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This report covers the period July 1, 1998-June 30, 1999.

1. THEORY

1.1 Theoretical Cosmology Group

The Theoretical Cosmology group, which consists of faculty members S. Dodelson, J. Frieman, E.W. Kolb, A. Olinto, and M.S. Turner, pursues a vigorous program of research on topics ranging from red shift $Z = 10^{32}$ to $Z = 0$. Emphasis is placed on the application of modern particle theory to cosmology, especially the earliest history of the Universe. Members of the group are also involved in the Sloan Digital Sky Survey project. Current topics of research include inflationary cosmology, the origin of density perturbations, topological defects (monopoles, strings, walls, textures), cosmological phase transitions (electroweak, QCD, GUT), baryogenesis, particle dark matter and its detection, primordial nucleosynthesis, the evolution of structure in the Universe, the origin of CBR anisotropies, gravitational waves, and the origin of highest energy cosmic rays. The group helped to pioneer the use of the Universe as a ‘‘heavenly laboratory’’ to probe fundamental physics in regimes not accessible in terrestrial laboratories and has used such arguments to constrain the properties of axions, neutrinos, neutralinos, and magnetic monopoles. Research associates currently working with the Theoretical Cosmology Group include S. Burles, D. Eisenstein, L. Fortson, E. Gates, M. Kaplinghat, L. Knox, S. Lee, J. Loveday, M.T. Ressel, G. Sigl, M. Subbarao, D. Thomas, M. Valluri, and G. Wolf-Chase.

The Theoretical Cosmology group works closely with the Theoretical Astrophysics group at Fermilab which is led by Kolb and whose faculty members are S. Dodelson, J. Frieman, E.W. Kolb, A. Stebbins, and M.S. Turner. The FNAL group’s current research associates are I. Albuquerque, M. Blanton, P. Blasi, R. Sheth, R. Toldra, and I. Zehavi.

1.1.1 Scott Dodelson

I am interested in cosmology, in particular in the broad question of how structure formed in the universe. This question is rich not only because it is fascinating in of itself, and not only because there is much data being taken that sheds light on it, but also because it touches so many issues in astrophysics and particle physics. How do galaxies form? Is there dark, non-baryonic matter? What is it? Will the universe continue to expand forever? Did the universe expand exponentially at some early phase in its history? If so, what is the particle physics responsible for this period of inflationary expansion? These are all remarkable questions; even more remarkable is the very real hope that we will be able to answer them in the coming decade.

I believe there are three ways theoretical cosmologists can help answer these and other questions in the general field of structure formation. First, we can introduce new theories or models of how structure formed. This is especially important at present since one general model – cold dark matter and its variants – so dominates the theoretical landscape. Second, we can calculate the predictions of existing theories. Finally, we can analyze the plethora of data that is coming in and will be coming in over the next decade. I am interested in all three of these areas, find them stimulating, and hope to work in all of them in the coming years.

PUBLICATIONS

- ‘‘CMB Anisotropy Induced by Cosmic Strings on Angular Scales > 15 Arcminutes’’ (with B. Allen, R. R. Caldwell, L. Knox, E. P. S. Shellard, and A. Stebbins), *Phys. Rev. Lett.* **79**, 2624-27 (1997).
- ‘‘Determining Lambda with the Sloan Digital Sky Survey’’ (with D. MacMinn), <http://www-astro-theory.fnal.gov/Personal/dodelson/donn.ps>
- ‘‘Cosmic microwave background measurements can discriminate among inflation models’’ (with W. Kinney and E. W. Kolb), *Phys. Rev. D* **56**, 3207-15 (1997).
- ‘‘Anisotropies in the Cosmic Microwave Background: Theory,’’ astro-ph/9702134, to be published in the Proceedings of the 18th Texas Symposium on Relativistic Astrophysics, ed. J. A. Frieman, A. Olinto, and D. N. Schramm (1997).
- ‘‘Dynamical Lambda Models of Structure Formation,’’ (with K. Coble and J.A. Frieman), *Phys. Rev. D* **55**, 1851-9 (1997).
- ‘‘Determining Cosmic Microwave Background Anisotropies in the Presence of Foregrounds,’’ *Astrophys. J.* **482**, 577-587 (1997).
- ‘‘Cold Dark Matter Models’’ (with E. Gates and M.S. Turner), *Science* **274**, 69-75 (1996).
- ‘‘Comment on a paper by Fang, Huang, and Wu’’ (with A.S. Stebbins), FERMILAB-PUB-96-068-A (1996).
- ‘‘Cold + Hot Dark Matter and the Cosmic Microwave Background’’ (with E. Gates and A.S. Stebbins), *Astrophys. J.* **467**, 10-18 (1996).

1.1.2 Joshua A. Frieman

Frieman’s primary research is in cosmology, especially the formation of large-scale structure and the interplay between cosmology, particle physics, and astrophysics. Current research interests include the analysis of large-scale structure in galaxy surveys such as the Sloan Digital Sky Survey, and the use of weak gravitational lensing observations to probe the distribution of mass on large scales. Frieman is a member of the Theoretical Astrophysics group at Fermilab, which has close connections with the cosmologists and theoretical astrophysicists at Chicago.

PUBLICATIONS

- “The Bispectrum as a Signature of Gravitational Instability in Redshift Space” (with R. Scoccimarro and H. Couchman), *Astrophysical Journal* 517, 531, 1999.
- “Hyperextended Cosmological Perturbation Theory: Predicting Non-linear Clustering Amplitudes” (with R. Scoccimarro), *Astrophysical Journal* 520, 35, 1999.
- “Weak Gravitational Lensing by Voids” (with Luca Amendola and Ioav Waga), astro-ph/9811458, *Monthly Notices*, in press.
- “High-Redshift Quasars Found in Sloan Digital Sky Survey Commissioning Data” (with X. Fan, et al, the SDSS Collaboration), *Astronomical Journal* 118, 1, 1999.
- “The Projected Three-Point Correlation Function: Theory and Observations” (with E. Gaztanaga), *Astrophysical Journal Letters* 521, 83, 1999.
- “High-Redshift Quasars Found in Sloan Digital Sky Survey Commissioning Data II: The Spring Equatorial Stripe” (with X. Fan, *et al.*, the SDSS Collaboration), submitted to *Astronomical Journal*.

1.1.3 Edward W. Kolb

The close collaboration between the Department of Astronomy and Astrophysics and the Astrophysics effort at Fermi National Accelerator Laboratory in nearby Batavia is indicative of the close ties between particle physics and cosmology/astrophysics. The major effort of my research is the attempt to understand physical processes that occurred in the very earliest moments of the “Big Bang.” In these very early moments the density, energy, and pressure of the universe resembled the conditions obtained in the collisions of particles at high energy accelerators. The microphysics of the very early universe leaves its imprint on the present large-scale structure of the universe in the form of galaxies, the baryon asymmetry, element abundances, etc.

PUBLICATIONS

- “GUT Baryogenesis after Preheating: Numerical Study of the Production and Decay of X Bosons” (with A. Riotto and I. I. Tkachev), *Phys. Lett.* B423, 348 (1998).
- “Superheavy Dark Matter” (with D. J. H. Chung and A. Riotto), *Phys. Rev. D*, submitted for publication (1998) hep-ph/9802238.
- “Exotic Massive Hadrons and Ultra-High Energy Cosmic Rays” (with I. F. M. Albuquerque and G. R. Farrar), *Phys. Rev. D*, submitted for publication (1998) hep-ph/9805288.
- “Particle Production and Symmetry Restoration in Collisions of Vacuum Bubbles” (with A. Riotto), *Phys. Rev. D* 55, 3313 (1997).
- “Cosmic Microwave Background Measurements Can Discriminate Among Inflation Models” (with S. Dodelson and W. H. Kinney), *Phys. Rev. D*, 56, 3207 (1997).

1.1.4 Angela Olinto

Olinto’s interests are in theoretical astrophysics, particle and nuclear astrophysics, and cosmology. Her recent work

has focused on cosmological effects of magnetic fields, the internal structure of neutron stars, and the highest energy cosmic rays.

