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KaufmanFest 2007: Plasma Theory, Wave Kinetics, and Nonlinear Dynamics

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Abstract. A symposium in honor of Professor Allan N. Kaufman’s 80th year was held at the University of California at Berkeley on October 5-7, 2007. The meeting celebrated Allan’s contributions to plasma physics as well as his friendship and guidance. The present paper very briefly summarizes the talks presented.

Figure 1. Allan N. Kaufman at work in Building 50 at Lawrence Berkeley National Lab in the late 1970’s shortly after the K-χ PRL paper (with John Cary) was accepted. (Photo courtesy of John Cary)
At least once in one’s professional career, it is a useful exercise to stop and look back at what one has achieved. We look at our actions in terms of our own achievements and the people we have interacted with and influenced. While the former actions might be a worthy source of pride in one’s skills, it is often the latter actions that have the most far-reaching impact.

As a teacher, mentor, and plasma physicist over the past 50 years, Allan Kaufman’s influence in theoretical plasma physics cannot be exaggerated. As a teacher at UC Berkeley, his lectures in plasma theory were masterfully crafted by his desire to uncover the most fundamental aspects of plasma physics. As a mentor, many young plasma theorists can attest to what Allan’s interest and support meant to them early in their careers. As a plasma theorist, Allan’s constant search for elegance and simplicity in his work have become a signature that is, unfortunately, not often replicated.

As a celebration of Allan’s contributions to plasma physics, as well as his friendship and guidance, a symposium in honor of Professor Allan N. Kaufman’s 80th year was held at the University of California at Berkeley on October 5-7, 2007.

1. KaufmanFest 2007
A summary of the talks presented at the symposium is given below, drawn largely from the abstracts provided by the authors. The talk titles with a ‘∗’ have associated papers that appear in these proceedings.

1.1. A. J. Brizard: Variational principles in plasma physics∗
Alain Brizard (Saint Michael’s College) began the symposium with a review talk about variational principles in plasma physics. The talk was both historical and conceptual, emphasizing the seminal role played by Allan Kaufman in either developing these ideas, or bringing them into plasma physics from other fields such as mathematics.

1.2. K. Sonnad: Analyzing charged particle beams using Lie transform perturbation theory∗
The plenary talk was followed by one by Kiran Sonnad (Center for Beam Physics, LBNL) concerning a recent application of Lie transform perturbation theory to analyze the dynamics of single charged particle motion in beams as well as for beams with space charge effects. In the first case, the analysis showed the existence of a condition that leads to improved integrability for a nonlinear focusing system. Numerical tracking of the particles showed that this condition provided an improved dynamic aperture. This analysis was then extended to study beams with space charge effects satisfying equations governed by a Vlasov-Poisson system. The latter work was used in calculating equilibrium phase space distribution functions.

1.3. B. A. Shadwick: Structure Preserving Numerical Methods for Differential Equations
Brad Shadwick (University of Nebraska) then spoke about new methods for the numerical study of differential equations. In physics one regularly encounters systems of differential equations that have a non-trivial dynamic or kinematic structure: the system may possess algebraic or differential invariants; the time advance transformation may belong to some symmetry group; the dynamics may take place on a manifold with non-trivial geometry; etc. Rarely will this structure not have a physical significance. Often this structure is responsible for important qualitative features of the system (and indeed may have purposely been built into the system). Generic numerical methods for solving initial value problems typically do not preserve any structure possessed by the system. By not preserving this structure, a numerical solution is generated which is allowed to exhibit behaviour denied to the physical system. The quintessential example of the importance of structure preserving methods is the success of symplectic integrators in accelerator physics and astronomy. A common theme of the talk was the computational efficiency gained by algorithms specifically designed to explicitly honor a system’s structure.
1.4. G. M. Webb: Variational Approach to Nonlinear, Oblique, Traveling Waves in Two-Fluid, Charge-Neutral, Electron-Proton Plasmas
Gary Webb (Institute of Geophysics and Planetary Physics, UC Riverside) then gave a talk about variational approaches to nonlinear waves in a two-fluid theory. Dual variational principles for nonlinear, oblique, traveling waves in charge-neutral, electron-proton plasmas were discussed. The equations are written as a dual spatial Hamiltonian system. The system is integrable in the case where the total transverse momentum integrals are zero in the de Hoffman-Teller frame of MHD shock theory.

