Statement of Research Interests

by Juan F. Lara, Center for Relativity, UT-Austin

In 1994 I began my research in Big Bang Nucleosynthesis (BBN). BBN refers to the epoch when free neutrons and protons form heavier and heavier nuclei via collisions. Before that epoch there are weak reactions that interconvert neutrons and protons. These reactions are in equilibrium, but then they fall out of equilibrium at a time depending on factors such as the expansion rate of the universe, the baryon-to-photon ratio η and the energy densities of photons, electrons and positrons, and neutrinos. Nuclear reactions then fuse neutrons and protons into nuclei.

I started my research by updating a BBN code used by Profs. Richard Matzner and Tony Rothman in the 1980's (the Texas code, [1], [2]). That code could calculate the abundances $Y(i)$ of nine light isotopes from ^{1}H to ^{7}Li produced by the Big Bang. I needed the code to be able to calculate abundances for a large isotope network (68) so that I could compare the results with the results from another code (The Thomas et al code, used for articles by TSOF [3] and TSOMMF [4]). In fixing the codes to make their results agree I learned in detail about how the codes run. I wrote up on my initial work on the two codes in a 1997 poster/article at Oak Ridge National Lab [5].

I then concentrated on one factor in BBN, neutrino heating. Electrons and positrons transfer energy to neutrinos by scattering off them or annihilating to form neutrino pairs. This heating affects the neutron-proton conversion rates and nucleosynthesis. For my Texas code I devised a way to calculate the distribution functions of neutrinos as they change due to the scattering and annhilation reactions. In my dissertation I mapped out how this heating changes the conversion rates and the production of ^{4}He, the most common isotope produced, among other isotopes. The mass fraction of ^{4}He, which is on the order of 0.25 for $\eta = [10^{-10}, 10^{-9}]$, increases by $[1, 2] \times 10^{-4}$ for that same range of η.

Ultimately I wanted to determine the neutrino heating effect for a baryon inhomogeneous model of the universe. Some theories on baryogenesis suggest that baryons form in high density clumps amidst a low density outside. [6] I wrote my own Inhogeneous Big Bang Nucleosynthesis (IBBN) code that started with a high baryon density core and a low density inner shell. In my dissertation as well as an article-poster for the Texas-Mexico Conference on Astrophysics [7] I showed that in my code neutrons would diffuse from the high density core to the low density inner regions before nucleosynthesis, but then diffuse back during nucleosynthesis as BBN depleted the neutrons in the core earlier. I made contour maps of final abundances dependent on η and on the initial size of the model (distance scale r_i). Neutron diffusion determined the features of the contour maps, and r_i and the initial ratio (R_p) between high and low densities determined neutron diffusion. Later in an article for the Texas Symposium on Relativistic Astrophysics [8] I discussed the IBBN code's results with the heating effect running. For the range of r_i and η I observed the change in ^{4}He mass fraction remained the same order of 10^{-4}. That change to ^{4}He resembled a slight upward shift of the value of η, but the change in deuterium production due to neutrino heating was an order of magnitude less than the change coming from such an upward shift.

The latest measurements of light isotope abundances include $Y(\mathrm{d})/Y(\mathrm{p}) = (3.3 \pm 0.5) \times 10^{-5}$ (measured from a spectral analysis of Quasi-Stellar Objects), $X_{^4\mathrm{He}} = 0.244 \pm 0.004$ (extrapolated from measurements of metal-poor extragalactic HII regions), and $Y(\mathrm{Li})/Y(\mathrm{p}) =$

$(1.7 \pm 0.1 \pm 0.2) \times 10^{-10}$ (measured from the plateau in old pop II halo stars). [9] In my IBBN code the 2σ constraints of these observations limit η_{10} to [4.0, 6.0], and limit $r(i)$ to less than 20000 cm. I get these results when I use the parameters $r_b = 1/2r_i$ for a boundary between high and low density regions and $R_p = 800$ for a density ratio. In the future I will vary these parameters. With new parameter values the contour maps for ^{4}He, ^{7}Li and deuterium should have the same features as in my disseration results, but η_{10} and $r(i)$ might have very different boundaries. I will also consider symmetries other than spherical. The code needs only slight modifications to run with planar or cylindrical symmetry. I currently am not certain as to how the contour maps would change with planar or cylindrical symmetry, but there exists baryogenesis models that can lead to cylindrical symmetry. [10].

A recent article by BNT [9] compared the critical density fraction $\Omega_B h^2 = 0.0190 \pm 0.0018$ measured from deuterium in QSO's with $\Omega_B h^2 = 0.032^{+0.009}_{-0.008}$ measured in Cosmic Microwave Background Radiation experiments. It might not be possible for a standard BBN code to produce constraints on $\Omega_B h^2$ that can agree with the CMBR constraints. Several research groups are now looking into models alternative to the standard model that can resolve the discrepency between CMBR and BBN results. In the future I want to see if there are any parameters in my IBBN code that could produce mass fractions that agree with both observations and the CMBR constraints.