PUBLICATIONS

- “Rapid dissipation of magnetic fields in neutron stars” (with S.I. Vainshtein and S. M. Chitre), submitted to *Phys. Rev. E* (1999).
- “Galactic Ultra-High-Energy Cosmic Rays” (with R.I. Epstein and P. Blasi), submitted to the proceedings of the 26th ICRC, Salt Lake City (1999).
- “Ultra-High Energy Cosmic Rays from Newborn Neutron Stars” (with P. Blasi and R.I. Epstein), submitted to *Phys. Rev. Letters* (1999).
- “Neutron Stars and Black Holes as MACHOs” (with A. Venkatesan and J. Truran), *Ap. J.* 516, vol. 2 (1999).
- “A Magnetized Local Supercluster and the Origin of the Highest Energy Cosmic Rays” (with P. Blasi), *Phys Rev D*, 59 023001 (1999).
- “Cosmological Magnetic Fields Limits in an Inhomogeneous Universe” (with P. Blasi and S. Burles), *Ap. J. Letters*, 512, L79 (1999).
- “Cosmological Magnetic Fields,” in the Proceedings of the XVIII Texas Symposium on Relativistic Astrophysics, Chicago, Dec 1996; Ed. A. V. Olinto, J. Frieman, and D. N. Schramm, (World Scientific 1998).
- “Cosmic Magnetic Fields,” in the Proceedings of the 2nd RESCEU Symposium, University of Tokyo, Nov. 1997, Ed. M. Minowa (Universal Academic Press, 1998).
- “Damping of MHD modes in Relativistic Plasmas” (with V. Katalinic and K. Jedamzik), *Phys. Rev. D* 57, 3264 (1998).

1.1.5 Michael S. Turner

My research focuses on the application of modern ideas in elementary-particle theory to cosmology and astrophysics. I believe that this approach holds the key to answering the most pressing questions in cosmology. For example, there is reason to believe that the ubiquitous dark matter that holds the Universe together is elementary particles left over from the earliest moments, that the primeval inhomogeneity in the distribution of matter, which was revealed by COBE and which seeded all the structure in the Universe seen today, arose from quantum-mechanical fluctuations occurring during a very early burst of expansion called inflation, and that the existence of ordinary matter resulted from particle interactions in the early Universe that make the proton unstable and do not respect the symmetry between matter and antimatter. By testing these ideas with cosmological data, outer space becomes a window to the earliest moments of creation and to the unification of the forces and particles of Nature. Over the next decade the search for particle dark matter, the mapping of the distribution of matter in the Universe a few hundred thousand years after the beginning through precision measurements of the cosmic microwave background radiation, and the mapping of structure in the present Universe by determining the positions of millions of galaxies should definitively test these bold ideas. Much of the crucial experimental work is being done by colleagues at Chicago; for

example, the Sloan Digital Sky Survey will map the positions of a million galaxies and the DASI, TopHat, MAP, and Python experiments will measure the fine-scale anisotropy of the cosmic microwave background radiation. Current specific areas of research include: big-bang nucleosynthesis in era of precision cosmology; theoretical aspects of inflationary cosmology; testing the inflationary paradigm; determining the nature of the dark energy that is causing the Universe to accelerate; dark matter and dark-matter detection; dark matter and the formation of structure in the Universe; the origin of the cosmic asymmetry between matter and antimatter; understanding how to use precision measurements of the fine-scale anisotropy of the cosmic microwave background and large-scale structure to probe inflation and fundamental physics; and aspects of axion, neutrino and string cosmology.

PUBLICATIONS

- “Probing Unstable Massive Neutrinos with Current Cosmic Microwave Background Observations” (R.E. Lopez, S. Dodelson, R.J. Scherrer, and M.S. Turner), *Physical Review Letters* 81, 3075 (1998) (astro-ph/9806116)
- “Large-scale Structure from Quantum Fluctuations in the Early Universe” (M.S. Turner), *Phil. Trans. R. Soc. Lond.* (1999) (astro-ph/9808149)
- “Cosmology Solved? Quite Possibly” (M.S. Turner), *Pub. Astron. Soc. Pac.* 111, 264 (1999) (astro-ph/9811364)
- “Cosmology at the Millennium” (M.S. Turner and J.A. Tyson), *Reviews of Modern Physics* 71, S145 (1999) (astro-ph/9901113)
- “Cosmic Rosetta Stone” (C. Bennett, M.S. Turner, and M. White), *Physics Today*, November 1997, p. 32
- “Inner Space & Outer Space” (M.S. Turner), *Beamline*, Fall 1997, p. 2
- “Sharpening the Predictions of Big-bang Nucleosynthesis” (S. Burles, K. Nollett, J. Truran and M.S. Turner), *Physical Review Letters*, 82 (1999) (astro-ph/9901157)
- “Prospects for Probing the Dark-energy via Supernova Distance Measurements” (D. Huterer and M.S. Turner), *Physical Review Letters* 82, (1999) (astro-ph/9808133)
- “Dark Matter and Dark Energy in the Universe” (M.S. Turner), *Physica Scripta*, in press (1999) (astro-ph/9901109)
- “Constraining Dark Energy with SNe Ia and Large-scale Structure” (S. Perlmutter, M.S. Turner, and M. White), *Physical Review Letters* 82, 1999 (astro-ph/9901052)

1.2 Arieh Königl

During the past year, Königl and his collaborators have carried out research in the areas of star formation and active galactic nuclei (AGNs). Work has continued with G. Ciolek (RPI) on extending previous molecular-cloud core collapse calculations to include rotation and magnetic transport of angular momentum, with the goal of accounting for the formation of rotationally supported circumstellar disks around young stellar objects (YSOs). Work has also continued on the evolution of diffusive, rotationally supported disks that are threaded by open magnetic field lines in an attempt to establish the conditions under which they could (a) transport

angular momentum vertically along the field lines, and (b) drive a centrifugally driven wind that may account for the commonly observed bipolar outflows in YSOs. Progress also continued to be made in work with S. Martin (NRL) on the formation of disk-driven outflows in the innermost regions of protostellar disks that become ionized as a result of a dwarf nova-type thermal ionization instability. This study aims to investigate the idea that the high-ionization phases of this instability are related to major (FU Orionis-type) outbursts from young stars, during which most of the mass accretion onto the star, as well as most of the the mass ejection through jets, could take place. In addition, work has been initiated with D. Uzdensky and C. Litwin on the detailed interaction of a protostellar magnetic field with the surrounding accretion disk. Particular attention is being given to the time evolution of magnetic field lines that thread both the star and the disk and to the implications of this evolution to the observational manifestations of accretion and outflows in YSOs. In the area of AGNs, work has continued in collaboration with J. Kartje on the incorporation of continuum and line radiation pressure effects into hydromagnetic disk-wind models. The goal is to account for a range of spectral characteristics in QSOs and BL Lacertae objects, including broad emission and absorption lines in the former and EUV and X-ray absorption features in the latter. Both uniform and clumped outflow scenarios are being investigated. As a test of these ideas, a program of confronting the models with multifrequency observations of BL Lac objects was begun in collaboration with R. Sambruna (Penn State) and graduate student J. Everett.

PUBLICATIONS

- Contopoulos, I., Ciolek, G. E., and Königl, A. (1998), “Self-Similar Collapse of Nonrotating Magnetic Molecular Cloud Cores,” *ApJ*, **504**, 247.
- Ciolek, G. E., and Königl, A. (1998), “Dynamical Collapse of Nonrotating Magnetic Molecular Cloud Cores: Evolution Through Point-Mass Formation,” *ApJ*, **504**, 257.
- Kartje, J. F., Königl, A., and Elitzur, M. (1999), “Megamaser Disks in Active Galactic Nuclei,” *ApJ*, **513**, 180.
- Königl, A. (1999), “Theory of Bipolar Outflows from High-Mass Young Stellar Objects,” *New Astronomy Reviews*, in press.

1.3 Don Q. Lamb

The focus of my research is the physics of matter and radiation under extreme conditions. Compact objects such as white dwarfs, neutron stars, and black holes provide an astrophysical laboratory for such studies. Their high internal densities enable non-ideal Coulomb solids, heavy nuclei, nuclear matter, and even quark matter to be probed. Hot dense matter is also crucial to an understanding of supernovae. The large gravitational potentials and the strong magnetic fields at the surfaces of these objects produce phenomena ranging from radio pulsars to active galactic nuclei. These phenomena can be used to test our understanding of nuclear reactions, hydrodynamics and shocks, and radiation transfer in magnetoactive and relativistic plasmas in new regimes, as well as to determine the properties, such as mass,

radius, and magnetic field, of the compact objects themselves. My current research activities include projects in the following areas: properties of relativistic pair plasmas and hot dense matter; structure and evolution of degenerate dwarfs and neutron stars; supernovae, pulsars; X-ray emission from degenerate dwarfs and neutron stars; X-ray and gamma-ray bursts; and active galactic nuclei.