1.5. C. Grebogi: Chaotic dynamics and modeling
The second plenary talk was given by Celso Grebogi (King’s College, University of Aberdeen). Scientists attempt to understand physical phenomena by constructing models. A model serves as a link between scientists and nature, and one basic goal is to develop models whose solutions accurately reflect the nature of the physical process. But a dynamical model uses simplifying assumptions and approximations. The question of whether a model accurately reflects nature is one constantly faced by scientists. Celso argues that there exist levels of mathematical difficulty, brought from the theory of dynamical systems, which can limit our ability to represent chaotic processes in nature using deterministic models.

1.6. A. Lichtenberg: Nonlinear dynamics of oscillator chains
Allen Lichtenberg (Electrical Engineering and Computer Science Department, UC Berkeley) then spoke. The Fermi-Pasta-Ulam (FPU) nonlinear oscillator chain has proved to be a seminal system for investigating problems in nonlinear dynamics. First proposed as a nonlinear system to elucidate the foundations of statistical mechanics, the initial lack of confirmation of the researchers expectations eventually led to a number of profound insights into the behavior of high-dimensional nonlinear systems. Some of these insights, both old and new, were described.

1.7. J. A. Krommes: Nonlinear theoretical tools for fusion-related microturbulence: Historical evolution, and recent applications to zonal-flow dynamics*
Fusion poses an extremely challenging, practically complex problem that does not yield readily to simple paradigms. Nevertheless, many of the theoretical tools and conceptual advances emphasized by Prof. Kaufman and others at the symposium have motivated and/or found application to the development of fusion-related plasma microturbulence theory. A brief historical commentary was given by John Krommes (PPPL, Princeton University) on some aspects of that specialty, with emphasis on the role (and limitations) of Hamiltonian/symplectic approaches, variational methods, oscillation-center theory, and nonlinear dynamics. The modern problem of zonal-flow dynamics illustrates a confluence of several of those methods, including (i) the use of Hamiltonian formalism to determine the appropriate (Casimir) invariant and wave-kinetic formalism for systems of interacting zonal flows and drift waves; and (ii) the application of nonlinear dynamics methods, especially center manifold theory, to the problem of the transition to plasma turbulence in the face of self-generated zonal flows. Finally, some unsolved problems of current interest (including intermittent chaotic statistics and the generation of coherent structures from turbulence) were mentioned, and an appeal was made for some new tools to cope with these interesting problems in nonlinear plasma physics.

1.8. C. S. Liu: Acoustic and gravity waves in dusty plasma
Chuan Liu (Physics Department, University of Maryland) gave a talk about acoustic and gravity waves in dusty plasma. A review was given of both theory and experiment concerning these topics with a particular emphasis given to wave-particle resonance.
1.9. G. J. Morales: Alfvénic phenomena triggered by resonant absorption of an O-mode pulse

George Morales (Physics and Astronomy Department, UCLA) then spoke about a simulation and modeling study of the nonlinear interaction of an electromagnetic pulse, in the O-mode polarization, with a magnetized plasma having a cross-field density gradient. For small amplitudes the pulse propagates up to the cutoff layer where an Airy pattern develops. Beyond a certain power level the ponderomotive force produced by the standing electromagnetic fields carves density cavities. The excess density piled-up on the side of the cavities causes secondary, field-aligned plasma resonances to arise. Strong electron acceleration occurs due to the short-scale of the secondary resonant fields. The fast electrons exiting the new resonant layers induce a return current system in the background plasma. This generates a packet of shear Alfvén waves of small transverse scale and increasing frequency. The results provide insight into microscopic processes associated with a recent laboratory investigation in which large amplitude Alfvén waves have been generated upon application of high-power microwaves.