Also, an article by EMMMP [11] looks at the possibility of resolving the discrepency by using a BBN model with electron neutrino degeneracy. In their model the chemical potentials μ_{ν_i} for each neutrino species can be nonzero, increasing the effective neutrino number N_ν from three. This larger neutrino number increases the expansion rate of the universe with respect to time, leading to a larger neutron-to-proton ratio when nucleosynthesis occurs, and a larger mass fraction of ^{4}He. On the other hand a positive value for μ_{ν_e} would increase the rates of the n $\rightarrow$ p conversion rates over the p $\rightarrow$ n conversion rates, and a negative value would do the opposite. The article by EMMMP and another article by EMMP [12] looked at likelihood functions of light element abundances, with μ_{ν_i}/T, N_ν and $\Omega_B h^2$ as the parameters. I want to see if neutrino degeneracy can be incorporated into the Texas code and my IBBN code. Perhaps neutrino degeneracy could yield new results when applied to a baryon inhomogeny, or when run with neutrino heating taken into account. I also want the experience in computational physics I would gain in constructing likelihood functions.

Another interesting problem is the possibility, suggested by higher-dimensional particle physics theories, that the coupling constants used in the fundamental forces of physics have had values that have varied in time. Present standard theories implicitly assume that coupling constants such as the gravitational constant, G, and the fine structure constant, α, stay constant as the universe evolves. So the detection of any changes in their values would then have far-reaching implications in the future development of fundamental physics. In a 1999 article BIR [13] demonstrated how to write the equations for the reaction cross sections so that they could vary α. BIR determined a 2 % constraint on the variation $\Delta\alpha/\alpha$ allowed by the current constraints on observed abundances of ^{4}He, deuterium and ^{7}Li. A 2001 article by AEMMMMPRV [14] updated BIR's results. Using a likelihood analysis that matched constraints on $\Delta\alpha/\alpha$ with the constraint $\Omega_B h^2 = 0.020^{+0.005}_{-0.003}$, AEMMMMPRV calculated a 2σ constraint of (0.7 ± 0.9) %. AEMMMMPRV also did a likelihood analysis on new CMBR data from BOOMERanG [15] and DASI [16]. For the same range of $\Omega_B h^2$ they got a 1σ constraint $\Delta\alpha/\alpha = -3 \pm 5$ %. I would be very interested in modifying codes to see how varying the coupling constants affects their results. I would like to see what results my own standard and IBBN codes yield if I work in the modifications the Naples group put in so that they could vary α.

My research in Big Bang Nucleosynthesis can be applied to Stellar and Supernova Nucleosynthesis as well. Stars are the main producers of heavier isotopes. Stellar Nucleosynthesis models need large reaction networks like the Texas code's current network. I can trace the production and destruction of heavier isotopes in these stellar models. Also, in supernovae the neutrino heating effect is more significant than in the Big Bang. An article by MB [17] deals with neutrino transport in stars by solving the Boltzmann equation. Supernova Nucleosynthesis models also might require the use of a configuration I'm interested in doing in the future: a model with a neutrino anisotropic distribution. A spherically symmetric supernova can produce a neutrino anisotropy that is axially symmetric along an outgoing direction. A quadrupole distribution is the simplest anisotropic distribution possible. Supernovae can be modelled using a quadrupole distribution for neutrinos. I want to see how a quadrupole distribution changes the results of nucleosynthesis, first in the Texas code and then in a supernova model. I also want to see if I can solve the Boltzmann equation to calculate the neutrino heating effect for such an anisotropic model. A general anisotropic distribution would increase the number of variables needed to integrate numerically in the Boltzmann Transport Equation, possibly making the running time of that section prohibitively long. But new numerical variables might not be needed for a quadrupole distribution. I want to see how far I can take solving the Boltzmann Equation analytically for this distribution.

I also want to have some experience in the experimental side of BBN as well. The discrepency between constraints due to abundance observations and those due to CMBR observations is the latest example of conflicts between experimental results. Before this controversy the measurement of $Y(\mathrm{d})/Y(\mathrm{p})$ was in dispute between the low value listed above and a high value of $Y(\mathrm{d})/Y(\mathrm{p}) = (2.0 \pm 0.5) \times 10^{-4}$ [11] also from QSO's. In recent articles consensus has built around the lower value of $Y(\mathrm{d})/Y(\mathrm{p})$, but this dispute could be revived again. The measurement of $X_{^4\mathrm{He}}$ is disputed between 0.234 ± 0.004 and 0.244 ± 0.004 [9] due to the accuracy of the method of measuring $X_{^4\mathrm{He}}$. Also, in a 2001 article WMFDBCPW [18] looked at shifts in the wavelengths of resonance transitions in QSO absorption systems. These shifts are proportional to α^2. So WMFDBCPW was able to put an experimental constraint on the change of the value of α: a $0.72 \pm 0.18 \times 10^{-3}$ % decrease. There will always be disputes to resolve on the experimental side of BBN. I would be very interested in working on the data analysis of observations needed to resolve these disputes. My time working on the BBN codes has given me the computational skill I'd need to write the programs needed for data analyses. I want to work on programs besides BBN codes, and gain a good understanding of both theoretical and experimental methods of testing nucleosynthesis theories.