1.4 Robert Rosner

R. Rosner and collaborators conduct both theoretical and observational research in solar and stellar astrophysics, more general plasma astrophysics, and fluid dynamics. This work entails both analysis and modeling of solar and stellar observations; analytical and computational studies of both laboratory and astrophysical fluids, especially in the context of stellar convection and stellar magnetic field generation. We also study the evolution and dynamics of magnetic fields in non-stellar contexts, such as in clusters of galaxies, in galaxies themselves, and in the young universe; and, most recently, have begun a major new initiative in computational fluid dynamics aimed at combustion and transient nucleosynthesis (as occurs in X-ray bursts, novae, and Type Ia supernovae).

PUBLICATIONS

- Ong, K.K., Musielak, Z.E., Rosner, R., Suess, S.T., & Sulkanen, M.E. (1997) "Self-consistent and Time-dependent Solar Wind Models," *ApJ (Letters)*, 474, L143
- Vainshtein, S., Sagdeev, R., & Rosner, R. (1997). "Stretch-twist-fold and ABC Nonlinear Dynamos: Restricted Chaos," *Phys. Rev. E*, 56(2), 1605-22
- Peres, G., Orlando, S., Reale, F., Rosner, R., & Hudson, H. (1997). "The Sun as an X-ray Star: Overview of the Method," *Solar Phys.*, 172, 239
- Vainshtein, S.I. (1997). "Probing Asymmetry and Self-similarity of Fully Developed Turbulence," *Phys. Rev. E*, 56, 6787
- Orlando, S., Lou, Y.-Q., Peres, G., & Rosner, R. (1997). "Alfvenic Fluctuations in the Fast and Slow Solar Winds," *JGR*, 102, 24139-49
- Vainshtein, S.I. (1997). "Non-Gaussian behavior of low-order moments in fully developed turbulence," *Phys. Rev. E*, 56, 447
- Young, Y.-N., & Rosner, R. (1998). "Linear Stability Analysis of Doubly Diffusive Vertical Slot Convection," *Phys. Rev. E*, 57, 1183-6.
- Vainshtein, S.I. (1998). "Exactly Solvable Model of Nonlinear Dynamo," *Phys. Rev. Letters*, 80, 4879
- Bodo, G., Rossi, P., Massaglia, S., Ferrari, A., Malagoli, A., & Rosner, R. (1998). "Three-dimensional Simulations of Jets," *A&A*, 333, 1117
- Lanza, A.F., Rodono, M., & Rosner, R. (1998). "Orbital Period Modulation and Magnetic Cycles in Close Binaries," *MNRAS*, 296, 893
- Litwin, C., & Rosner, R. (1998). "Alfven Wave Transmission and Heating of Solar Coronal Loops," *ApJ*, 499, 945
- Young, Y.-N., & Rosner, R. (1998). "Linear and Weakly Non-linear Analysis of Doubly Diffusive Vertical Slot Convection," *Phys. Rev. E*, in press
- Cattaneo, F., Hughes, D.W. & Kim, E. (1998). "Nonlinear Multi-cellular Fast Dynamos," *Studia Geoph. et Geod.*, in press
- Litwin, C., & Rosner, R. (1998). "Relativistic Space-charge Limited Bipolar Flow," *Phys. Rev. E*, in press
- Vainshtein, S.I. (1998). "Refined Similarity Hypothesis and Asymmetry of Turbulence," *Phys. Rev. E*, in press
- Lenz, D.D., Lou, Y.Q., & Rosner, R. (1998). "Density Structure in a Multi-Component Coronal Loop," *ApJ*, in press

1.5 James W. Truran

Truran, Ami Glasner, and Eli Livne have completed a preliminary investigation of the influence of convection on thermonuclear ignition of hydrogen burning in accreted shells on white dwarfs, using two dimensional simulations. The earliest stages of the runaway were calculated using a 1D hydrodynamic code developed by Glasner and Truran (1996). When the temperature at the base of the accreted envelope reached 10^8 K and the total rate of nuclear energy generation was approximately $10^5 L_{\odot}$ (e.g the runaway was fully developed), the 1D flow was mapped onto a 2D grid and the simulation continued in two dimensions, using the code VULCAN developed by Livne (1993; see also Glasner and Livne 1995). The 2D grid consisted of 90 radial zones and 220 equal lateral zones, occupying an angle of 0.1 'pi' radians, and included both the entire accreted hydrogen layer and the upper 15 zones of the underlying carbon-oxygen core. At the onset of the stage of evolution studied with the 2D code, the envelope was already convectively unstable. Within a very short time (approximately 10 seconds), the numerical noise acted to seed an intense convective flow in the envelope, without the introduction of any artificial perturbations. The initial convective cells were found to be almost circular and of a size comparable to the pressure scale height ($\sim 10^7$ cm), while the convective velocities were close to the values predicted by the mixing length theory - several times 10^6 cms^{-1} . After a relatively short transition period of order 40 seconds, the flow reached a quasi-steady state, where convection was fully developed. The buildup of convective cells at the base of the envelope induced shear flow at the core-envelope interface, which is Kelvin-Helmholtz unstable, and mixing between the outer layers of the core and the burning zone ensued. By the end of their simulation, covering approximately 240 seconds of the evolution of the runaway, the hydrogen envelope had been 'enriched' to about 30 percent by mass in carbon and oxygen from the underlying core. Such a level of enrichment is entirely consistent with observations of the compositions of the ejected shells of classical novae (Livio and Truran 1995) and with our theoretical understanding of the thermonuclear outbursts of novae. The outward mixing of the short lived positron-unstable isotopes O^{14} , O^{15} , F^{17} , and F^{18} also served to redistribute the nuclear energy output from the nuclear burning shell (charged particle reactions can only occur in the hotter regions near the base of the envelope) and thereby to moderate the temperature gradient across the envelope. Such studies are critical to our ultimate understanding of the nature of the outbursts of classical novae - including our un-

derstanding of the early evolution of the visual light curves, which is immediately relevant to the use of bright novae as distance indicators to nearby galaxies.

