TASK C: PARTICLE PHYSICS AND COSMOLOGY

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RESEARCH ACCOMPLISHMENTS AND PUBLICATIONS

Since January 1991

Over the past year or so the research of our group has spanned many topics at the boundary of particle physics and cosmology. The major focus has been in the general areas of inflation, cosmological phase transitions, astrophysical constraints to particle physics theories, and dark matter/structure formation as it relates to particle physics. Narrative summaries of the research of the individual group members are given below, followed by a list of our publications.

Edward W. Kolb

My work over this period covered a range of topics in particle cosmology and astrophysics.

With a group at The University of Sussex (Barrow, Copeland, and Liddle) I completed a study of baryogenesis in models of extended inflation. We discussed the possibility of generating the asymmetry through the out of equilibrium conditions at the end of extended inflation either through the production and decay of some supermassive boson or through the production and decay of black holes.

With collaborators at Carnegie Mellon (Holman and Wang) and my student at Chicago (Sharon Vadas) I completed a series of papers on models of extended inflation. We considered two types of models. The first type are models with extra dimensions, where the radius of the internal space plays the dynamical role of the Jordan-Brans-Dicke dilaton of extended inflation theories. We found that these theories were not promising for extended inflation. The second class of models considered were models where the dilaton of extended inflation models is identified with the dilaton that results from non-linearly realized scale invariance of GUT theories. We found that this was indeed a promising model for extended inflation. A generic prediction of such models is that there should be two periods of inflation. We analyzed such double inflation models in detail in a subsequent paper.

With Turner, Chakravorty (a student at Chicago), and Schramm, I continued the program of investigating the effects of massive neutrinos in cosmology. We showed that a tau neutrino with a mass in the range 0.5 to 25 MeV can have a significant effect on the outcome of primordial nucleosynthesis. This result, coupled with potential new limits from the CLEO collaboration at CESR, could have a significant impact on limits to the properties of massive neutrinos. With Turner, I also considered the astrophysical and cosmological problems of a 17 keV neutrino.

With Gupta and Holman of Carnegie Mellon and Chris Hill of the Fermilab particle theory group, I studied the statistical mechanics of phase transitions involving pseudo-Nambu-Goldstone bosons in the early Universe. With Yun Wang (at Florida) I used these results to show that domain wall production is *not* a robust prediction of models with late-time phase transitions.

With a group at the Institute for Theoretical Physics (Holman, Hsu, Kephart, Watkins, and Widrow) I studied possible limitations on the consideration of spontaneously broken global symmetries in particle physics and cosmology. We showed that due to gravitational effects, global symmetries with either 1) a spontaneously broken scale close to the Planck scale, or 2) with a scale for explicit breaking of the global symmetry much less than the spontaneous scale, may not be self consistent. Examples of such models are global texture, invisible axions, majorons, and familons.

With Rick Watkins of Chicago and Marcelo Gleiser of Dartmouth, I considered the dynamics of very weakly first-order phase transitions in the early Universe. These may be very important because it is very likely that the electroweak transition is weakly first order, and models of electroweak baryogenesis depend upon the details of the electroweak transition.

Michael S. Turner

My research has focussed on the topics of first-order phase transitions, inflation, astrophysical/cosmological constraints, and dark matter.

With Erick Weinberg and Lawrence Widrow I studied the kinematics of bubble nucleation in first-order phase transitions. We identified measures of progress of a phase transition, which be used to determine whether or not a phase transition leaves "unacceptable cosmological scars," and derived general constraints that the nucleation rate must satisfy in a successful first-order transition as well as the distribution of bubble sizes. Our work is particularly applicable to models of first-order inflation and to the calculation of gravitational radiation from vacuum bubble collisions.