1.10. R. L. Dewar: The evolution of a meme: the quest for an oscillation-center variational principle*

Bob Dewar (Department of Theoretical Physics and Plasma Research Laboratory, Australian National University) gave a historical talk on the development of a variational principle for oscillation center formulations. The Lie transform approach was originally introduced in the hope of finding a canonical transformation, continuously connected to the identity, that would reduce nonresonant wave-particle interactions to a smoothly varying ponderomotive Hamiltonian quadratic in the wave amplitude, leaving only an irreducible strong interaction between waves and particles due to wave-particle resonances. A variational principle was later proposed in the hope of making such a separation between “resonant” and “nonresonant” unique. Although never very successful in the context of weak turbulence theory, this meme moved into KAM theory and now forms part of the memetic material in a current body of work on 3D MHD equilibrium theory.

1.11. M. Porkolab: Mapping of RF Waves in Tokamak Plasmas by Phase Contrast Imaging

Miklos Porkolab (Department of Physics and Plasma Science and Fusion Center, MIT) discussed recent progress in measuring RF waves in the ion cyclotron range of frequencies in the Alcator C-Mod tokamak by means of the Phase Contrast Imaging (PCI) diagnostic. This diagnostic allows one to map the radial extent of mode converted plasma waves, including their dispersion and direction of propagation. By such techniques the MIT researchers have discovered that at the ion-ion hybrid layer in a two ion species plasma, mode conversion into kinetic ion cyclotron waves (ICW) may dominate conversion into ion Bernstein waves (IBW). This is a consequence of strong magnetic shear off the mid-plane in tokamak plasmas. The results are in good agreement with earlier theoretical calculations and more recent full wave code predictions. In principle, using a calibrated PCI diagnostic, power flow among the different waves inside the tokamak plasma could be measured, thus providing a complete test of theoretical models.

1.12. B. I. Cohen: Hamiltonian Methods, Action-Angle Variables, Perturbed Trajectory Calculation, Nonlinear Dynamics and Quasilinear Theory Under the Influence of Allan Kaufman

Bruce Cohen (LLNL) provided a retrospective review of the calculation published in G. R. Smith and B. I. Cohen, Phys. Fluids 26, 238 (1983). This calculation used Hamiltonian methods, action-angle variables, and perturbed trajectory methods to derive a quasilinear theory for ion-cyclotron fluctuations in mirror machines. The dominant decorrelation mechanism turned out to be ion-bounce resonance overlap determined by a Chirikov analysis of the nonlinear dynamics. This calculation (performed by two of Allan Kaufman’s Ph.D. students in the 1970s)
was profoundly influenced by Allan’s research and exemplified his research interests and the methods that he developed.

1.13. Bedros Afeyan: Kinetic Electrostatic Electron Nonlinear (KEEN) Waves in Vlasov Plasmas

Bedros Afeyan (Polymath Research) elucidated the properties of nonlinear non-stationary self-organized asymptotic (NNSA) states in plasmas which have no fluid nor a linear, small amplitude limit. These states are truly nonlinear constructs in phase space involving wave-particle interactions that are not strictly local in space and time. As particles give energy back to waves which trap them, and are, in turn, accelerated by those waves, the multimode (multiple harmonic) field structures that are created self-consistently, need not either trap once and for all or leave a particle untrapped forever. Instead, trapping, untrapping and retrapping oscillations occur which allow a given particle to interact intermittently with the self-consistent field (of all the particles) at different locations and with different outcomes. This leads to a partitioning of phase space into a few significant regions with different breathing trapping fractions, each of which has its own unique temporal signature. The collective action of these phase-space partitions is to maintain a long lived (undamped) self-consistent, non-stationary state in the plasma that is robust. KEEN waves are an example of NNSA structures that continuously span the frequency range somewhat below the electron plasma wave (EPW) frequency to around a tenth that frequency for all $k \lambda_D$ values up to order one, and for reasonable (finite duration) drive amplitudes, where conventional wisdom would have said no sustainable waves of this nature should have been possible. The multimode structure of NNSA states is a key feature as is their non-stationarity. These two features allow the interaction between KEEN waves, for example, and conventional weak amplitude and delicate waves such as EPWs to be very strong and nonlocal in phase space. Under the right conditions KEEN waves can siphon off energy from EPWs and thus turn off undesirable instabilities such as Raman and Two Plasmon Decay that rely on EPWs and which are of considerable worry in Inertial Fusion Energy applications and High Energy Density Laboratory Plasma Physics. The pioneering work of Kaufman and his students starting in the early 1970's was instrumental in the creation of this field of research where the kinetic properties of plasmas play such a central role, where nonlinear dynamics and statistical mechanics meet and get stirred up by coherent laser energy. This work was done in collaboration with Mathieu Charbonneau-Leford, Marine Mardirian, Vlad Savcheko, Kirk Won (Polymath Research, Pleasanton, CA) and Magdi Shoucri (IREQ, Quebec, Canada) and was supported by the DOE NNSA SSAA Grants program.