PUBLICATIONS

- Burles, S., Nollett, K.M., Truran, J.W., & Turner, M.S., "Sharpening the Predictions of Big-Bang Nucleosynthesis," *Physical Review Letters*, 1999.
- Kercek, A., Hillebrandt, W., & Truran, J.W., "Three Dimensional Simulations of Classical Novae," *Astronomy & Astrophysics*, Vol. 345, P. 831, 1999.
- Starrfield, S., Sparks, W.M., Truran, J.W., & Wiescher, M.C., "The Effects of New Nuclear Reaction Rates and Opacities on Hydrodynamic Models of the Nova Outburst," *Astrophysical Journal, Supplement*, in press, 1999.
- Starrfield, S., Schwarz, G.J., Truran, J.W., & Sparks, W.M., "The Effects of Metallicity on Hydrodynamic Models of the Nova Outburst," *Bulletin of the American Astronomical Society*, Vol. 194, p. 611, 1999.
- Belle, K.E.,, & Truran, J.W., "NICMOS Imagery of Nova Shells," *Bulletin of the American Astronomical Society*, Vol. 194, p. 611, 1999.
- Starrfield, S., Truran, J.W., & Sparks, W.M., "The Nova Outburst: Thermonuclear Runaways on Degenerate Dwarfs," in *Proceedings of the Warner Symposium on Cataclysmic Variables*, in press, 1999.
- Wanajo, S., Nomoto, K., & Truran, J.W., "Nucleosynthesis in ONeMg Novae: Comparison with Observations," in *Cosmic Chemical Evolution*, in press, 1999.
- Truran, J.W., "Abundances in the Cosmos," in *Cosmic Chemical Evolution*, in press, 1999.
- Niemeyer, J.C. & Truran, J.W. (Editors), "Type Ia Supernovae: Theory and Cosmology," Cambridge University Press, Cambridge, in press, 1999.
- Truran, J.W., "Nova Explosions: Abundances and Light Curves," in *Nuclear Astrophysics*, Eds. Hillebrandt, W. and Müller, E., Publications of the Max-Planck-Institute for Astrophysics, p. 107, 1998.
- Kercek, A., Hillebrandt, W., & Truran, J.W., "Two and Three Dimensional Simulations of Thermonuclear Runaways in Accreted Atmospheres on White Dwarfs," in *Nuclear Astrophysics*, Eds. Hillebrandt, W. and Müller, E., Publications of the Max-Planck-Institute for Astrophysics, p. 56, 1998.
- Truran, J.W., "The Early Stages of a Nova Outburst," in *Proceedings of the Second Oak Ridge Symposium on Atomic and Nuclear Astrophysics*, Ed. Mezzacappa, A., IOP Publishing Ltd, pp. 425-431, 1998.
- Cowan, J.J., Sneden, C., Truran, J.W., & Burris, D.L., "Stellar Abundance Observations," in *Proceedings of the Second Oak Ridge Symposium on Atomic and Nuclear Astrophysics*, Ed. Mezzacappa, A., IOP Publishing Ltd, pp. 621-630, 1998.
- Cowan, J.J., Sneden, C., Truran, J.W., & Burris, D.L., "GHRS Observations of Neutron-Capture Elements in Metal-Poor Stars," in *The Scientific Impact of the Goddard High-Resolution Spectrograph*, Eds. Brandt, J.C., Ake, T.B., & Peterson, C.C., ASP Conference Series, San Francisco, 1998.
- Starrfield, S., Truran, J.W., Sparks, W.M., Hauschildt, P., Shore, S.N., & Krautter, J., "Observational and Theoretical Studies of the Nova Outburst," in *Wild Stars in the Old West*, Eds. Howell, S., Kuulkers, E., & Woodward, C., Cambridge University Press, Cambridge, pp. 352-367, 1998.
- Truran, J.W., "The Age of the Universe from Nuclear Chronometers," *Proceedings of the National Academy of Sciences*, Vol. 95, pp. 18-21, 1998.
- Gehrz, R., Truran, J.W., Williams, R.E., & Starrfield, S., "Nucleosynthesis in Classical Novae and its Contributions to the Interstellar Medium," *Publications of the Astronomical Society of the Pacific*, Vol. 110, pp. 3-26, 1998.
- Sneden, C., Cowan, J.J., Burris, D.L., & Truran, J.W., "HUBBLE Space Telescope Observations of Neutron-Capture Elements in Very Metal Poor Stars," *Astrophysical Journal*, Vol. 496, pp. 235-245, 1998.
- Starrfield, S., Truran, J.W., Wiescher, M.C., & Sparks, W.M., "New Evolutionary Sequences for ONeMg Novae," *Monthly Notices Royal Astronomical Society*, Vol. 262, p. 502, 1998.
- Tuchman, Y. & Truran, J.W., "The Influence of Composition on the Core Mass-Luminosity Relation for Degenerate Cores and its Relevance to the Extinction Timescales of the Classical Novae," *Astrophysical Journal*, Vol. 503, p. 381, 1998.
- Starrfield, S., Schwarz, G.J., Truran, J.W., & Sparks, W.M., "Hydrodynamic Studies of the Evolution of the Extraordinary Nova LMC 1991," *Bulletin of the American Astronomical Society*, Vol. 193, p. 101, 1998.
- Kercek, A., Hillebrandt, W., & Truran, J.W., "2D Simulations of Thermonuclear Runaways on White Dwarfs," *Astronomy & Astrophysics*, Vol. 337, P. 379, 1998.
- Kercek, A., Hillebrandt, W., & Truran, J.W., "Two and Three Dimensional Simulations of Classical Novae," Workshop on Fluid Dynamics, Bordeaux, France, p. 14, 1998.

1.6 Peter O. Vandervoort

Vandervoort has continued to study the oscillations and the stability of galaxies. This work is based on the Lagrangian representation of small perturbations in stellar systems, and it has both analytic and numerical aspects. The effort of the last year has been devoted to (1) an N-body method for a numerical solution of the Lagrangian perturbation equations, (2) a matrix method of the Rayleigh-Ritz type for a stellar-hydrodynamical solution of the perturbation equations, and (3) a matrix method of the Rayleigh-Ritz type for a fully stellar-dynamical solution of the perturbation equations. An account of the N-body method is contained in the publication referenced below. The method has now been extended successfully to a study of radial oscillations in a sequence of spherical systems with substantially higher degrees of central concentration than the systems studied earlier. A stellar-hydrodynamical framework for the study of small perturbations is provided by the moments of the colli-

sionless Boltzmann equation. For an infinitesimal perturbation of a system in equilibrium, the moment equations are linearized and written, as is customary in hydrodynamics, in terms of a Lagrangian displacement. That vector describes the displacement of a fluid element at a given time relative to the position that the element would have had at that time in the absence of the perturbation. The formulation allows for the tensor character of the pressure in a stellar system. The system of linearized equations is closed here with the aid of an assumption that the divergence of the heat flow tensor (whose elements are the third velocity moments of the distribution function) vanishes. The perturbations thus considered are stellar-hydrodynamical counterparts of the adiabatic perturbations of a fluid system. The perturbation equations can be reduced to a characteristic value problem for the normal modes of the system, and the characteristic value problem admits of a variational principle for the determination of the characteristic frequencies of the modes. The variational principle provides the basis for the formulation of a matrix method of the Rayleigh-Ritz type for the solution of the characteristic value problem. An application of this method has been carried out to completion in a study of radial modes in spherical systems, and work is beginning on the study of nonradial modes in spheres. A fully stellar-dynamic framework for the study of small perturbations in stellar systems is provided by an old investigation in which Vandervoort formulated the characteristic value problem governing normal modes in the Lagrangian representation and showed that the problem admits of certain variational principles. In new work, one of the variational principles is made the basis for the formulation of a matrix method of the Rayleigh-Ritz type for the solution of the governing equations. This method has been worked out fully for and applied to the radial oscillations of a spherical system. A central part of the work is the construction of a suitable set of basis vectors for the representation of the Lagrangian displacement of a particle in the six-dimensional phase space of a single star. Work is starting on the formulation of the method and its application to the non-radial modes in spheres. The N-body method and the two matrix methods have been applied to the study of the fundamental mode of radial pulsation in centrally concentrated, spherical systems. Values of the period of the mode obtained in these applications are in very good agreement in systems spanning a wide range of central concentrations.

PUBLICATIONS

“On an Example of an N-Body Method for the Study of Small Perturbations in Galaxies,” *MNRAS*, 303, 393.

2. HISTORY

2.1 Noel M. Swerdlow

I worked on a number of projects this year. The first was an addition to my book, *The Babylonian Theory of the Planets*, which appeared in April of last year, an addition I began working on shortly after the book appeared. It is concerned with the use of acronychal risings of superior planets, when the planet is last seen to rise in the east just after the sun sets in the west, for determining the length of synodic periods. At

first I could only approximate acronychal risings by computing oppositions, when the longitude of the planet and sun differ by 180deg, but then I worked out a method of computing acronychal risings, although I could only estimate the essential empirical parameter, the depression of the sun below the western horizon when the planet become visible above the eastern horizon. What I found is that intervals between acronychal risings agree with the synodic times computed with the Babylonian ephemerides with a maximum error for Saturn of less than one day, for Jupiter of one day, and for Mars of three days, in each case excellent agreement. It thus appears that acronychal risings were the empirical basis of the parameters of the ephemerides for synodic time and thus indirectly for synodic arc. During the latter part of the summer and fall I returned to work on my book on Galileo's contribution to astronomy and conflicts with the Church. I carried out a more extensive investigation than had previously been done of his concern with the new star of 1604, which he believed to result from condensing vapors at high altitude, beyond any noticeable parallax, which was also his explanation of the aurora borealis. I found a diagram in his hand, published once but it appears neither noticed nor understood, of the locations of the planets at the exact time of the appearance of the news star, and what is interesting about this diagram is that it is fully Copernican, with the earth and planets shown in circles about the sun. This proves beyond a doubt that Galileo was a Copernican several years before his telescopic observations, which has been questioned, and there is evidence from an early version of his tidal theory that he was Copernican by 1595. The current version of the book is about half complete-there is an earlier version, but the revision is extensive-and I hope to return to it during the summer and complete it in the fall. Before that I have to write a shorter book on Renaissance astronomy for the Dibner Institute for the History of Science and Technology using illustrations from the Dibner Library that I hope to complete in the next couple of months. The project of editing, with Trevor Levere of the University of Toronto, the collected papers of Stillman Drake, the greatest scholar of Galileo of our age, for the University of Toronto Press is nearing completion. In the last few months I have gone through proofs of all three volumes. The first volume should appear very shortly, the second in the fall, and the third late this year or early next year. This is a very large and lengthy project - work began in 1993, the three volumes run over 1200 pages - and I believe the edition will be recognized as a major resource for the history of science. It has been a frightful amount of work, but worth it. Other papers completed in the course of the year include the article on “Planetary Theory from Eudoxus to Copernicus” for the *Encyclopedia of Astronomy and Astrophysics* and a paper on Ptolemy's cosmology that I have not yet decided where to publish. An editing project still awaiting publication after numerous delays is the volume *Ancient Astronomy and Celestial Divination*, to be published by MIT Press later this year, I hope.

