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I. INTRODUCTION

Due to the finite charge/mass ratio of the constitutent particles, plasmas can react to perturbations so intensely that the self-generated fields (net induced charge density and currents) impose on the particle-field system large secular modifications, driving it into regions where characterization by the usual thermodynamic state parameters - temperature, pressure - is no longer adequate. In Vlasov plasmas strong interactions may be generated by relatively modest excitation levels. Consequently they abound in nature, and are probably responsible for a variety of unexplained (or mis-explained) phenomena.

The description of such processes requires the measurement of both particle and field properties at the detailed (kinetic) level, and with high time and space resolution. An important class of strong interactions - intrinsic stochasticity - have been theoretically studied for a considerable time, but experimental demonstrations have been very limited, because kinetic features could not be measured with sufficient precision. Due to current advances in experimental methods, these details are now becoming observable. Specifically, intrinsic stochasticity in ion waves has been demonstrated in two separate experiments, in linear and toroidal (confined) geometries, involving driven as well as unstable wave fields.The configurations are sufficiently simple and the data adequate for comparison with theory. We discuss here underlying concepts and results from the experimental viewpoint, emphasizing the interplay between physical processes and the diagnostic method needed for their observation. For this purpose it is instructive to invert the canonical order, and discuss first i. solutions of the particle dynamic equation which exhibit stochasticity;followed by ii. derivation of the equation for a realizable plasma geometry, and by iii. the description of the force which drives the dynamics. It is shown how new techniques enable us to attack problems formerly beyond our reach, and reopen questions left unanswered.

II. INTRINSIC STOCHASTICITY IN ION WAVES

Intrinsic stochasticity, the process describing the chaotic response of a system to a regular (non-chaotic) applied force, has a venerable theoretical pedigree (1), but few experimental treatments in plasma physics beyond Doveil's original experiment on electrons (2). We consider "phase" transitions between a regular state, where charged particles in applied fields execute orbits which stay in a limited region of phase-space, to a state where any particle can be expected to appear at every point of phase-space. This is illustrated in coordinate space by Fig. 1, a schematic based on calculations of the ion motion starting from rest, in a configuration consisting of a magnetic field in the z-direction (normal to the trajectory plane), varying in strength as r^{-1} (where r is the radial coordinate in the plane);and a superposed double-humped potential field, rotating in the plane at a frequency below the magnetic (ion cyclotron) particle frequency, whose equipotentials are sketched out in trace (a).

When the potential gradient is low, as for (b), the ion orbits are shallow arc segments with uniform curvature and length, precessing with nearly constant radius (closed orbit) within a restricted space region about around a fixed guiding axis. In contrast, when the potential strength exceeds a threshold value, as in (c), the ion executes open orbits of widely varying curvatures and radii, with itinerant guiding axes which carry the particle across much of the plane, and would in fact fill the space were it not arbitrarily interrupted by a "wall". This is equivalent to heating, in the sense that measurements ascribing the range of sizes and curvatures of the orbits of many such particles to kinetic velocities, would attribute to the system a low temperature in case (b), but a much higher temperature in (c).

Similarily, the migration of the particle far beyond the limited orbital region (b) is a form of spatial diffusion. Evidently a requirement for describing such transitions is a diagnostic technique which measures ion orbits and their distribution with high resolution in both "curvature" (velocity) and coordinate space.

III. LASER DIAGNOSTICS OF PLASMA IONS

The experimental problem is to invent the combination of plasma medium and measurement technique most appropriate for the physical concepts to be studied. Here laser-induced fluorescence (LIF) turns out to have essential advantages, and is beginning to yield results in describing intrinsic stochasticity of ions in plasma waves. From these initial measurements we learn also how to extend the technique and plan further, more sophisticated experiments.

In LIF, a laser beam is tuned to resonate with a quantum-state transition of the test ion, and the spectral intensity $I(\lambda)$ of the fluorescence emitted by the ion following laser excitation is detected and analysed. One can sweep the wavelength λ of a narow-band laser across the absorption linewidth of the ions, or else disperse the emitted fluorescence, to extract the Doppler broadening of the transition. Using the formula $f(v/c) = I(d\lambda/\lambda)$, the Boltzmann velocity distribution f of the initial quantum state of the ions is obtained. Space resolution is obtained by using high f-number detection optics focused onto a point on a small-diameter laser beam. Time resolution can be obtained by gating and sampling the fluorescence detection, by pulsing the laser.