1.14. A. Bhatacharjee: Landau damping in weakly collisional plasmas and BGK waves

Amitava Bhatacharjee (University of New Hampshire) then spoke about progress he and co-workers have made to the understanding of the effects of collisions on Case-van Kampen (CvK) modes. They have shown that the CvK method for constructing solutions of the initial value problem is significantly modified and the CvK continuum is destroyed by the perturbation. This is because the collision term is a singular perturbation. Amitava spoke about more recent results where these ideas have now been extended to included nonlinear effects and BGK waves.

1.15. R. R. Lindberg: Nonlinear Langmuir Waves in Slowly-Varying Thermal Plasmas

Ryan Lindberg (Physics Department, UC Berkeley) gave a talk about the longitudinal dynamics of a resonantly driven Langmuir wave. The dynamics are analyzed in the limit that the growth of the electrostatic wave is slow compared to the bounce frequency. Using simple physical arguments, the nonlinear distribution function is shown to be nearly invariant in the canonical particle action, provided both a spatially-uniform term and higher-order spatial harmonics are included along with the fundamental in the longitudinal electric field.
1.16. C. B. Schroeder: Warm Wavebreaking of Nonlinear Laser-Driven Electron Plasma Waves

This talk was followed by one from Carl Schroeder (L’OASIS Group, LBNL). Short-pulse (sub-ps), intense (> 10^{18} W/cm^2) laser-plasma interactions are in a regime where the plasma electrons undergo relativistic motion while the plasma temperature (momentum spread) remains small. The nonequilibrium plasma is typically created by the laser through photoionization of a gas, and the laser-plasma interaction occurs on a timescale short compared to the ion motion and the collision frequency. The nonlinear Langmuir waves excited by intense lasers propagating in underdense plasma are analyzed using a warm, relativistic fluid model of a nonequilibrium, collisionless plasma. Properties of the nonlinear electron plasma waves, such as the plasma temperature evolution and nonlinear wavelength, are examined, and the maximum amplitude of the nonlinear oscillation (wavebreaking field) is derived. Electron plasma waves with relativistic phase velocities driven by intense short-pulse lasers can accelerate charged particles, and the maximum plasma wave amplitude sets a limit to the achievable accelerating gradient.

1.17. E. R. Tracy: Ray-based methods and linear mode conversion*

Gene Tracy (William and Mary) gave a plenary review talk about ray-based methods and linear mode conversion. A survey of a few of the many contributions that Allan Kaufman has made to the study of waves in plasmas and fluids was given, with an emphasis upon the use of ray-based (WKB) methods. The talk was largely historical and conceptual rather than technical. Themes included the use of geometrical pictures as a guide for asymptotic approximations, the use of symmetries and action principles as a means to derive conservation laws, and examples of the fruitful use of modern mathematical ideas to solve physics problems. Applications that were briefly touched upon include RF heating in tokamaks, equatorial waves in the Atlantic, neutrino oscillations, and magnetohelioseismology.