PUBLICATIONS

- Review of Nachum Dershowitz and Edward F. Reingold, *Calendrical Calculations. Annals of the History of Computing* 20 (1998), 78.
- “Regiomontanus’s Concentric-Sphere Models for the Sun and Moon,” *Journal for the History of Astronomy* 30 (1999), 1-23.
- Review of *Nicolaus Copernicus Gesamtausgabe*, vi/1: *Briefe*, vi/2: *Urkunden, Akten und Nachrichten*, Ed. A. Kühne, in *Journal for the History of Astronomy* 29 (1998), 386-89.
- Review of Lis Brack-Bernsen, *Zur Entstehung der babylonischen Mondtheorie, Beobachtung und theoretischen Berechnung von Mondphasen*, in *Journal for the History of Astronomy* 30 (1999), 169-72.
- “Acronychal Risings in Babylonian Planetary Theory,” to appear in *Archive for History of Exact Science*.
- Ancient Astronomy and Celestial Divination*, Editor. Proceedings of a conference at the Dibner Institute for the History of Science and Technology in May of 1994.
- “The Derivation of the Parameters of Babylonian Planetary Theory with Time as the Principal Independent Variable,” to appear in *Ancient Astronomy and Celestial Divination*, Ed. N. Swerdlow.
- An Essay on Thomas Kuhn’s First Scientific Revolution, “The Copernican Revolution,” to appear in *The Legacy of Thomas S. Kuhn*.
- “Ptolemaic Astronomy,” to appear in *Encyclopedia of the Scientific Revolution*.
- “Copernicus,” to appear in *Encyclopedia of the Scientific Revolution*.
- “Planetary Theory from Eudoxus to Copernicus,” to appear in *Encyclopedia of Astronomy and Astrophysics*.
- “Stillman Drake,” in *Essays on Galileo and the History and Philosophy of Science* (with T. Levere, ed.), 3 vols. University of Toronto Press. To appear 1999.

3. EXPERIMENTATION**3.1 John E. Carlstrom**

John Carlstrom continues his research with Caltech graduate student Nils Halverson, Chicago graduate students Sam LaRoque and Erik Reese, and research associates Erik Leitch, Joe Mohr, and Clem Pryke. Questions on the origins of solar-like stars and planetary systems and on the origins of structure in the universe are both being pursued with new observational techniques and instrumentation. We are using interferometric techniques to enable detailed imaging of the cosmic microwave background which has been scattered by hot gas associated with clusters of galaxies, the Sunyaev Zel’dovich effect. Combining these measurements with x-ray observations allows an independent determination of the expansion history of the universe, as well as detailed information about these extremely large structures. A major expansion of this project, which includes building a dedicated ten element array of telescopes has been proposed. We are also finishing a novel new interferometric array to image the anisotropy in the cosmic microwave background radiation; the Degree Angular Scale Interferometer (DASI) will be fin-

ished this year and deployed to the South Pole in December 1999, where it will observe year-round. We are also using interferometric techniques to study the role of magnetic fields in the formation of nearby, young solar-like stars and their protoplanetary disks. The high resolution observations are enabled by a unique polarimetric system installed on the OVRO mm-wave array.

PUBLICATIONS

- “Sunyaev-Zel’dovich Effect as a Cosmological Probe,” Co-oray, A. R., Carlstrom, J. E., Joy, M., Grego, L., Holzapfel, W. L., & Patel, S. K 1998, *Dark Matter 1998*, Elsevier Science Pub., ed D. Cline.
- “The Degree Angular Scale Interferometer,” Halverson, N., Carlstrom, J. E., Dragovan, M., Holzapfel, W. L., *Symposium on Astrophysics from Antarctica*, ed. R. Landsberg and G. Novak, 1998 ASP Conference series, V141, p121.
- “DASI: A Degree Angular Scale Interferometer for Imaging Anisotropy in the Cosmic Microwave Background,” Halverson, N., Carlstrom, J. E., Dragovan, M., Holzapfel, W. L., Kovac, J. 1998, *Int’l Symp. on Astronomical Telescopes and Instruments*, SPIE 3357.
- “Interferometric Observation of Cosmic Microwave Background Anisotropies,” White, M., Carlstrom, J. E., Dragovan, M., 1999, *ApJ*, 514, 12.

3.2 Roger Hildebrand

During the last year our observations with the University of Chicago polarimeter, Hertz, at the Caltech Submillimeter Observatory have led to a wholly unexpected discovery. The surprise appeared when we compared the results of these observations at a wavelength of 350 μ m with results obtained at 60 μ m and 100 μ m with our earlier polarimeter, Stokes, on the Kuiper Airborne Observatory. Contrary to all predictions we found that the degree of polarization often depends strongly on the wavelength, in some cases rising steeply and in others falling. An analysis of the results indicates that in regions where the spectrum falls, typically in the envelopes of molecular clouds, the cloud medium must be heterogeneous. There must be warm domains containing aligned dust grains and cool domains containing unaligned grains. We speculate that low mass embedded stars may be responsible for the heterogeneous structure. Radiation from the stars may heat nearby material and also spin up the grains to suprathermal velocities thus enabling them to become aligned with the ambient magnetic fields. This picture supports a theory by Draine and Weingartner concerning sustained radiation torques on interstellar grains. It thus appears that measurements of the polarization spectrum point-by-point may reveal both the magnetic structure and the radiation structure of the clouds. The principles discovered in the course of this work have led us to make several predictions concerning the polarization spectra and thermal profiles in several astrophysical environments (e.g., a steeply rising spectrum in tenuous clouds). We are currently working on a conceptual design for a polarimeter for SOFIA, NASA’s new airborne observatory to be commissioned within the next three years. This instrument will provide the only access to the polarization spectrum in the range 60 to 200 microns, the range in which we

expect the most rapid dependence on wavelength. Also in the last year I have completed my work on the construction of an echelle spectrometer for the Apache point observatory. Don York took over responsibility for this instrument in December when we jointly obtained the first stellar spectra at the observatory. Two of my students, Darren Dowell and David Schleuning, received their Ph.D. degrees during the last year. Ramprasad Rao, a student of R. Crutcher at the University of Illinois, has recently completed his graduate work at the University of Illinois and has won the Grainger Postgraduate Fellowship of the University of Chicago Department of Physics. He will work with me and with John Carlstrom.