This technique is finding extensive use (3). In addition, using the variant known as Optical Tagging (4), the transport of ions can be followed across the plasma, enabling a direct measurement of ion diffusion (with causality) to be carried out. Finally, LIF can be used to deduce the strength of the fields (5) applied or generated by the self-consistent collective plasma response. These techniques are relatively unambiguous and non-perturbing, in the sense that the quantum state of the ion does not affect the plasma properties and conversely as long as collisionality and the strengths of the self-consistent fields are low.

IV. THE PROCESS : ELECTROSTATIC WAVES IN MAGNETIC FIELD

Among systems known to exhibit stochasticity are those described by two nonlinear coupled differential equations. If the equations correspond to two resonant oscillators, the nonlinear parameter may have values such that the some of the two kinds of resonances overlap, leading to a situation where a small change in initial conditions can result in large changes in the type of solution. Under these conditions, fluctuations can render the final configuration chaotic. A physical example considered under a variety of conditions (6), (7) is the behaviour of a free charged particle, embedded in a plasma which supports an electrostatic wave propagating across a uniform, static magnetic field. Here the oscillators are i. the Larmor orbit of the particle in the magnetic field, with eigenfrequency ω_{ci},the (ion) cyclotron frequency; and ii. the trapping oscillations of the particle within the potential trough of the wave, with eigenfrequency $\omega_b = (ek^2\phi/m)^{1/2}$ The governing equation turns out to be, for several configurations, of the type :

$$\ddot{y} + y - \alpha \sin (y - \upsilon t) = 0 \qquad (1)$$
$$\ddot{x} = \dot{y}$$

Here x,y represent the normalized particle position in the plane normal to the magnetic field; α is the nondimensional ratio $ek^2\phi/m\omega_{ci}^2 = \omega_b^2/\omega_{ci}^2$,and ϕ and k are the potential field strength and wave number respectively. The frequency $\upsilon = \omega/\omega_{ci}$,and the normalizations of x,y and t are to k^{-1} and ω_{ci}^{-1} respectively.

To see that this equation may undergo a "phase transition" of the type involved in transition to chaos, consider the exactly-integrable limit $\upsilon = 0$,(ref. 6). Equation (1) then yields :

$$\dot{y}^2/2 + y^2/2 + \alpha \cos y = H\text{,a constant} \qquad (2)$$

For small values of α the solutions of eq. (2) are a family of slightly distorted, concentric circles with a single, common O-point close to the coordinate origin. At large $\alpha >>1$,the solutions go over to a radically different system, which contains several 0- and X-points. This becomes evident by differentiating eq.(2) and seeking the extrema :

$$dH/d\dot{y} = dH/dy = 0, \text{requiring } \dot{y} = 0 \text{ and } y = \alpha \sin y \qquad (3)$$

These O and X points lie on the y - axis, and their number depends on the possible intersections of the straight line y with the harmonic α sin y. This number increases with α,indicating as expected that the complexity and multivaluedness of the solutions are dependent on the nonlinear parameter. For $\alpha <1$,$y = \alpha \sin y$ has only $y = 0$ as solution,as before, indicating that $\alpha =1$ can indeed be expected to be a threshold to a new, more complex state. The transition discussed here, "driven" by the parameter α,is to a state which is still regular (non-stochastic) in our example, since only the time-independent case was considered. If instead the time dependent term is left in ($\upsilon \neq 0$), then instead of a regular type of solution the end - state (particle trajectory in $\dot{y}$, y space) becomes stochastic above some threshold value of α.

The various cases,$\upsilon <1$,$\upsilon= 1$ and $\upsilon >>1$ have been analyzed by Drake and Lee (6), Smith and Kaufman, Fukuyama et al, and Karney and Bers respectively (7). It turns out that the thresholds are not very large, indicating that laboratory experiments to demonstrate these transitions are feasible. In fact experiments which illustrate the first two cases have just been carried out. Note that, though some analyses are concerned with electron stochasticity, one can think of ions as "heavy electrons" with the opposite charge, and apply the analysis to that case. The evident advantage of ions is that LIF affords the type of diagnostic not available for electrons, so that meaningful experimentation may be possible using ions, when it is not with electrons.