1.18. A. Jaun: Ray tracing for ICRF, including mode conversion and caustics

Andre Jaun (Royal Institute of Technology, Stockholm) spoke about work he has done with Allan to develop practical ray-tracing codes that are based upon many of the ideas Allan has developed. Ray optics is used to model the propagation of short electromagnetic plasma waves in toroidal geometry. The new RAYCON code evolves each ray independently in phase space, together with its amplitude, phase and focusing tensor to describe the transport of power along the ray. Particular emphasis was laid on caustics and mode conversion layers, where a linear phenomenon splits a single incoming ray into two. The complete mode conversion algorithm was described along with its use to study the two space dimensions that are relevant in a tokamak. Applications were shown using a cold plasma model to account for mode conversion at the ion-hybrid resonance in the Joint European Torus.

1.19. J. R. Cary: Nonlinear harmonic generation in EBW propagation

John Cary (Tech-X Corporation and Department of Physics and Center for Integrated Plasma Studies, University of Colorado at Boulder) then spoke about how second harmonic Electron Bernstein Waves (EBW) can be generated due to the self-interaction of the fundamental wave as it propagates into the plasma. With variation of plasma parameters, there is generically a point at which one can obtain matching of both the frequency and the wavenumber. Moreover, the energy transfer can be large, because the matching point can occur where the second harmonic has nearly zero group velocity, and so builds to large amplitude. Nonlinear Pf and full particle-in-cell (PIC) simulations show that the amount of power pulled out of the fundamental can be a significant fraction of power levels expected to be used in experiments. The resulting power can be deposited at the half sub-harmonic resonance of the plasma in a completely different spatial location.
1.20. A. E. Charman: A new variational principle for synchrotron radiation

Andrew Charman (Physics Department, UC Berkeley) gave a talk about a new variational principle for synchrotron radiation. Within the framework of a Hilbert space formalism, he derives a maximum-power variational principle applicable to classical spontaneous radiation from prescribed classical harmonic current sources. A simple derivation was provided for the case of three-dimensional fields propagating in vacuum, and specialization to the case of paraxial optics was discussed. The techniques have been developed to model undulator radiation from relativistic electron beams (for which an example involving high harmonic generation is reviewed), but are more broadly applicable to synchrotron or other radiation problems, and may generalize to certain structured media. This variational principle appears to be independent of other well-known variational principles in electrodynamics based on action or reaction.

1.21. E. Knobloch: Convectons

Edgar Knobloch (Physics Department, UC Berkeley) spoke about convectons. Recent simulations of binary fluid convection with a negative separation ratio reveal the presence of multiple numerically stable spatially localized steady states he calls “convectons”. These states consist of a finite number of convection rolls embedded in a nonconvecting background and are present at supercritical Rayleigh numbers. Below a critical Rayleigh number the convectons are replaced by relaxation oscillations in which the steady state is gradually eroded until no rolls are present (the slow phase), whereupon a new convecton regrows from small amplitude (the fast phase) and the process repeats. Both He\textsubscript{3}-He\textsubscript{4} mixtures and water-ethanol mixtures exhibit this remarkable behavior. Stability requires that the convectons are present in the regime where the conduction state is convectively unstable but absolutely stable. The multiplicity of stable convectons can be attributed to the presence of a ‘pinning’ region in parameter space, or equivalently to a process called homoclinic snaking. In the pinning region the fronts bounding the convecton are pinned to the underlying roll structure; outside it the fronts depin and allow the convecton to grow at the expense of the small amplitude state (large Rayleigh numbers) or shrink back to the small amplitude state (low Rayleigh numbers). The convectons may exist beyond the onset of absolute instability but the background state is then filled with small amplitude traveling waves. A theoretical understanding of these results was developed.