With Kosowsky and Watkins I studied the production of gravitational radiation from bubble collisions in inflationary (and other) first-order phase transitions. The gravity-wave background from first-order inflation is a unique signature that may be detectable in the LIGO's under development. I also studied the "relics" of the pre-inflationary Universe that could be with us today, including a dipole temperature anisotropy which provides a very unconventional explanation for the large-scale velocity flows that have been observed by the Seven Samurai and others.

With various collaborators I addressed the astrophysical and cosmological constraints that apply to a 17 keV neutrino (motivated by the continued evidence for such a neutrino massive eigenstate). These constraints severely restrict the properties of such a particle if it exists. In particular, I studied the constraints that can be derived from SN 1987A. They all but preclude the possibility of a 17 keV Dirac neutrino and rule out essentially all decay modes that involve electron and tau neutrinos.

Finally, I continue to be actively involved in a collaboration (led by Karl van Bibber and Pierre Sikivie) that seeks to build a "Sikivie-type" axion detector to detect relic axions, and definitively test the hypothesis that the dark matter is comprised of relic axions in the mass range 10^{-6} eV to 10^{-4} eV.

Richard Watkins

My recent research has focused on cosmological phase transitions, including their implications for large-scale structure and their possible observational signatures.

Cosmological phase transitions are usually associated with the very early Universe. For example, the electroweak phase transition, where $SU(2)_L \otimes U(1)_Y$ was spontaneously broken down to $U(1)_{EM}$, probably took place when the Universe was only $\sim 10^{-11}$ sec old. With Josh Frieman and Chris Hill, I have studied a class of particle physics models in which a second-order phase transition occurs relatively late, after the decoupling of matter and radiation. A key ingredient in these models is an ultra-light pseudo-Nambu-Goldstone boson similar to the axion, whose small mass arises in a natural way and whose Compton wavelength can be cosmological in size ($\sim$ Mpc). We have analyzed the dynamics of the phase transition in these models, and find that the very light bosons can provide a significant fraction of the critical density, making them a candidate for the dark matter. In related work, Josh Frieman and I have found that these phase transitions can also generate a potentially interesting spectrum of density fluctuations on large scales, while inducing relatively small fluctuations in the microwave background. These scenarios provide an important alternative to the conventional picture of gravitational growth of density perturbations, which is beginning to be challenged by improved measurements of the microwave background radiation.

Recently, there has been a revival of interest in theories where inflation is terminated in a first-order phase transition. Reheating in these models is much more complex than in "slow-rollover" inflation due to the inhomogeneities induced in both the field and the metric during the transition. With Larry Widrow, I have studied the processes involved in reheating in some detail, including the conversion of vacuum energy into bubble-wall kinetic energy and both quantum and classical particle production in bubble-wall collisions. We have found these processes to be quite efficient, an important result for determining the reheat temperature in these scenarios. We have also found that very massive particles can be produced in relativistic wall collisions, which may have implications for baryogenesis. Bubble wall collisions also produce a background of gravitational radiation, which may provide a detectable signature for these scenarios. As a first step in calculating this background, Arthur Kosowsky, Michael Turner, and I have calculated the gravitational radiation from two-bubble collisions. We have found that the result depends only on the gross features of the collision on scales of the bubbles themselves. This allows us to derive a number of scaling relations which we use to estimate the amount of gravitational radiation emitted in realistic phase transitions. In other work, we have applied these results to estimate the gravitational radiation produced in other strongly first-order phase transitions in the early Universe.

Until gravity is successfully incorporated into quantum field theory, the models we construct must be thought of as being effective field theories with a cutoff of order the

Planck scale. This implies that the underlying fundamental theory should include higher dimensional operators which are suppressed by appropriate powers of the Planck mass. These operators could in principle violate global symmetries, since there is some evidence that gravity does not respect global symmetries. With collaborators, I have explored some of the consequences of these higher dimensional operators. In particular, we find that both the axion model for the solution of the strong CP problem and the cosmic texture model of large-scale structure require operators that break global symmetries to be suppressed to very high order. We have constructed an axion model where this suppression can be achieved, but we find it unlikely that the texture model can survive unless gravity respects global symmetry.