IV. PARTICLE DYNAMICS

Equation (1) is known to be a reasonable model for the behaviour of free particles in a crossed electrostatic and constant magnetic field configuration. Start with the Larmor equation of motion

$$d/dt\ \mathbf{V} = e/m\ (\mathbf{E} + \mathbf{V}\mathrm{x}\mathbf{B}) \qquad (4)$$

In the simplest geometry, the magnetic field $\mathbf{B} = B_o\mathbf{z}$ is constant, uniform and parallel to the z axis, while the electric field $\mathbf{E} = E\mathbf{y}$ is space- and time dependent and parallel to the y axis, i.e. normal to the magnetic field. In the guiding center approximation:

$$\mathbf{V} = \mathbf{V}_{\mathrm{Larmor}} + v_{\mathrm{ExB}}\ \mathbf{x} + v_{\mathrm{polarization}}\ \mathbf{y} \qquad (5)$$

with v_{ExB} and v_{pol} representing components of the velocity which are slowly varying in comparison with the Larmor orbit. Introducing (5) into eq.(4), the coupled "slow" equations are isolated :

$$v_{\mathrm{ExB}} = e/m\ v_{\mathrm{pol}}\ B_o\ ; \qquad (6)$$
$$v_{\mathrm{pol}} = e/m\ (E - v_{\mathrm{ExB}}\ B_o) \qquad (7)$$

Integrating (6) to eliminate v_{ExB} from (7), and taking E to be derivable from a plane-wave propagating potential field $\phi\cos(ky-\omega t)$,as $E = -\,\mathrm{grad}\ \phi = k\ \phi\sin(ky-\omega t)$,the integro-differential equation obtained is :

$$\dot{v}_{\mathrm{pol}} = e/m\ k\ \phi\sin(ky-\omega t) - \omega_{ci}^2 \int v_{\mathrm{pol}}\ dt \qquad (8)$$

Approximating $\dot{y}$ by means of v_{pol},and normalizing time to ω_{ci}^{-1} and space to k^{-1}, the result is eq. (1), an equation shown to become stochastic when the nonlinear parameter $ek^2\phi/m\omega_{ci}^2 = \alpha = \omega_b^2/\omega_{ci}^2$ is of order unity. Recalling that the trapping frequency for a particle in the bottom of the potential well of the propagating wave $\omega_b = (ek^2\phi/m)^{1/2}$, this threshold is equivalent to requiring the two oscillator resonances to be equal, as expected.

VI. THE WAVE

Recently two sets of experiments have demonstrated transition to stochasticity in electrostatic ion waves propagating across magnetic fields, using LIF. These experiments were carried out in the regimes $\upsilon = 1$ and $\upsilon < 1$, the excitation being antenna-driven ion Bernstein waves in an (unconfined) plasma column, and unstable drift-Alfven waves in a (confined) toroidal plasma, respectively (8), (9). The case $\upsilon = 1$ is the topic of the subsequent paper, " Intrinsic Stochastic Ion Heating ", by F. Anderegg et al, and described in full detail there. The second case will be outlined here. To reach the region $\upsilon < 1$ in a magnetic field, a very low-frequency electrostatic wave must be used. The lowest frequency eigenmodes of a uniform plasma occur for $\omega > \omega_{ci}$ and are not suitable for our regime. Hence one turns to non-uniform plasmas, where an obvious candidate is the drift wave, whose dispersion relation is, in the lowest approximation for a slab geometry:

$$\omega / k_y = -KT_e \, d/dx \, n_o / e n_o B_o$$

Here the magnetic field **B** defines the z coordinate, k_y is the propagation vector perpendicular to the field,and $n_o(x)$ is the plasma density profile, varying in the other perpendicular direction. This acoustic-type dispersion relation passes through $\omega = k_y = 0$ at finite magnetic fields, and is therefore suitable for studying the case $\upsilon < 1$.

The actual mode used is the current-destabilized drift-Alfven wave, a hybrid which has both electrostatic and electromagnetic field components and propagates obliquely to the magnetic field, but still exists at $\upsilon < 1$. This wave, described by Frederickson and Bellan (10), dominates as an m=2, n=1 mode in the ENCORE toroidal plasma, and has the double-humped potential structure shown (idealized) in Fig. 1 (a). At low currents the drift-Alfven wave field is coherent and intense, providing the regular, strong excitation mechanism required for demonstrations of intrinsic stochasticity. Note that in ENCORE the field parallel wavelength is the torus circumference, nearly 240 cm, while the perpendicular wavelength is less than the minor radius, 12.6 cm;thus the propagation direction is very closely normal to the toroidal magnetic field, as assumed in the analysis.

