TASK C: PARTICLE PHYSICS AND COSMOLOGY

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II. RESEARCH ACCOMPLISHMENTS AND PUBLICATIONS

Inflationary Cosmology

Inflation has revolutionized the way we think about the earliest history of the Universe. It provides a means for understanding the origin of the smoothness and flatness of the Universe, the origin of the seed inhomogeneities for structure formation, and a resolution to the monopole problem.^{1,2} In the past decade our group has made important contributions to the development of the inflationary paradigm: elucidating the mechanism for reheating in new inflation³ and for the origin of curvature⁴ and isocurvature⁵ perturbations. In addition, we have shown that inflation proceeds from very general initial conditions,⁶ we have proposed several models for inflation,⁷ including double inflation,⁸ and have addressed the production of gravitational waves,⁹ of large-scale primeval magnetic fields,¹⁰ and of massless particles.¹¹

Last year La and Steinhardt proposed an extremely interesting new variant of inflation, called extended inflation.¹² Extended inflation allows inflation to be once again tied to a first-order, SSB phase transition. Extended inflation closely resembles Guth's original model of inflation, with one important difference: the bubble nucleation rate per Hubble volume per Hubble time (Γ/H^4) increases with time rather than remaining constant (Γ is the bubble nucleation rate and H is the Hubble constant). This means that at early times, the nucleation rate can be small so that the Universe (or a small part of it) can become trapped in the false vacuum and inflates, and that at late times it can be large so that bubbles of true vacuum nucleate rapidly enough to complete the phase transition and reheat the Universe. In the original La-Steinhardt model, based upon the Jordan-Brans-Dicke theory of gravity, the variation of Γ/H^4 came about because H slowly decreased during inflation (due to the evolution of the "gravitational constant"). While the original model is inconsistent with precision solar-system tests of gravity (sufficiently rapid bubble nucleation requires the Brans-Dicke parameter ω to be less than about 20,¹³ while solar system tests require it to be greater than about 500), it provides an interesting toy model, the key new element being the variation of Γ/H^4 .

We have analyzed the origin of density perturbations in extended inflation models, and showed that by a simple conformal transformation to the Einstein frame (where gravity is that of general relativity, but the couplings of scalar fields have been modified) extended inflation closely resembles new inflation and the formalism developed to analyze density perturbations in new inflation⁴ is directly applicable.¹⁴ Moreover, the result is very encouraging, the amplitude of density perturbations is related to the ratio of the phase transition energy scale to the Planck scale to a power close to two, and for a phase transition energy scale of about 10^{14} GeV density perturbations of the correct size arise. (In contrast, in new inflation, achieving density perturbations of an acceptable size required the inflaton field to be very, very weakly coupled, raising the issue of "fine tuning.") We also showed that isocurvature fluctuations can arise just as they do in new inflation.

We have studied a number of other issues associated with extended inflation. Because the phase transition is completed by bubble nucleation, bubble collisions can have important effects. They lead to a new source of relic gravitational waves that are likely to be much more important (and more accessible to detection) than those produced by quantum fluctuations.¹⁵ Bubble collisions can also lead to the production of primordial black holes,¹⁶ whose evaporations can produce the baryon asymmetry of the Universe and are an additional new source of gravitational waves, and topological defects, such as monopoles and cosmic string.¹⁷ We have also studied the issue of baryogenesis, which can proceed very differently in extended inflation.¹⁸

The origin La-Steinhardt model¹ points the way to a new and potentially very promising model of inflation, the key feature of which is the variation of the bubble nucleation rate per Hubble volume per Hubble time. It is also appealing because a generic prediction of superstring (and higher dimensional) theories is the existence of a Brans-Dicke-like field (or dilaton). However, as noted earlier, the La-Steinhardt model requires modification. We have considered the possibility that Brans-Dicke field becomes massive,¹⁴ which would remedy the conflict with solar system tests, or that extended inflation derives from a higher dimensional theory.¹⁹