Andrew Jaffe

During 1991, I completed a paper with Josh Frieman on the cosmological and astrophysical constraints to pseudo-Nambu-Goldstone bosons (PNGBs). These particles, whose best-known example is the axion, arise when a spontaneously broken global symmetry is itself explicitly and weakly broken, giving a small mass to the would-be Nambu-Goldstone boson. PNGBs are well-described by only two mass parameters, the scales of these two symmetry breaking transitions, which roughly describe their (small) mass and (weak) couplings. (For the axion, the explicit breaking scale is $\Lambda_{\text{QCD}} \approx 200$ MeV, and the spontaneous breaking scale has been limited to $f_a \approx 10^{10} - 10^{13}$ GeV.) Thus, their physics can be described in a relatively model-independent way. Because of the large possible ranges of these parameters, PNGBs can arise in a large variety of astrophysical and cosmological situations, which in turn allows us to put limits on their properties.

In the early Universe, PNGBs can be produced in several ways. As the Universe cools below the symmetry-breaking scales, the particles gain a mass as the potential develops a minimum, and they contribute more strongly to the density of the Universe. Furthermore, topological defects such as domain walls or cosmic strings may be produced in these transitions, which may in turn decay into PNGBs. Finally, they may be produced in thermal scattering processes in the hot and dense early Universe. In order not to violate current observations of the mass and density of the Universe today, we can constrain the physics of these production mechanisms, and thus constrain the properties of the PNGBs.

The PNGB can crop up in several astrophysical contexts, as well. In general, it is expected to be weakly-coupled to normal matter; if PNGBs are produced in the interior of stars, they can easily stream out and cause an efficient cooling of the stellar core. The strongest constraints from this technique occur from its use in the study of red giant evolution and on the physics of the neutrino pulse from supernova SN1987A.

Arthur Kosowsky

My research during the past year has focused on the production of gravitational radiation by cosmological first-order phase transitions. In a strongly first-order phase transition,

bubbles of the new phase are nucleated via quantum tunnelling; these bubbles then expand and collide, eventually filling all of space with the new “true-vacuum” phase. As the vacuum bubbles expand, they store the liberated energy of the old “false-vacuum” in their walls as kinetic and field-gradient energy. The collision between bubbles is thus a violent event with high energy densities, making bubble collisions a potentially potent source of gravitational radiation.

Our investigations confirm that this is indeed the case. In collaboration with Michael Turner and Rick Watkins, I evolved a pair of vacuum bubbles numerically and calculated the resulting gravitational radiation emitted. Our results confirmed numerically several scalings earlier conjectured by Turner and Wilczek; specifically that the total energy radiated in gravity waves scales as the fifth power of the bubble separation and the square of the vacuum energy. We also demonstrated that the spectrum of radiation does not depend on the details of the potential, but only on the false-vacuum energy and the duration of the phase transition. We have applied our results to various cosmological phase transitions to estimate the gravitational-wave background expected.

I am now working on a thin-wall approximation of the bubble dynamics, which allows the calculation of the radiation emitted by the collision of numerous bubbles (of order 100). We have shown that this approximation accurately reproduces our results for two bubbles (where we evolved the bubbles as scalar-field configurations); we are currently running numerical simulations of phase transitions involving several hundred bubbles, nucleated according to an exponential nucleation rate (as would apply to a typical strongly first-order transition).

Alessandro Massarotti

Non-standard approaches to large-scale structure formation. The recent discovery of a strong spatial correlation in the galaxy distribution even at scales as large as $30h^{-1}$ Mpc, and of an intergalactic medium probably already ionized at $z \sim 5$ has prompted new interest in models of galaxy formation alternative to the standard cold dark matter (CDM) scenario. As is well known, the simplest version of the CDM model finds it increasingly difficult to generate the very large galaxy clustering scales we observe.