PUBLICATIONS

- “Submillimeter Polarimetry of Sagittarius,” A. G. Novak, J. L. Dotson, T. Renbarger, C. D. Dowell, R. H. Hildebrand, & D.A. Schleuning, in *Proceedings of IAU Symposium #184 on “The Central Regions of the Galaxy and galaxies”*, ed. Y. Sofue (Kluwer, Dordrecht), ASP San Francisco, (1998).
- “Hertz, an Imaging Polarimeter,” R.H. Hildebrand. J. L. Dotson, C.D. Dowell, D.A. Schleuning, & J. Vaillancourt, in *SPIE International Symposium on Astronomical Telescopes and Instrumentation*, (1998).
- “Submillimeter Array Polarimeter with Hertz,” C.D. Dowell, R.H. Hildebrand, D.A. Schleuning, J.L. Dotson, G. Novak, T. Renbarger, & M. Houde, *ApJ*, Sept. 1 (1998).
- “Samuel King Allison; November 13, 1900 - September 15, 1965,” R. H. Hildebrand, in *Biographical Memoirs*, Volume 76, pp 3-17. National Academy Press. (1998)
- “First Results of Spectropolarimetry at 60 m to 350 m,” R.H. Hildebrand, J. L. Dotson, C. D. Dowell, D.A. Schleuning, and J.E. Vaillancourt. *ApJ* , In press (1999)

3.3 Edward Kibblewhite

This year, the Chicago Adaptive Optics system (ChAOS) was removed from the 3.5-meter ARC telescope at Apache Point for refurbishing at Chicago. ChAOS achieved Strehl ratios of 0.15 at 0.85 microns in 1.6 arcsecond seeing conditions giving Strehl improvements of 14 at this wavelength. The performance of the system is currently limited by high frequency vibrations of the telescope. A program to reduce these vibrations was devised and is being carried out. Power spectra analysis of the angle of arrival of the wavefront also showed that there is more power at high frequencies due to atmospheric turbulence than is predicted by conventional theory and the data taken at other sites supports this conclusion. These data suggest that factors of 2-3 higher bandwidths may be required for high order AO systems over those predicted by the Greenwood and Tyler frequencies. A Prototype Adaptive optics Near Infra-red Camera (PANIC) was completed which will enable routine observations to be made at 1-2.3 micron wavelengths. A coronagraphic upgrade has been designed with a consortium based at New Mexico University. The sum frequency laser was transferred to the NOAO Vacuum Telescope Tower at Sac peak for photometric, beacon diameter and operational measurements. For an overall transmission of the telescope of 30beacons with a brightness equivalent to a 9.2 v magnitude star under median

sodium column densities. This laser has proved to be outstandingly reliable in the field and has the highest figure of merit of any laser currently under development. A major NSF grant was awarded this year to allow integration of the laser with the AO system on the 3.5 meter ARC telescope. Horizontal path experiments carried out at Yerkes using a laser source across Lake Geneva beamed to the 41 inch telescopes showed that phase-only adaptive optic correction can achieve substantial improvements in image quality even in the presence of severe scintillations and that the measured isoplanatic angle is larger than is usually assumed. Mathematical studies showed the importance of branch points under conditions of high scintillations and a robust technique was developed to minimise these effects. Software to generate optimal matrix coefficients for use in adaptive optics reconstructors continues to be improved. The latest version, A++, is now used throughout the adaptive optics community.

3.4 Stephan S. Meyer

The research in S. Meyer’s group centers on the investigation of the Cosmic Microwave Background Radiation (CMBR) anisotropy and the development of bolometric techniques useful for anisotropy measurements. We are part of the Microwave Anisotropy Probe (MAP) satellite team. MAP, which is scheduled to fly in late 2000, will make a full sky image of the CMBR anisotropy with 12’ resolution. The instrument makes measurements at four frequencies from 22 to 90 GHz to separate the CMBR signal from the galactic foregrounds. Our research has focussed on design of the instrument electronics and on the instrument testing and characterization. This year, the testing of the entire instrument in the spacecraft will be a major activity. Meyer is also a US collaborator on the High Frequency Instrument (HFI) of the Planck Satellite. The effort at Chicago is centered on the development of high efficiency polarization selective bolometers for the HFI instrument. The Chicago group is part of the TopHat collaboration which is preparing a balloon-borne instrument to measure a large part of the southern sky with a long-duration flight in late 1999. The TopHat instrument has five bolometric channels sensitive from 150 to 600 GHz. This instrument will provide a map of a 42 degree diameter area centered on the South Celestial Pole. With it’s high frequency sensitivity, it will complement MAP and other lower frequency experiments and have similar angular resolution and sensitivity. The sensitivity of the TopHat map is expected to be 20 μ K per beam after subtraction of a galactic dust component and cover 2500 square degrees centered on the south celestial pole.

3.5 Richard H. Miller

Numerical experiments, carried out on self-consistent, self-gravitating systems by means of fully three-dimensional N-body computer programs, are the best tool available today for studies in the dynamics of galaxies, clusters of galaxies, and star clusters. Relaxation effects are suppressed by using 100,000 to a million particles. The programs are extremely versatile. These experiments play the same part for galaxy

dynamics as laboratory experiments do in physics. Dynamics of Galaxies is a beautiful problem in Computational Physics. Beautiful objects (galaxies and star clusters) are studied by means of a beautiful formalism (Hamiltonian mechanics). Important discoveries have come from this work. These include, among others (1) that the nucleus of a galaxy orbits around the galaxy's mass centroid, which can cause the nucleus to appear slightly off-center or to have a velocity that differs from the rest of the galaxy by tens of km/sec, (2) that galaxies oscillate in normal modes with surprisingly large amplitudes, (3) that the strong contractions evident in galaxy collisions are normal modes of oscillation, (4) that barlike forms are dynamically preferred for rapidly rotating self-consistent stellar systems while the traditional axisymmetric disk-like form is dynamically unstable, and (5) that the gravitational N-body problem is chaotic. Recent work includes dynamical studies to determine whether a galaxy that forms around a pre-existing supermassive black hole look different from a galaxy that formed without one, and studies to find what physics must be invoked in order that clusters of galaxies may form with rounded central density profiles. Rounded centers have been found by Tyson and his co-workers through observational studies based on gravitationally lensed images. The problem is to find how the cluster profile can be rounded while the galaxies within it have cuspy centers. New experimental methods and techniques must be developed for each of these problems. They are challenging, but new discoveries are likely to follow.

4. OBSERVATION

4.1 Kyle M. Cudworth

Cudworth has continued his proper motion and photometric studies of star clusters using plates from the Yerkes 40-inch refractor and a variety of other telescopes, scanned on the PDS microdensitometer at MADRAF (located at the University of Wisconsin). While the primary long-term emphasis of this program is globular clusters, some work on open clusters has continued, as well as studies of dwarf spheroidal galaxies. Cudworth and Rees (U. Minn.) worked on improvements to the proper motions in NGC 6397 derived here a few years ago (but not yet published). Cudworth also further improved his new proper motion study of M15. Cudworth is continuing his collaboration with S. Majewski (Virginia) and others in a program to obtain proper motions for distant globulars and dwarf spheroidals. In addition to deriving membership for stars in these systems (many of which are very sparse) we are deriving tangential velocities using galaxies and QSO's to set the zero-point of the proper motions, thus allowing derivation of the orbits of the distant satellites and better constraining estimates of the mass of the Milky Way. A paper discussing the sparse globular Pal 5 is nearly complete, while some progress has been made on the studies of Pal 13, Pal 15, and Arp 2. Cudworth extended the thesis work by Schweitzer (former student at Wisconsin) on the proper motion of the UMi system. A journal paper describing the entire project, co-authored with Schweitzer and Majewski, has been submitted and is being revised. In addition to membership probabilities for stars over a large area of

UMi, they have derived an absolute proper motion of the system with unprecedented precision, yielding a total Galactocentric space velocity of 209 ± 20 km/s. Ursa Minor is moving along the Magellanic Stream in the same sense as the Large Magellanic Cloud. Cudworth and Hobbs are investigating the distance scale and kinematics of high $-|b|$ OB stars using radial velocities and HIPPARCOS proper motions. This is an extension of the program begun some years ago by Cudworth using photographic proper motions from Yerkes plates. K. Cudworth and H. Cudworth continued the Yerkes Space Explorer program which they started a few years ago, funded by NASA IDEA grants. This is an educational outreach directed toward middle-school students in communities near Yerkes Observatory. Students constructed 4-inch telescopes from kits and participated in astrophotography projects as well as other hands-on activities. R. Evans and C. Rockosi provided valuable assistance. A presentation regarding this program was made to the National Science Teachers Association meeting in Pittsburgh.

PUBLICATIONS

Schweitzer, A. E., Cudworth, K. M., & Majewski, S. R. (1997). "The Absolute Proper Motion and a Membership Survey of the Ursa Minor Dwarf Spheroidal Galaxy," (submitted to AJ)

4.2 Douglas K. Duncan

Duncan continues to serve as Education Coordinator for the American Astronomical Society. Recent research continues investigation of lithium, beryllium and boron abundances in stars of different metallicities, aimed to test the mechanisms responsible for the formation of the light elements and their evolution throughout galactic history. The initial suggestion made by Duncan, Lambert, and Lemke (Ap. J. 401, 552) that light elements may be mostly produced from spallation by cosmic rays (CR) originating in regions of massive star formation, rather than by CR protons and alpha particles in the general interstellar medium seems now to be confirmed by several theoretical investigations (e.g. Ramaty *et al.* 1997; Ap. J. 488, 730). Thesis student L.M. Rebull has published a determination of the B11/B10 isotopic ratio which produced a rough limit on the ratio in the metal-poor star HD 76932, with evidence for a possible blending feature in the spectrum. Her thesis research is a study of the rotation and disk evolution of young stars in the Orion Nebula region, based on a very large set of photometric and spectroscopic data obtained by S. Strom *et al.* Duncan continues experimenting with the use of peer, small-group instruction in large introductory astronomy classes for non-majors. Results last year documented a remarkable 88(positive) change in student attitudes about science. This experiment is being published by the National Institute for Science Education (NISE, at the U. of Wisconsin). Duncan has been named a Visiting Scholar of NISE.