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Dark-matter Detection

Most of the matter in the Universe is dark, i.e., does not give off any detectable radiation.¹ Primordial nucleosynthesis provides a stringent constraint to the fraction of critical density contributed by baryons: $\Omega_B \lesssim 0.1$.² If Ω is greater than about 0.1 then the dark matter cannot be baryonic. Moreover, inflation “predicts” that the Universe is flat ($\Omega = 1$) and consideration of structure formation also strongly argues for $\Omega = 1$. Thus, a line of sound reasoning leads one to consider seriously the possible existence of large amounts of nonbaryonic matter in the form of relic elementary particles. (The possibility that baryon number inhomogeneities produced by a strongly first-order quark/hadron transition would modify nucleosynthesis sufficiently to permit $\Omega_B = 1.0$,³ no longer seems viable.⁴)

At present the three most promising dark matter candidates are the axion, the lightest supersymmetric partner (usually the neutralino), or a light neutrino species. (For purposes of structure formation the first candidates behave like cold dark matter, while the neutrino behaves like hot dark matter.⁵ At present, cold dark matter and inflation-produced curvature perturbations provides a very successful paradigm for structure formation.) We have been very active in studying the possibility that the dark matter in the Universe is either relic axions or neutralinos. We will discuss our work on axions in the following Section.

In order to calculate the relic abundance⁵ of neutralinos, the annihilation of neutralinos in the halo, earth, or sun, or the interactions of relic neutralinos with ordinary matter, one needs the annihilation cross section of two neutralinos into anything. For a light neu-

tralino, mass less than m_W , the final states include fermion–antifermion pairs; for a heavy neutralino the final states include in addition WW , ZZ , HW , HZ . We have calculated the total annihilation cross section for the most general neutralino (a Higgsino/gaugino mixture)—light⁶ or heavy⁷—in the minimal supersymmetric extension of the standard model.⁸ Over most of parameter space (μ , M , $\tan\beta$, m_{top} , and the squark and slepton masses) relic neutralinos contribute at least 1% of critical density, and in many regions of parameter space they contribute critical density, making the neutralino a very attractive dark matter candidate. The lack of any evidence of supersymmetry in recent hadron and lepton collider experiments has generally pushed up the scale for supersymmetry and the mass of the neutralino. We have shown that the maximum cosmologically acceptable mass for a neutralino is 3.2 TeV (a more massive neutralino would contribute too much mass density today; coincidentally, a neutralino heavier than this would not be attractive in the context of “low-energy” supersymmetry).⁷ (Along these same lines we have shown that there is a very general upper bound to the mass of a point-like particle relic based upon unitarity: to avoid “overclosing” the Universe, any stable, point-like species must be less massive than about 340 TeV.⁹) The cross sections that we have calculated are very important theoretical input for the direct and indirect detection of neutralino dark matter.

We have also explored two interesting and very distinctive signatures of dark matter annihilation in the galactic halo: mono-energetic positrons¹⁰ and mono-energetic photons.¹¹ While the rates for both of these cosmic-ray signatures are likely to be too small to make them observable, they are worthy of note: If seen, they are a “smokin’ gun” for particle dark matter in the halo.

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Axions, Astrophysics, and Cosmology

Peccei-Quinn (PQ) symmetry and its axion is still the most attractive solution to the strong- CP problem,¹ and therefore a most compelling and very minimal extension of the standard model. Axion models have one basic free parameter: the axion mass (or equivalently the PQ-symmetry breaking scale, $m_a \simeq 0.6 \text{ eV} \cdot 10^7 \text{ GeV} / (f_{PQ}/N)$), which a priori could have a value anywhere between about 10^{-11} eV and 1 MeV . Laboratory experiments (in particular the unobserved decays $K^+ \rightarrow \pi^+ + a$, $\Psi/J \rightarrow \gamma + a$, and $\Upsilon \rightarrow \gamma + a$) have ruled out an axion more massive than a few keV. The rest—and bulk—of the axion parameter space has been explored by use of the Heavenly Laboratory. At present two “windows” remain:² 10^{-6} eV to about 10^{-3} eV and 3 eV to 8 eV (for the hadronic axion only).