From the beginning the main appeal of general relativity to me has been the mathematics behind it. In 1991 I did a senior seminar at Columbia University on the classical wormhole solutions of Kip Thorne that could possibly be used to make closed timelike curves [19]. I was entranced by the derivation of the Reimann and Einstein tensors from the metric Thorne started with, and the metric's solutions to the Einstein field equations. I felt a similar entrancement when I derived my analytic solutions to the Boltzmann transport equation. So along with nucleosynthesis I could also someday work on projects involving the solving of the Einstein field equations. I have the analytical skill and the drive to do the mathematics behind those solutions. I also worked for a couple of months on a large-scale structure project with Robin Tuluie before I started my nucleosynthesis work. I would be very interested in working in the simulation programs involved in large-scale structure. Although my recent efforts have been in cosmic nucleosynthesis, I have developed an interest in the broad area of cosmology problems. So I am confident of my ability to contribute significantly to any area of General Relativity.

References

[1] T. Rothman & R. Matzner. Physical Review Letters. **48**, 1565 (1982).

[2] T. Rothman & R. Matzner. Physical Review D. **30**, 1649 (1984).

[3] D. Thomas, D.N. Schramm, K.A. Olive & B.D. Fields. Astrophysical Journal. **406**, 569 (1993).

[4] D. Thomas, D.N. Schramm, K.A. Olive, G.J. Mathews, B.S. Meyer & B.D. Fields. Astrophysical Journal. **430**, 291 (1994).

[5] J.F. Lara. "Comparison of Two Distinct BBN Codes". in **Stellar Evolution, Stellar Explosions and Galactic Chemical Evolution**, proceedings of the Second Oak Ridge Symposium on Atomic and Nuclear Astrophysics. Oak Ridge, Tennessee, 1997. Edited by Anthony Mezzacappa (Institute of Physics Publishing, Bristol, 1998), p. 123.

[6] K. Kainulainen, H. Kurki-Suonio, & E. Sihvola. Physical Review D. **D59**, 083505 (1999).

[7] J.F. Lara. "Neutron Diffusion and Nucleosynthesis in an Inhomogeneous Big Bang Model". To appear in **The Seventh Texas-Mexico Conference on Astrophysics: Flows, Blows, and Glows**, Revista Mexicana de Astronomia y Astrofisica, Serie de Conferencias. Austin, Texas, 2000. Edited by William Lee and Silvia Torres-Peimbert.

[8] J.F. Lara. "Neutrino Heating in an Inhomogeneous Big Bang Nucleosynthesis Model". In **The 20th. Texas Symposium on Relativisitic Astrophysics**. Austin, Texas, 2000. Edited by J. Craig Wheeler and Hugo Martel (American Institute of Physics, Melville, 2001), p. 349.

[9] S. Burles, K.M. Nollett & M.S. Turner. astro-ph/0008495.

[10] M. Orito, T. Kajino, R.N. Boyd, & G.J. Mathews. Astrophysical Journal **488**, 515 (1997).

[11] S. Esposito, G. Mangano, A. Melchiorri, G. Miele, & O. Pisanti. Physical Review D. **63**, 043004 (2001).

[12] S. Esposito, G. Mangano, G. Miele, & O. Pisanti. Journal of High Energy Physics. **0009**, 038 (2000).

[13] L. Bergstrom, S. Iguri, & H. Rubinstein. Physical Review D. **60**, 045005 (1999).

[14] P.P. Avelino, S. Esposito, G. Mangano, C.J.A.P. Martins, A. Melchiorri, G. Miele, O. Pisanti, G. Rocha, & P.T.P. Viana. astro-ph/0102144

[15] C.B. Netterfield, et al. astro-ph/0104460.

[16] C. Pryke, et al. astro-ph/0104489.

[17] A. Mezzacappa & S.W. Bruenn. Astrophysical Journal **405**, 669 (1993).

[18] J.K. Webb, M.T. Murphy, V.V. Flambaum, V.A. Dzuba, J.D. Barrow, C.W. Churchill, J.X. Prochaska, & A.M. Wolfe. Physical Review Letters. **87**, 091301-1 (2001).

[19] M.S. Morris & K. Thorne. American Journal of Physics **56**, 395 (1987).