VII. THE TEST PLASMA

The medium is a singly-ionized Argon plasma confined within a toroidal chamber 38.1 cm major radius and 12.6 cm. minor radius, by 24 equally-spaced field coils generating a toroidal field up to 1.5 KG. The plasma is produced by a transformer induction discharge (Ohmic heating - coil) with field strength of about 1 V/cm. After initial breakdown, a sustaining field of up to 0.05 V/cm can be maintained, driving a current of typically 6 KA for durations up to 5 msec. Plasma densities range up to $2x10^{12}$ cm^{-3}, and ionization is 100%. Initial ion temperatures are about 0.2 eV, and electron temperatures typically 10 eV. The unique features of ENCORE are its high repetition rate (up to 15 Hz) and very high shot to shot reproducibility, affording fast data rates and processing.

To enable full use of the diagnostic, the original torus was modified through the construction of a quadrant specially designed for laser and optical beam access. It contains continuous optical ports allowing unimpeded light-beam access across the entire plasma cross-section, along two orthogonal axes. The laser beam is steered by means of a motorized input mirror along one axis, while the objective (detection) lens, optical line filter and PMT are mounted rigidly together onto a separated motorized translator, and can be scanned along the other axis. Computer controll of the stepping motors ensures that the intersection of the laser and lens optical axes is always maintained in the focal plane of the detection lens. This point can be scanned across the plasma cross-section, enabling the local ion temperature distribution to be measured with a spatial resolution (diagnosed volume) of about 0.1 cm^{-3}.

VIII. LASER TECHNIQUE

To foster progress in experimental methods, it is necessary to "aim high" and develop diagnostic techniques which are not just narrowly adequate to the immediate measurement task, but have also the potential to carry out more sophisticated tasks. As an instance, the laser system used in the ENCORE experiment consists of various state-of-art lasers combined and adapted to work in conjunction : specifically, a copper-vapor pump laser is used to drive a dye laser with intercavity scannable Fabry-Perot etalon. The copper vapor laser affords one of the highest pulse repetition rates available - 6 KHz in our case - at a relatively intense level, up to 8 mJ over 30 nsec. The average pump power is 40 W, much higher than excimer lasers, while the pulse power is sufficiently high to allow efficient doubling, for generating short-wavelength radiation. The dye laser power levels, with about 25% conversion efficiency, reach a few tens of KW, enabling the "target" ion quantum transition to become saturated, thereby decreasing shot-to-shot variation.

The dye laser has a bandwidth of about 1 GHz, corresponding to a velocity resolution of 5×10^{4} cm sec^{-1} in Argon, i.e. a temperature resolution of 1/20 eV, close to room temperature. This is adequate for measuring ion heating, e.g. in ENCORE, where the initial temperatures are of order 0.2 eV and increase by nearly two orders of magnitude. The time resolution is limited by the pulse width, and the spatial resolution by the intersection of the viewing (objective) lens axis and the laser beam diameter. With the highest temperatures, the ion displacement within the pulse duration is below 0.3 mm, smaller than the laser beam diameter (typically 3 mm), so that the time- and space scales were uncoupled in this experiment.

IX. TEST RESULTS

Figures 2 and 3 display the direct data and results obtained using LIF at above-threshold intensities of the drift-Alfven wave field. The top traces in Fig. 2 show the evolution in time of the measured ion velocity distribution function, after the heating field is applied. The corresponding ion "temperatures" of the Gaussian distributions best fitted to the observed functions are shown, as are the measured electron temperatures, obtained from Langmuir-probe data at the same points and conditions. The lower graph plots the ratio T_i / T_e obtained from these points.The bottom line is a calculation of the theoretical ratio which would result from Spitzer (electron-ion collision) heating for the same conditions, based on the actual Langmuir-probe values of the electron temperature and density. As can be seen, the stochastic process heating rate (initial slope) is more than an order of magnitude higher than the collisional rate.

Figure 3 shows the radial variation of the rise in the ion temperature with time during stochastic heating. Note that the rate of heating (initial slope) is highest at a radial point roughly 2/3 out from the center of the torus, where the potential gradient of the drift-Alfven wave is highest,even though the electron density and hence the collisional heating rate are smaller than at the center. The fact that the asymptotic values of the ion temperatures are the same at all values of the radius, including the center where the field is smallest, is an illustration of the stochastic diffusion process;note that these saturated values are reached within 1.2 msec,a time at which collisional heating predicts only 1/4 of the observed ion temperature.