The pioneering papers of Sato³ and of Kolb et al.⁴ pointed out that a light, weakly coupled particle like the axion could have a profound effect on the evolution of stars. Because axions interact so weakly, they provide an additional, very efficient means of transporting energy away from a star, and can thereby accelerate stellar evolution. (For a pedagogical discussion of the effect of axion emission on stars, see Frieman, Dimopoulos, and Turner.⁵) Very stringent limits to the axion mass based on the evolution of various types of stars—from the sun to red giants to white dwarfs to neutron stars—have been derived.² Taken together, they preclude an axion more massive than about 10^{-3} eV , except for a small window around 3 eV to 8 eV (for hadronic axions only). This is an impressive improvement of almost seven orders of magnitude on laboratory experiment.

Two of the most stringent limits, that based upon the evolution of red giants and that based upon the cooling of SN 1987A, involved the work of our group.^{6,7} The constraint based upon SN 1987A is perhaps the most direct astrophysical limit, as the 19 anti-electron neutrino events provide a detailed record of the entire initial cooling phase of that newly born neutron star. The duration of the observed neutrino bursts—about 6 sec for IMB and about 12 sec for KII—exclude an axion in the mass range of about 10^{-3} eV to 3 eV . (In particular, we have shown that the response of the KII and IMB detectors to the neutrino flux from a hot neutron star with axion cooling would lead to a burst duration of significantly less than this for an axion in this mass range.⁸)

It may seem surprising that the SN 1987A data do not exclude an axion heavier than

about 3 eV, as the coupling strength of an axion increases with its mass. The reason is simple and remarkable: the core of the newly born neutron star is opaque to axions more massive than about 10^{-2} eV, so that an axion heavier than this is radiated from an “axion sphere.” An axion more massive than about 3 eV interacts so strongly within the core that their effect on the cooling of the core is not significant. (In treating the so-called trapping regime, we computed the axion opacity of nuclear matter(!), and incorporated full axion transport into detailed models of the initial cooling of the newly born neutron star.⁸)

Axions arise as cosmological relics through three distinct mechanisms: (1) As thermal relics—axions more massive than about 10^{-3} eV come into thermal equilibrium through pion-axion conversion,⁹ $\pi + N \rightarrow a + N$ (N is a nucleon), and have a relic abundance comparable to that of a light neutrino species, about 30 cm^{-3} . (2) The misalignment process—at high temperatures ($\gg \Lambda_{\text{QCD}}$) the free energy of the QCD vacuum becomes independent of the axion angle, and the value of the axion angle through the Universe will, in general, be misaligned with the minimum of the free energy at low temperatures. When the Universe cools to temperatures of order a GeV, the free energy develops a minimum at the CP -conserving value of the axion angle due to instanton effects, and throughout space the axion field will be misaligned with this minimum, and hence will begin to oscillate. These oscillations correspond to a condensate of very low-momentum axions.¹⁰ (3) Axionic string decay—if the Universe did not inflate or inflated before PQ-symmetry breaking, then the breaking of PQ symmetry also leads to the production of axionic strings, which ultimately decay and produce large numbers of axions—comparable to or greater than the number produced by the misalignment mechanism (the precise number is still a matter of intense debate).¹¹

Thermal axions cannot close the Universe. However, the decays of multi-eV thermal axions that reside in rich clusters offer a means of detecting such axions. We applied for telescope time at Kitt Peak to carry out such a search, received the telescope time, and carried out the observations last May. While the data analysis is not quite complete, we have ruled out an axion more massive than 5 eV; with the data in hand we will be able to search for an axion as light as about 3.1 eV.¹² In the end we should be able to explore the entire multi-eV window.