PUBLICATIONS

Rebull, L. M., Hillenbrand, L. A., Strom, S. E., Duncan, D. K., Patten, B. M., Pavlovsky, C., Makidon, R., & Adams,

- M., "Circumstellar Disk Candidates Identified from UV Excesses in the Orion Nebula Cluster Flanking Fields," 2000, AJ, submitted
- Hobbs, L. M., Thorburn, J. T., & Rebull, L. M., "Lithium Isotope Ratios in Halo Stars III," 1999, ApJ, 523, 797
- Rebull, L. M., Duncan, D. K., Johansson, S., Thorburn, J. T., & Fields, B., "Limits on the Boron Isotopic Ratio in HD 76932,," 1998, ApJ, 507, 387
- Duncan, D. K., Rebull, L. M., Primas, F., Boesgaard, A. M., Deliyannis, C. P., Hobbs, L. M., King, J., & Ryan, S., "The Boron Abundance of BD-13D3442," 1998, A&A, 332, 1017
- Duncan, D. K., Primas, F., Rebull, L. M., Boesgaard, A. M., Deliyannis, C. P., Hobbs, L. M., King, J., & Ryan, S., "The Evolution of Galactic Boron and the Production Site of the Light Elements," 1997, ApJ, 488, 338
- Duncan, D. K. & Rebull, L. M., "Lithium in Young Solar-Type Stars in the Orion Nebula Region," 1996, PASP, 108, 738

4.3 Doyal A. Harper, Jr.

D. A. Harper's research focuses on observational studies of star formation, galactic evolution, and the physics of the interstellar medium. Observing infrared radiation from circumstellar and interstellar dust around young stars at the highest possible angular resolution yields information on the energetics of the sources, the nature of the interactions between the stars and their environments, and the composition of the interstellar material. Studying a variety of star-forming regions in our Galaxy and in other nearby galaxies provides clues to how the star-forming regions and interstellar medium evolve in time. Current observing projects include comparisons of the distribution of near-infrared emission from very small dust grains and PAH particles obtained with the 60-cm SPIREX telescope at the South Pole with observations of far-infrared radiation from large grains made with the 91-cm telescope of NASA's Kuiper airborne observatory. Both types of emission arise from grains heated by starlight, but trace different components of the interstellar dust and different parts of the transition regions between ionized and molecular gas. Of particular interest are recent observations of star-forming regions of the Large Magellanic Cloud. Understanding how star-formation differs in low-metallicity systems like the LMC and high-metallicity systems like the Milky Way illuminates how the first generations of stars and galaxies formed after the Big Bang. Harper's research group is also building a far-infrared facility camera for NASA's Stratospheric Observatory for Infrared Astronomy (scheduled to begin operation in 2002) and participating in design studies for a larger infrared telescope at the South Pole.

4.4 Lewis M. Hobbs

Since July 1, 1998, and with a variety of collaborators, I have carried out studies of (1) the light elements lithium and boron in the Galactic center today and in the early Galaxy, and of (2) the nearby interstellar medium. These investiga-

tions relied primarily upon high-resolution spectra obtained in the ultraviolet, optical, or radio wavelength regions. Some highlights of the work are the following.

4.4.1 Lithium and Boron in the Galactic Center

As reported in these pages last year, D. A. Lubowich (Hofstra Univ.), B. E. Turner (NRAO), and I searched for absorption toward the Galactic center at the 803 Mhz hyperfine-structure transition in the ground level of Li I and similarly at the 732 Mhz transition in the ground level of B I. No absorption was detected in either transition, although terrestrial interference severely limited the useful observing time, and hence the detection sensitivity, at the B I line. For the dense Sgr A molecular cloud at 20 km/s, we obtained upper limits $\text{Li}/\text{H} < 3.9 \times 10^{-8}$ and $\text{B}/\text{H} < 2.7 \times 10^{-6}$. The largest uncertainties in these final results arise from uncertainties in the ionization balances, Li I/Li and B I/B, and in the hydrogen column density $N(\text{H})$ in the molecular cloud. Nevertheless, the cited upper limits imply that the Galactic center has not had an extended period of AGN activity, a large flux of cosmic rays (including low-energy cosmic rays), or a large gamma-ray flux, and that the 2H previously measured by this method in the Galactic center originated primarily in the infall of primordial matter.

4.4.2 Lithium-6 in the Early Galaxy

J. Thorburn and L. Rebull (both U. of Chicago) and I analysed our high-quality observations of the Li I blend at 6707 Å in the spectra of four halo stars with metallicities in the range $-2.0 < [\text{Fe}/\text{H}] < -0.9$. No positive detections of the ${}^6\text{Li}$ isotope were found, at upper limits in the range $0.02 < {}^6\text{Li}/{}^7\text{Li} < 0.08$. With a goal of determining the evolution of the ${}^6\text{Li}$ abundance in the early Galactic gas in order to understand the nucleosynthetic origin of this isotope, we further collected and analyzed the accumulated ${}^6\text{Li}$ data reported so far for 18 halo stars by three different groups, including ours. The lighter Li isotope has been detected to date in the spectra of only two of the eighteen well-observed halo stars, and the subsequent depletion of any ${}^6\text{Li}$ initially present in the surface layers of most halo stars appears to provide an important barrier to more frequent detections of the lighter isotope. The extremely low cosmic proportions of both ${}^6\text{Li}$ and Be are expected to have been produced principally by the reactions of cosmic rays with the interstellar gas. The relatively high ${}^6\text{Li}/\text{Be}$ ratios measured in the two very old stars in whose spectra ${}^6\text{Li}$ has been detected are consistent with this prediction and indicate that most of the ${}^6\text{Li}$ was produced by the double-alpha fusion reaction, as would be expected at the relevant low metallicities.

4.4.3 Interstellar Matter

D. E. Welty and D. G. York (both U. of Chicago), J. T. Lauroesch (Northwestern U.), D. C. Morton (Herzberg Institute, Canada), L. Spitzer (Princeton U.), and I used the HST/GHRS to carry out the most comprehensive study to date of the various diffuse interstellar clouds found along the line of sight to a Galactic star. The target star was 23 Orionis, located at a distance of about 300 pc from the Sun. If additional higher-resolution data in the optical region are in-

cluded along with the predominantly UV data, we measured the strengths of more than 250 interstellar line transitions of 43 ionization stages of 24 elements. The data reveal the presence of at least 21 distinct absorbing clouds along the light path to the star, with a wide range of physical properties; in each of these clouds some subset of the indicated list of interstellar lines was definitely detected. These many data were then consistently synthesized into a comprehensive picture of the interstellar gas found along this light path. The different types of gas found include cold neutral, warm neutral, and at least two different kinds of warm ionized gas. The typical density, temperature, and elemental abundances in each kind of gas were estimated. Differences in the electron density within the cold, neutral gas that were deduced from the ionization balances of nine different elements suggest that processes other than photoionization and radiative recombination are important for some of these elements.

PUBLICATIONS

- D. E. Welty, P. C. Frisch, L. M. Hobbs, D. G. York, J. T. Lauroesch, J. C. Blades, G. Sonneborn 1998, "Interstellar Abundances in the Magellanic Clouds," IAU Symposium #190, in press.
- D. A. Lubowich, B. E. Turner, & L. M. Hobbs 1998, "A Search for Enhanced Galactic Center Lithium and Boron," *ApJ*, 508, 729
- L. M. Hobbs 1999, "Observations of ${}^6\text{Li}$ in Halo Stars," Proceedings of the LiBeB Workshop, December 1998, Paris, France, in press (invited review).
- L. M. Hobbs, J. A. Thorburn, L. M. Rebull 1999, "Lithium Isotope Ratios in Halo Stars. III," *ApJ*, 524, xxx (October 10, 1999 issue).
- D. E. Welty, L. M. Hobbs, J. T. Lauroesch, D. C. Morton, L. Spitzer, & D. G. York 1999, "The Diffuse Interstellar Clouds toward 23 Orionis," *ApJS*, in press.
- L. M. Hobbs 1999, "Stellar Lithium, Primordial Nucleosynthesis, and Cosmic Rays," *Physics Reports*, in press (invited review).