1.22. K. A. Mitchell: The Topology of Nested Tangles

Kevin Mitchell (School of Natural Sciences, UC Merced) then spoke about homoclinic and heteroclinic tangles. These are fundamental geometric objects that organize the phase space of chaotic systems, providing a framework for chaotic transport and escape processes. The topology of such tangles exhibits a striking richness in complexity and variability, which continues to be an active field of fundamental and applied research. Recently, Kevin and co-workers introduced a new topological technique, “homotopic lobe dynamics”, that provides a systematic approach to defining symbolic dynamics for tangles of arbitrary complexity by inputting information about the short time structure of a general tangle, one can predict the resulting structure forced at later times. For area-preserving maps, the topology of a homoclinic tangle is typically complicated by the presence of stable island chains, which pull the tangle into their vicinity, thereby increasing the tangle complexity. He studies this process by considering the heteroclinic tangles attached to the hyperbolic periodic orbits situated between the stable islands. This results in a system of homoclinic and heteroclinic tangles nested within each other, to which he applies the techniques of homotopic lobe dynamics, producing an enhanced symbolic description of the map. The net result is to generate symbolic dynamics that serve as a topological approximation to the map that includes the influence of stable island chains. Such symbolic descriptions are useful in the study of fractal self-similarity in chaotic scattering and escape data, the computation of escape rates, the calculation of topological entropies, etc.
1.23. P. J. Morrison: Thoughts on Brackets and Dissipation: Old and New*

Phil Morrison (UT Austin) gave a retrospective talk on the notion of the dissipative bracket. In 1981 Allan had the idea to formulate dissipation in terms of brackets with some algebraic properties, an extension of Phil's work on noncanonical Poisson brackets that he had begun with John Greene a couple of years before. Allan invited Phil to join him and this resulted in a paper on quasilinear theory. By 1984 they had gone our separate ways on this topic. Later, two papers appeared by other authors that introduced the double bracket for describing a kind of dissipation. In this talk Phil reviewed some of the above, talked about some old ideas he had in the mid-1980's that were never published, and described what happened when he started thinking about them again while preparing this talk.

1.24. S. Omohundro: Self-Improving Artificial Intelligence and the Future of the Universe: Where Physics Meets Computation

The last talk of the symposium was by Steve Ohmohundro (Self-Aware Systems). His topic concerned self-improving artificial intelligence and the connection between physics and computation. Can we predict the behavior of systems that modify themselves? Can we design them to embody our values even after many generations of self-improvement? This talk presented a framework for answering questions like these. It showed that self-improving systems converge on a specific cognitive architecture that arose out of von Neumann’s foundational work on microeconomics. In these systems there is a universal principle which governs the organization of physical and computational resources at every level. These systems exhibit four natural drives: 1) efficiency, 2) self-preservation, 3) resource acquisition, and 4) creativity. Unbridled, these drives lead to both desirable and undesirable behaviors. The efficiency drive leads to algorithm optimization, data compression, atomically precise physical structures, reversible computation, adiabatic physical action, the virtualization of the physical, and governs a system’s choice of memories, theorems, language, and logic. The self-preservation drive leads to defensive strategies such as “energy encryption” for hiding resources and promotes replication and game theoretic modeling. The resource acquisition drive leads to a variety of competitive behaviors and promotes rapid physical expansion and imperialism. The creativity drive leads to the development of new concepts, algorithms, theorems, devices, and processes. The best of these traits could usher in a new era of peace and prosperity; the worst are characteristic of human psychopaths and could bring widespread destruction. How can we ensure that this technology acts in alignment with our highest values? We have leverage both in designing the system’s initial values and in creating the social context within which they operate. But we must have great clarity in imagining the future we want to create. We need not just a logical understanding of the technology but a deep introspection into what we cherish most. With both logic and inspiration we can work toward building a technology that empowers the human spirit rather than diminishing it.

2. Summary

As this summary shows, it was a very stimulating two days of talks. The range and depth of the topics reflects the impact that Allan has had either directly or indirectly on the conference participants, many of whom have worked directly with Allan, or admired his work from afar.

The conference organizers would like to take this opportunity to thank all the speakers, and the participants who presented posters, for making this a memorable meeting.