The coherently produced axions can close the Universe, for an axion mass in the range of about 10^{-6} eV to about 10^{-4} eV (and perhaps as high as 10^{-3} eV if axionic string decay is very prolific). Three first-generation “Sikivie detectors” have been built to search for cosmic axions in our halo in this mass range.¹³ While these first generation detectors did not have sufficient sensitivity to detect halo axions (if the axion has the canonical coupling to two photons), they did establish the feasibility of the concept. A second generation detector with the required sensitivity to explore the mass range from about 10^{-6} eV to 10^{-4} eV has been proposed,¹⁴ and we are part of this collaboration.

We have addressed a number of issues regarding the relic abundance of cosmic axions in the 10^{-6} eV to 10^{-4} eV mass range. We carried out the most detailed calculation of

the relic abundance due to the misalignment mechanism,¹⁵ studied various theoretical uncertainties including entropy production and the effects of the QCD phase transition,¹⁶ and recently discussed the additional cosmological constraints that apply if the Universe inflated after PQ-symmetry breaking. We have also studied the periodic signatures—due to the earth's orbital and rotational motions—that arise in the detection of relic axions and that can be used to confirm the existence of axions in the halo and to probe the distribution of material in the halo.¹⁷

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Topological Defects

Perhaps the most interesting consequence of spontaneously broken gauge theories is the fact that at high temperatures broken symmetries are stored.[†] Because of the high temperatures that existed during the earliest history of the Universe, there should be several—if not many—symmetry-breaking phase transitions, e.g., chiral symmetry breaking, electroweak symmetry breaking, and GUT symmetry breaking (?). The most interesting cosmological consequence of such phase transitions is the possibility that these transitions proceed “imperfectly” and that topological (and nontopological) defects are left behind as relics. There are a variety of topological defects possible.¹ Suppose that the group $\mathcal{G}$ is broken down to the smaller group $\mathcal{H}$; magnetic monopole solutions exist if $\Pi_2(\mathcal{M}) \neq \mathcal{I}$; (cosmic) string solutions exist if $\Pi_1(\mathcal{M}) \neq \mathcal{I}$; and domain wall solutions exist if $\Pi_0(\mathcal{M}) \neq \mathcal{I}$ (where $\mathcal{M} = \mathcal{G}/\mathcal{H}$ is the manifold of vacuum states). (If $\mathcal{G}$ is a global symmetry, then textures are also possible, provided that $\Pi_3(\mathcal{M}) \neq \mathcal{I}$; see, e.g., Ref. 2.) The existence of particle horizons in the standard cosmology preclude correlations on scales larger than about ct , and so if a topological soliton solution exists, of order one per horizon volume should be produced during the symmetry-breaking phase transition, through the so-called Kibble mechanism.³

Through the years our group has been very active in exploring the astrophysical and cosmological consequences of topological defects produced in the early Universe. We derived very stringent constraints to the flux of relic magnetic monopoles based upon the survival of astrophysical magnetic fields,⁴ and monopole catalysis of nucleon decay in various astrophysical objects.⁵ By the use of variational solutions, we have studied the in

[†] Of course, there are examples of the converse, where the full symmetry is restored at low temperatures.

detail the properties of cosmic strings, both ordinary and superconducting.⁶ We have also studied the important issue of whether or not superconducting cosmic string solutions arise in realistic models,⁷ and the phase transition that occurs when the critical current is exceeded.⁸ We have explored the possibility that cosmic string loops could seed structure formation in the Universe, including the first numerical simulation structure formation seeded by cosmic string loops.⁹

Two of the most recent Ph.D. theses produced by students in our group have involved numerical simulations of phase transitions. Hodges carried out real-time simulations of scalar field theories that support domain wall and cosmic string solutions by numerically solving the classical field equations with an appropriate noise term to simulate the effects of the thermal bath. His work was the first real-time simulation of a phase transition. While none of the results were unexpected, Hodges' work put the standard lore for the production of topological defects (the Kibble mechanism) on a very firm basis.¹⁰