A simple question may arise at this point : are the broadened ion velocity distributions observed here truly "random"? If so, they should affect collective properties of the plasma, e.g. wave propagation and dispersion, as described by kinetic theory.As a test, ion -acoustic waves were launched by probes and detected in the direction normal to the toroidal field, at frequencies (typically 500 KHz) much higher than the ion-cyclotron frequency. Measurements revealed that the wave damping, a sensitive function of the ratio T_i / T_e, corresponds closely to the values obtained from the LIF and probe measurements (11). This can be taken as an independent confirmation of the stochastic nature of the field-particle interaction described here.

More details, including threshold data (dependence of heating rate on field) and comparison with numerical calculations, can be found in ref. (9). Experiments are continuing, and Optical Tagging has been successfully tried in this configuration. It can be expected that a complete demonstration of stochastic ion heating by self- consistent (unstable) fields in a confined, toroidal plasma will be obtained in this way.

XI. CONCLUSIONS

New developments in diagnostics are yielding a much more detailed picture of stochastic processes in plasmas than was previously possible. To date, the actual velocity distribution functions as well as preliminary data on spatial diffusion have been obtained. This should enable the trajectories of the particles in phase-space to be constructed, so that matches between calculations and experiments may be carried out. A further, major step will consist in measuring the self-consistent field strengths, with space and time resolution matching that of the particle property measurements. It is conceptually possible to extend the diagnostic methods in this direction, and thus obtain a complete experimental description of strong field-particle interactions.

It is noteworthy that intrinsic stochasticity in ion waves, where the self-consistent electric fields are usually much weaker than in electron waves, can nevertheless occur under relatively weak perturbations, and turn out to dominate over the classical processes, sometimes by orders of magnitude. The fundamental experimental findings discussed here suggest that several unexplained phenomena reported in fusion physics (9) may be attributable to stochastic processes, and demonstrate the close relationship which could exist between basic and directed research.

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REFERENCES AND FOOTNOTES

(1) Note that the first Workshop in the present series was concerned with this subject. For reference, see " Intrinsic Stochasticity in Plasmas" Int'l Workhop,17-23 June 1979,Eds. G. Laval and D. Gresillon,Les Editions De Physique Courtaboeuf,BP 112, 91402 Orsay, France. A recent review can be found in D.F. Escande, Physics Reports 121, 165 (1985)

(2) F. Doveil, Phys. Rev. Letters 46, 532 (1981)

(3) A recent application of LIF to measurement of ion heating is described in F. Anderegg, R.A. Stern, F. Skiff, B.A. Hammel, M.Q. Tran, P.J. Paris and P. Kohler, Phys. Rev. Letters 57, 329 (1986)

(4) R.A. Stern, D.N. Hill and N. Rynn, Physics Letters 93A, 127 (1983);R. A. Stern, Europhysics News 15, 2 (1984)

(5) R. A. Stern, Rev. Sci. Instruments 56, 1006 (1985);W.P. West, D.M. Thomas, J.S. deGrassie and S.B. Zheng, Phys. Rev. Letters 58, 2758 (1987)

(6) J.F. Drake and T.T. Lee,Phys. Fluids 24, 1115 (1981)

(7) Gary R. Smith and Allan N. Kaufman, Phys. Rev. Letters 34, 1613 (1975) and Phys. Fluids 21, 2230 (1978);C.F.F. Karney and A. Bers, Phys. Rev. Letters 39, 550 (1977), and C.F.F. Karney, Phys. Fluids 21, 1584 (1978) & 22, 2188 (1979);A. Fukuyama, H. Momota, R. Itatani and T. Takizuka,Phys. Rev. Letters 38, 701 (1977)

(8) F. Skiff, F. Anderegg and M.Q. Tran, Phys. Rev. Letters 58, 1430 (1987), and F. Skiff, F. Anderegg, M.Q. Tran, P.J. Paris, T.N. Good, N. Rynn and R.A. Stern, 1987 Int'l Conf. on Plasma Physics, Kiev, Ed. A.G. Sitenko, Proc. Invited Papers 1, 441 (1987)

(9) J.M. McChesney, R. A. Stern and P.M. Bellan, Phys. Rev. Letters 59, 14 (1987)

(10) E.D. Fredrickson and P.M. Bellan,Phys. Fluids 28, 1866 (1985)

(11) J.M. McChesney,R. A. Stern and P.M. Bellan, to be published .

