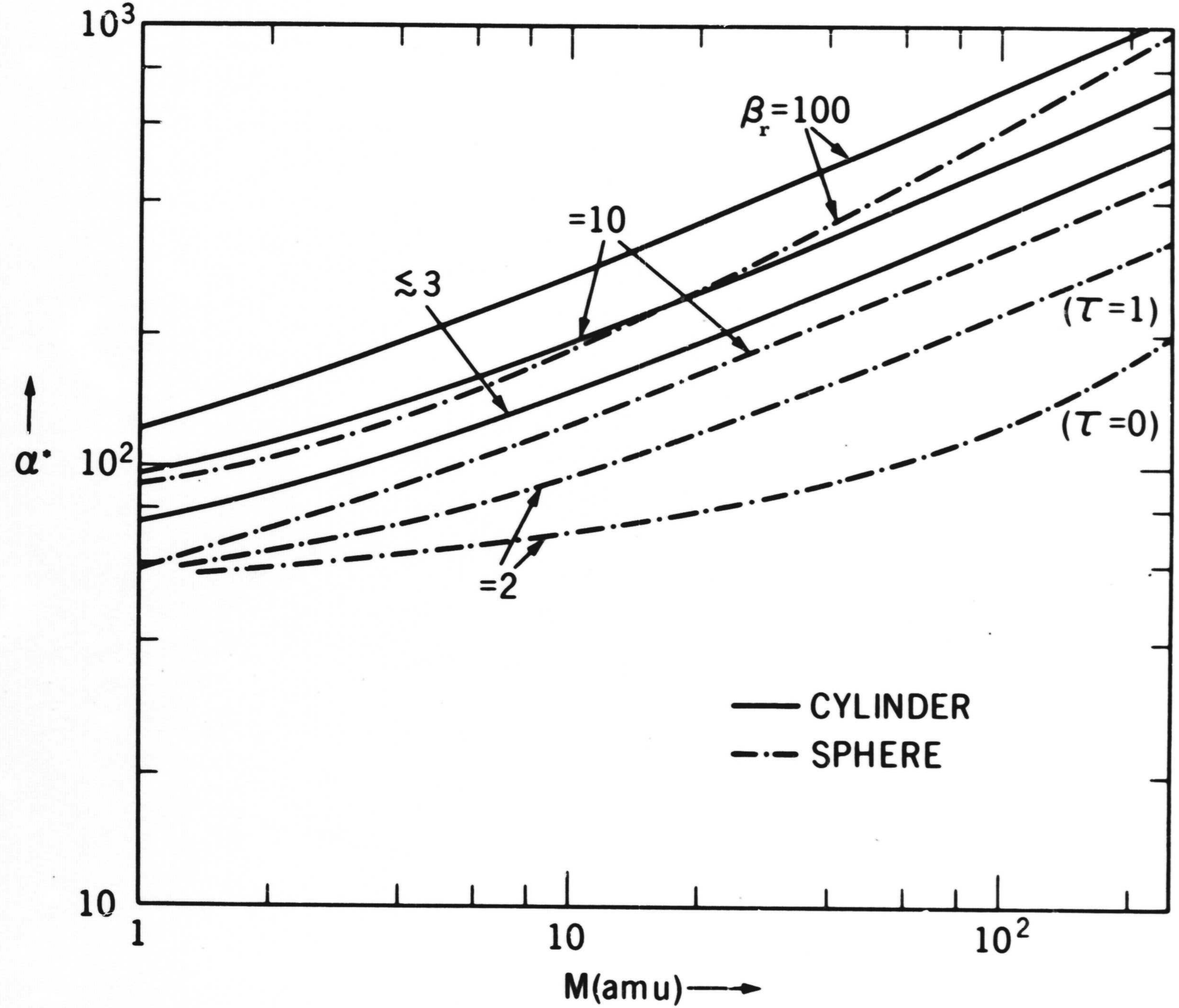


Figure 7