Kawano's thesis dealt with the formation and early evolution of a domain wall network. Rather than solving the classical field equations, he used the thin-wall approximation, deriving the equations of motion for the wall from a generalized Nambu action. His work indicates that shortly after the domain wall network forms, it consists of a single wall that extends across the horizon, with very few vacuum bubbles (closed regions of one vacuum state surrounded by the other vacuum state). Moreover, he found that because of the finite velocity of the walls the energy density in walls evolves as $R^{-4/3}$ rather than R^{-1} , which would pertain if the walls were motionless (R = the cosmic scale factor).¹¹

Many classical field theories admit non-topological soliton solutions. They were first discussed a number of years ago by Rosen, and by Friedberg, Lee, and Sirlin.¹¹ They have more recently been studied (and called Q-balls) by Coleman.¹³ Unlike topological solitons such as magnetic monopoles, cosmic strings, and domain walls that arise in spontaneously broken gauge theories with nontrivial vacuum topology, non-topological solitons (NTS's) exist as the result of a conserved Noether charge carried by some field confined to a finite region of space (and can even arise in the electroweak model¹⁴). NTS's have also recently been considered in theories with cosmic neutrino balls,¹⁵ quark nuggets,¹⁶ and soliton stars.¹⁷ We have studied many aspects of NTS's, including their formation and subsequent evolution.¹⁸

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Astrophysical/Cosmological Constraints to Particle Properties

Over the past decade members of our group have used various apparatus in the Heavenly Laboratory—including SN 1987A, primordial nucleosynthesis, the galactic magnetic field, the sun, red giants, and neutron stars—to explore regions of particle-property parameter space that are beyond the reach of terrestrial laboratories to place very stringent limits to the properties of neutrinos (mass, lifetime, magnetic moment, chemical potential, number of flavors, and secret interactions), superheavy magnetic monopoles (relic abundance), neutralinos, and axions.¹ The most well known of these limits, the limit to the number of flavors of light (mass less than about 1 MeV) neutrino flavors: $N_\nu \leq 4$,² has recently been confirmed by experiments at both SLC and LEP; the current determination of the number of neutrino flavors, based upon Z^0 boson production and decay is $N_\nu = 3.0 \pm 0.1$,³ which is a striking confirmation of this cosmological constraint and further verification of our excellent understanding of the Universe at 1 sec after the bang.

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Other Activities

In addition to the research activities discussed above, members of our group have been involved in many other smaller projects. For example, we analyzed and discussed the nonadiabatic MSW solution to the solar neutrino problem.¹ Taken at face value, the SAGE nonobservation of low-energy solar neutrinos² favors this solution with its distinction signature of very few low-energy solar neutrinos. Since the SAGE results are consistent with the standard solar model at the 2σ level, it is prudent to wait for more definitive results, which should be forthcoming soon from both the SAGE and GALLEX experiments.

Motivated by the theoretical speculation of Hill and Ross³ that there could be other, even lighter pseudo-Nambu-Goldstone bosons in addition to the axion, we have considered the possible cosmological effects, including a late-time phase transition that could seed the formation of large-scale structure,⁴ or temporal oscillations in some of the fundamental constants,⁵ which would lead to apparent spatial periodicity in the Universe (similar to that recently reported by Broadhurst et al.⁶). Needless to say, both of these possibilities are highly speculative!

There is a growing consensus that nonperturbative effects associated with field configurations known as sphalerons lead to rapid violation of fermion number ($B + L$) in the standard electroweak theory at temperatures around 200 GeV to 300 GeV, and probably at all temperatures well above the phase transition.⁷ This has important implications for the origin of the baryon asymmetry of the Universe: Either it must be produced at temperatures below about 200 GeV or the baryon asymmetry produced must have associated with it a nonzero value of $B - L$. We have taken the first steps towards a detailed re-examination of baryogenesis, and have shown that if the latter is true, then there are severe constraints to neutrino masses (if they are generated by the see-saw mechanism).⁸

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