Most of my research in the year 1991 has been spent investigating the dynamics of domain walls, generated through “late” cosmological phase transitions. My aim was to study the cosmological consequences of a non-gravitational coupling between walls and dark matter. The resulting friction can be effective in keeping the walls at very non-relativistic speeds, and give rise to network scale of order $10 - 100h^{-1}$ Mpc, much smaller than the horizon (one would expect a network scale of the order of the horizon for uncoupled walls). As a byproduct of this mechanism, matter wakes (whose thickness is of the order of $1 - 10h^{-1}$ Mpc) are generated in front of the moving walls. The gravitational collapse of the wakes could prompt an early epoch (at $z > 5$) of galaxy formation, earlier than what predicted by the standard Cold Dark Matter model. Additionally, since one would expect

the gravitational collapse to arise mainly at the proximity of the domain wall surface, the position of the protogalaxies generated in such a model should be strongly correlated even at early times.

I have addressed the question of the onset of the network scale in some detail, for models involving both hot and cold dark matter, and for different wall-particle scattering parameters. In particular, I found that domain walls could begin their evolution virtually “uncoupled” to matter and rapidly evolve to a “freeze-in” only at a later stage. At the initial stage, the network scale would evolve as fast as the horizon, while at the later stages the comoving network scale would converge to a constant value. Network scales of order $30h^{-1}$ Mpc can be naturally obtained.

The problem of writing down a Lagrangian that could give rise to late phase transitions is still largely in development. However, in collaboration with Chakravorty, I studied the wall-particle scattering, in the context of my cosmological model.

Sharon Vadas

Most of the work I have completed in the past year has been in the field of extended inflation. I have mainly concentrated on extended inflationary model building as well as the evolution of super-horizon-sized voids from extended inflation. We found extended inflation solutions in several different models (higher dimensional, scale-invariant, as well as variants of the original Brans-Dicke model), and calculated the resulting spectrum of density fluctuations. Unlike old inflationary models, extended inflation produces non-scale-invariant density perturbations due to the introduction of the Brans-Dicke field which might help enhance large-scale structure. We also proposed as a model for extended inflation the dilaton of hidden scale-invariance where the dilaton plays the role of the Brans-Dicke field. This leads to extended inflation at GUT scales with a non scale-invariant spectrum. In addition, this model also predicts that due to the small mass of the pseudo-Nambu-Goldstone boson, for a certain broad range of initial conditions, a second period of slow-roll inflation will follow, which could smooth out the density perturbations produced from the bubbly reheating following extended inflation. However, a fair amount of fine-tuning is involved to have the transitional scale at cosmologically interesting sizes.

I have also spent a good part of the year working on the evolution of general relativistic large-scale voids which could have arisen in extended inflation from the early nucleation of bubbles. This is done by numerically evolving void-like density distributions using the spherically symmetric general relativistic fluid equations in the radiation and matter dominated periods. Various finite-difference methods have been employed, with the MacCormack predictor-corrector scheme being settled upon. This is, to my knowledge, the first careful examination of the evolution of horizon-sized voids. For a broad range of initial velocity profiles, I find that shocks are formed inside shells during matter domination. This phenomenon is known to occur in the Newtonian limit. In the zero-pressure Tolman-Bondi models, shell-crossing, rather than shock formation, occurs. I have also found that

voids evolve straightforwardly during radiation-domination. At present, fluids with real and artificial viscosity are being examined for their damping effects on the formation of structure, especially in the matter-dominated period. (This work will comprise my Ph.D. thesis next fall.)

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Nuclear Physics B **358**, 447 (1991).
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Physical Review Letters **67**, 533 (1991).
10. The Tilted Universe (and other remnants of the pre-inflationary Universe)
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11. Astrophysics and Cosmology Confront the 17 keV Neutrino

- E.W. Kolb and Michael S. Turner
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 13. Dirac Neutrinos and SN 1987A
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