4.5 Stephen M. Kent

Stephen Kent continues work on the Sloan Digital Sky Survey in various capacities. The 2.5-m telescope and the imaging camera have been engaged in extensive commissioning activities and have collected imaging data for over 300 square degrees of sky along the celestial equator. Although these data is technically of engineering quality only, they have been used by various SDSS collaboration members to discover the highest redshift quasar, two new brown dwarfs, and a new comet, and are being used to study the distribution of stars in the outer halo of the Milky Way and to identify and correlate clusters of galaxies with ROSAT and FIRST catalogs. The first spectra have also been obtained and reduced. Stephen Kent was recently appointed head of the Experimental Astrophysics Group at Fermilab.

PUBLICATIONS

- "The Sloan Digital Sky Survey Camera," Gunn, J. E., *et al.*, *Astronomical Journal*, 116, 3040, 1998.

"High-Redshift Quasars Found in Sloan Digital Sky Survey Commissioning Data," Fan, X. *et al.*, *Astronomical Journal*, July 1999 issue.

4.6 Richard G. Kron

Richard Kron continued to work on the Sloan Digital Sky Survey as a member of the Experimental Astrophysics Group at Fermilab. One aspect of the effort leading up to the operations phase has been supervising the development (by graduate student Gordon Richards) of "survey strategy" software. These tools will provide a basis for planning the order in which the scans and spectroscopic exposures are taken in order to minimize the overall time-to-completion for the survey. Graduate student Bradford Holden worked with Kron on three projects. First, the Serendipitous High-Redshift Archival ROSAT Cluster survey (in collaboration with others) covers 200 square degrees using archival ROSAT PSPC pointings. This area is large enough to contain 40 luminous clusters of galaxies, including about 10 systems at redshifts greater than 0.3 with X-ray luminosities brighter than $5e_{44}$ ergs per second. This sample is expected to contain some of the most distant and massive systems known; Holden is completing the optical follow-up. Second, Holden, with M. Takamiya and Kron, is contributing to the Deep Extragalactic Evolutionary Probe by analyzing Hubble Space Telescope imaging data related to the evolution of the morphologies and stellar populations of distant field galaxies. Finally, Holden is working with the spectroscopic team of the Palomar Distant Cluster Survey. This project will measure the cluster mass function at redshifts near 0.5, which in conjunction with other samples is expected to provide strong constraints on the formation and evolution of massive structures.

4.7 Takeshi Oka

In collaboration with T.R. Geballe of the Joint Astronomy Centre, we have detected interstellar H^{3+} in dense clouds towards the direction of young stellar objects GL2136 and W33A using the CGS4 infrared spectrometer of UKIRT [T.R. Geballe and T. Oka, *Nature*, 384, 334 (1996)]. This has provided the most direct evidence for the ion-neutral reaction scheme for the chemical evolution of molecular clouds. Subsequent observations conducted under the leadership of graduate student Ben McCall in a sequence of 8 observational sessions encompassing 28 nights, in UKIRT with T.R. Geballe and at KPNO with K. Hinkle, have revealed that H^{3+} is abundant not only in dense clouds but also in diffuse clouds.

4.8 Patrick Palmer

My work contains two related themes: star formation and the nature of comets. These themes are related both phenomenologically - both involve study of cold, low density gases - and at a deeper level - comets provide the most pristine remaining samples of the material out of which our star, the Sun, formed. Because of the appearance of a truly great comet, comet Hale-Bopp in 1997, comets have taken up most of my time for the past several years. I participated in

many collaborations using optical and radio telescopes around the world to collect data on this comet. Now we are extremely busy analyzing this unique collection of data. In collaboration with Lewis E. Snyder and J. Veal (U. of Illinois), Imke de Pater and M. Wright (U. C. Berkeley), Michael A'Hearn and L. Woodney (U. of Md.) and others, I used the BIMA array to image both continuum and molecular line emission with a resolution of $\sim 10''$. We discovered emission from HCO^+ ; which, although well known in the interstellar medium, had never before been observed in a comet. We imaged the HCN emission on 13 dates near closest approach, which allowed us to 1) test that the photodissociation lifetime of HCN is in fact the accepted one, 2) determine the fractional abundance of HCN (relative to H_2O), and 3) study asymmetries in the emission - jets and the location of active regions on the nucleus. In another project, we imaged CS emission on three dates, with very similar goals. We found that the photodissociation lifetime of CS was in error by a factor of 10, which has implications for all previous reports of the abundance of CS in comets. We also analyzed 3mm continuum emission images, and found that at this wavelength, the nucleus is not visible because of the extended emission from the dust flowing away from the nucleus. In another project, with B. Butler (NRAO) and V. Strel'nitski (MMO), we searched for H_2O maser emission from comet Hale-Bopp. Such emission had been reported from several previous comets, but in many other cases, this emission had been searched for and not found. By searching in such an excellent comet on four different epochs with the VLA, which provided greater sensitivity than any previous search, we hoped to settle the question. We did not see any emission. I have started (or re-started) several projects on star formation while the comet data is being written up. The first is analysis of excited OH maser emission (observed with the VLA) from several regions of star formation. This emission seems to pick out the most active and youngest regions. Further analysis is continuing.

PUBLICATIONS

- “VLA Observations of the Sagittarius D Star-Forming Region,” Mehringer, D. M., Goss, W. M., Lis, D. C., Palmer, P., and Menten, K. M. 1998, *Ap. J.*, 493, 274.
- “BIMA and VLA Observations of Comet Hale-Bopp at 22 – 115 GHz,” de Pater, Imke, Forster, J. R., Wright, M., Butler, B., Palmer, P., Veal, J. M., A'Hearn, M. A., and Snyder, L. E. 1998, *A. J.*, 116, 987.



“Mosaiced Images and Spectra of $J=1-0$ HCN and HCO^+ Emission From Comet Hale-Bopp (1995 O1),” 1998, Wright, M. C. H., de Pater, I., Forster, J. R., Palmer, P., Snyder, L. E., Veal, J. M., A'Hearn, M. F., Woodney, L. M., Jackson, W. M., Kuan, Y.-J., and Lovell, A. J. 1998, *A.J.*, 116, 3018.

4.9 Donald G. York

Studies of the interstellar medium and intergalactic medium are underway using Earth-orbiting and ground-based spectrographs. For gas near the Sun, absorption lines of interstellar gas in stellar spectra are used to study abundances, ionization states, phases of the medium and the make-up of interstellar grains. The locations in space and the masses of interstellar clouds are being determined. Intergalactic gas is used to probe and map halos of galaxies to determine the distribution of light elements that may be products of primordial nucleosynthesis, and to study the temperature, pressure, and element evolution in the gas between the galaxies. Studies of such absorption lines in spectra of distant QSOs aid in discovering high redshift galaxies. The build-up of the elements through continuing nucleosynthesis is being used to chart galaxy evolution early in the history of the Universe. For the next few years, the primary instruments used will be the FUSE (Far Ultraviolet Spectroscopic Explorer), to observe hot UV objects to about 14th magnitude; the ARC 3.5-meter telescope at Apache Point Observatory, with an echelle spectrograph and a Fabry-Perot imager; the 2.5-meter telescope of the Sloan Digital Sky Survey (to construct a complete atlas of intergalactic absorption lines); and the Hubble Space Telescope STIS spectrograph, for studies of interstellar lines down to the FUSE magnitude limit.

5. WEBSITES

Updates on selected projects can be found on the World-wide Web: UC Astronomy & Astrophysics: <http://astro.uchicago.edu/> Sloan Digital Sky Survey: <http://www-sdss.fnal.gov.8000/> Yerkes Observatory: <http://astro.uchicago.edu/Yerkes.html> Apache Point Observatory: <http://www.apo.nmsu.edu/>

6. IN MEMORIAM

This report is dedicated to the memory of Walter J. Wild (October 11, 1954-January 11, 1999).