FIGURE CAPTIONS

FIG. (1) Schematic picture of potential field lines and calculated ion trajectories. (a) : Equipotential plot of an m = 2 mode (rotating at half the Alfven-wave frequency about an axis normal to the plane of the figure). Outermost equipotential surface corresponds to the plasma chamber wall. (b) : Calculated plot of an ion orbit starting from rest, when the potential gradient is below threshold for stochastic heating. (c) : As (b),but with potential gradient above threshold. Particle orbit is stopped on its first intersection with the plasma chamber wall.

FIG. (2) Experimentally measured evolution of the ion velocity distribution function and electron temperature during Ohmic heating in the ENCORE torus, in the presence of intense, coherent drift-Alfven waves.

FIG. (3) Comparison of ion temperature evolution with time at three radii r.Here a = 12.6 cm, minor radius.

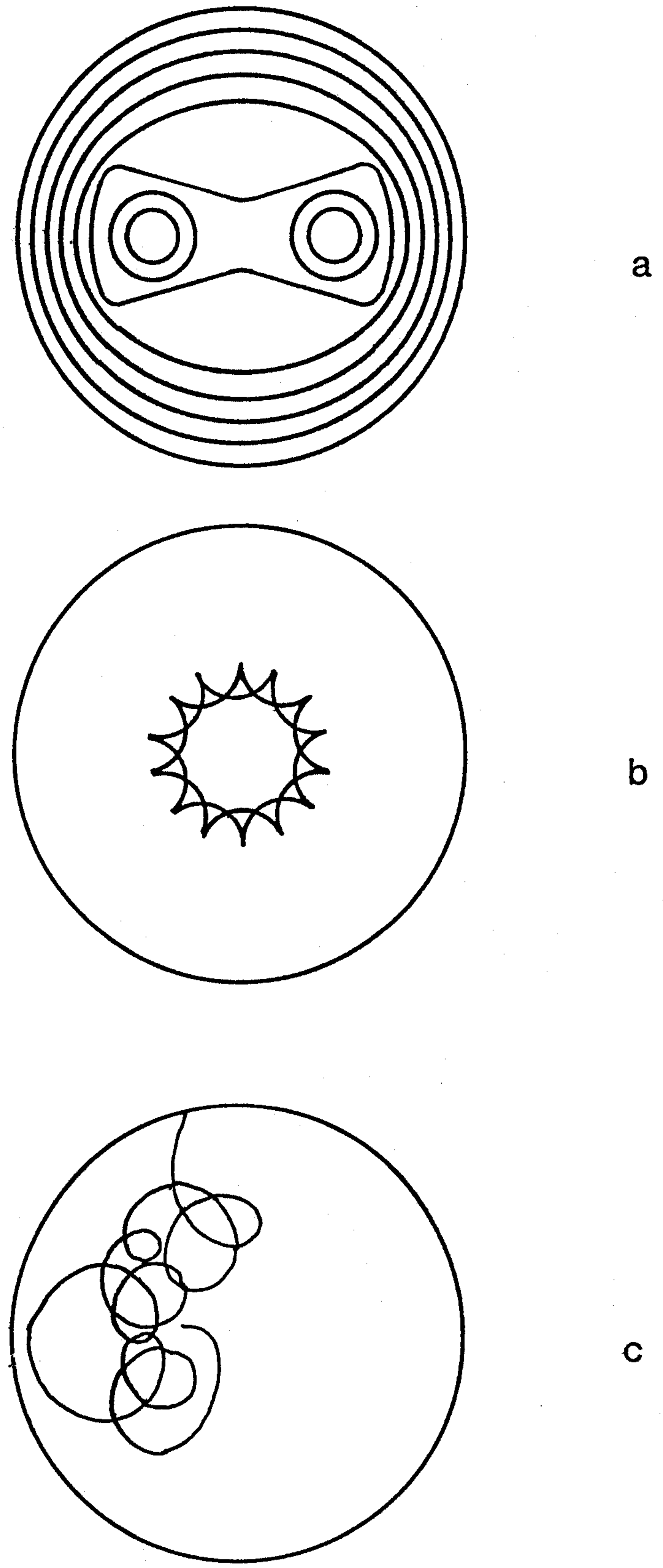

FIGURE 1

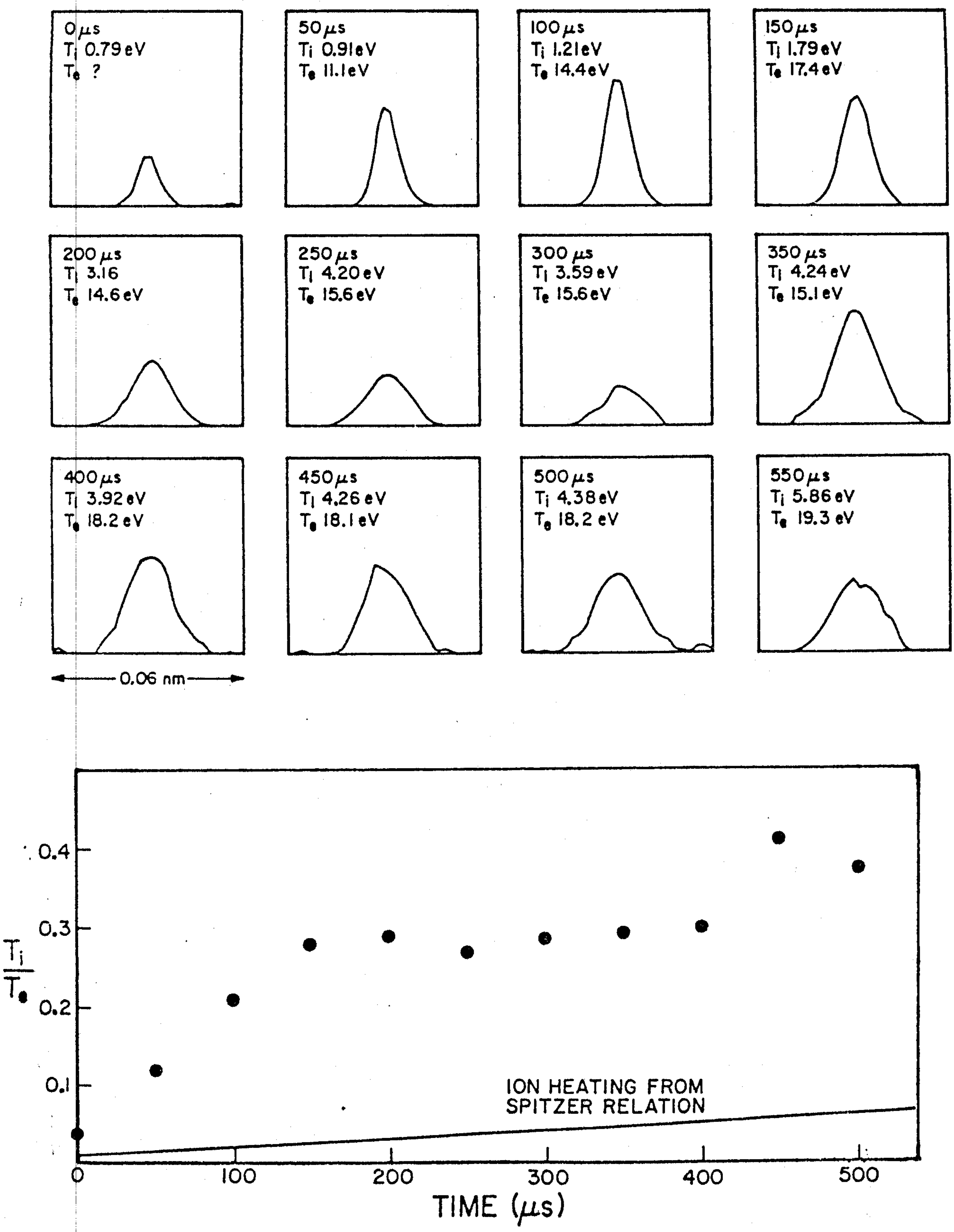
0 μs
T_i 0.79 eV
T_e ?
50 μs
T_i 0.91 eV
T_e 11.1 eV
100 μs
T_i 1.21 eV
T_e 14.4 eV
150 μs
T_i 1.79 eV
T_e 17.4 eV
200 μs
T_i 3.16
T_e 14.6 eV
250 μs
T_i 4.20 eV
T_e 15.6 eV
300 μs
T_i 3.59 eV
T_e 15.6 eV
350 μs
T_i 4.24 eV
T_e 15.1 eV
400 μs
T_i 3.92 eV
T_e 18.2 eV
450 μs
T_i 4.26 eV
T_e 18.1 eV
500 μs
T_i 4.38 eV
T_e 18.2 eV
550 μs
T_i 5.86 eV
T_e 19.3 eV
0.06 nm
T_i/T_e
0.4
0.3
0.2
0.1
ION HEATING FROM
SPITZER RELATION
0
100
200
300
400
500
TIME (μs)

FIGURE 2

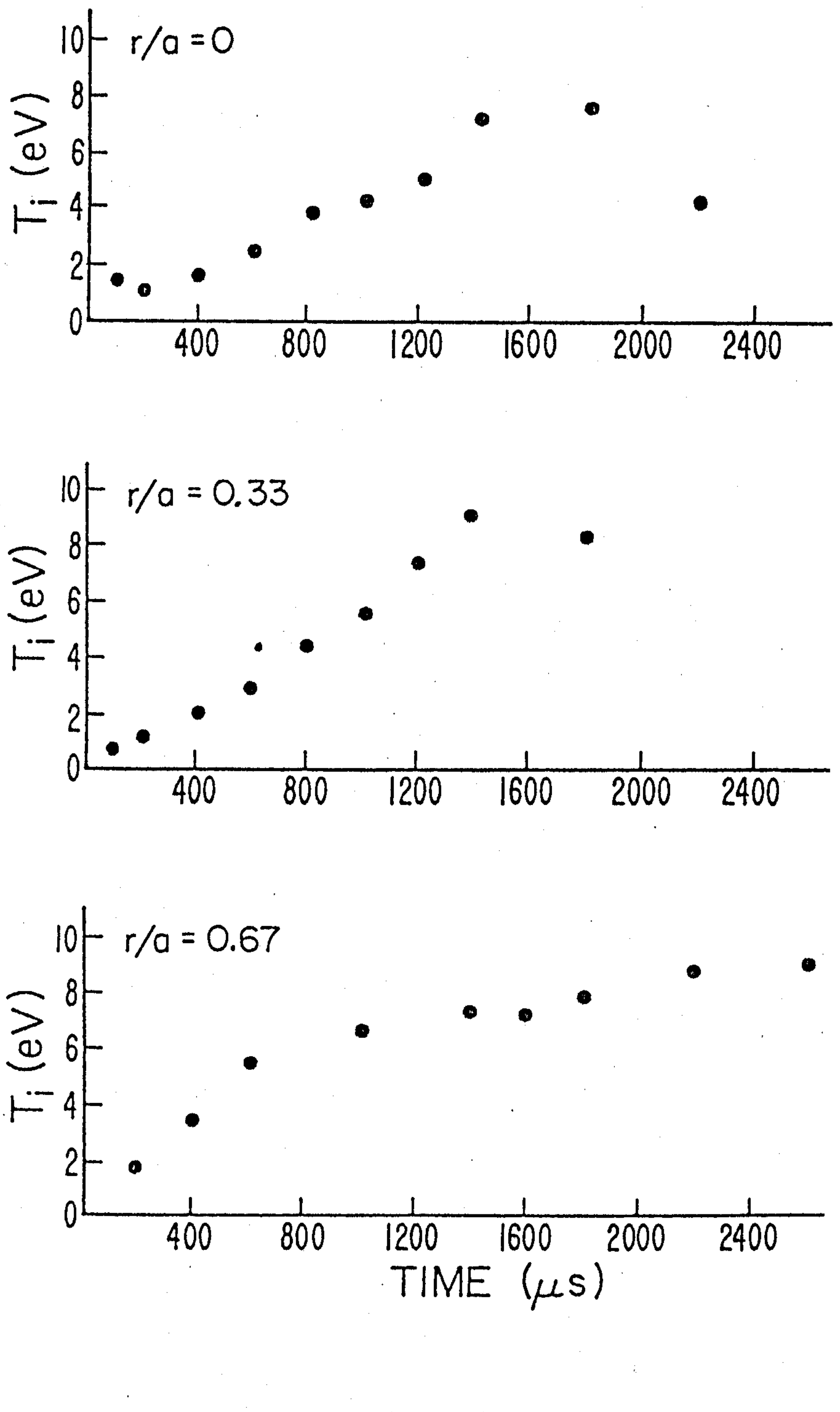

FIGURE 3