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This report covers the period July 1, 1999-June 30, 2000.

1. THEORY

1.1 Theoretical Cosmology Group

The Theoretical Cosmology group, which consists of faculty members S. Carroll, S. Dodelson, J.A. Frieman, W. Hu, 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 and on using astronomical observations to test theories of the early universe.

Current topics of research include inflationary cosmology, models with large extra dimensions, the origin of density perturbations, baryogenesis, particle dark matter and its detection, dark energy, primordial nucleosynthesis, the large scale structure of the Universe, anisotropies in the cosmic microwave background, gravitational waves, gravitational lensing, and the 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 physics beyond the Standard Model. Many of these interests have converged recently on the Sloan Digital Sky Survey, which will contain crucial information about large scale structure, information which, when properly analyzed, can be used to test inflation and models of the dark matter and dark energy.

Research associates currently working with the Theoretical Cosmology Group include M. Bernardi, D. Eisenstein, L. Fortson, E. Gates, M. Kaplinghat, M.T. Ressell, 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 J. Beacom (David N. Schramm Fellow), M. Blanton, P. Blasi, R. Sheth, 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.

Recently I have been focusing on models of the dark energy that appears to permeate the universe. I am particularly excited about models which allow the dark energy to be important not only today (Why should today be special?) but at all times in the past. We must also sharpen the predictions of existing theories. Towards that end, I am investigating some features of inflation that have not yet been explored. Most interesting is the possibility that physics at the Planck scale may impact the predictions of generic inflationary models. I am also working on a hydrodynamic code for cosmology which will enable us to follow the structure in the universe from early times until today. Finally, with the Sloan Digital Sky Survey starting up, I am looking at the spatial distributions of galaxies and quasars in the early SDSS data. These distributions contain information about the underlying mechanism responsible for structure in the universe, but also about such intriguing ideas as gravitational lensing and galaxy formation.

PUBLICATIONS

R. Scranton and S. Dodelson, ''Non-Linear Effects on the Angular Correlation Function,'' *submitted to MNRAS* astro-ph/0002360 (2000).

S. Dodelson, M. Kaplinghat, and E. Stewart, ''Tracking, Oscillating Energy,'' *to be published in Phys. Rev. Lett.* astro-ph/0003034 (2000).

S. Dodelson, ''Cosmic Microwave Background: Past, Future, and Present,'' *to be published in Int. J. Mod. Phys.* hep-ph/9912470 (1999).

P.M. Ricker, S. Dodelson, and D. Q. Lamb, ''COSMOS: A Hybrid N-Body/Hydrodynamics Code for Cosmological Problems,'' *Astrophys. J.* **536**, 122 (2000).

S. Dodelson and L. Knox, ''Dark Energy and the CMB,'' *Phys. Rev. Lett.* **84**, 3523 (2000).

S. Dodelson and E. Gaztanaga, ''Inverting the Angular Correlation Function,'' *Mon. Not. Roy. Ast. Soc.* **312**, 774 (2000).

G. W. Wilson *et al.*, ''New CMB Power Spectrum Constraints from MSAMI,'' *Astrophys. J.* **532**, 57 (2000).

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 Wayne Hu

I am a cosmological theorist and phenomenologist. My main interests center around the formation of structure in the universe and its relation to the dark side of the universe: namely the dark matter and dark energy that seems to pervade space.

We are fortunate to be in a time when the data that can help answer these fundamental questions is literally flooding in. I have devoted much of my recent research to two such sources: the Cosmic Microwave Background and the weak gravitational lensing of faint galaxies. The tools needed to understand these data sets encompass both analytical and numerical elements. The former involves relativistic perturbation theory, simple radiative transfer and fluid dynamics. The latter includes cosmological simulations and data analysis.

PUBLICATIONS

''Gravitational Time Delay Effects on CMB Anisotropies'' (with A.R. Cooray) astro-ph/0008001

''CMB Observables and Their Cosmological Implications'' (with M. Fukugita, M. Zaldarriaga, and M. Tegmark) astro-ph/0006436

''Delayed Recombination'' (with P.J.E. Peebles and S. Seager) *Astrophys. J. Lett.* **539**, L1 (2000)

''Ringing in the New Cosmology'' *Nature* **404** 939 (2000)

''Weak Gravitational Lensing Bispectrum'' (with A.R. Cooray) astro-ph/004151

''Cold and Fuzzy Dark Matter'' (with R. Barkana and A. Gruzinov) *Phys. Rev. Lett.* **85** 1158 (2000)

''Weak Lensing by Large-Scale Structure: A Dark Matter Halo Approach'' (with A.R. Cooray and J. Miralda-Escude) *Astrophys. J. Lett.* **535** L9 (2000)

''Large-Scale Sunyaev-Zel'dovich Effect: Measuring Statistical Properties with Multifrequency Maps'' (with A.R. Cooray and M. Tegmark) *Astrophys. J.* **540** 1 (2000)

''Weak Lensing of the CMB: A Harmonic Approach'' *Phys. Rev. D.* **62** 043007 (2000)

''Imprint of Reionization on the Cosmic Microwave Background Bispectrum'' (with A.R. Cooray) *Astrophys. J.* **534** 533 (2000)

''A Model for Structure Formation seeded by Gravitationally Produced Matter'' (with P.J.E. Peebles) *Astrophys. J. Lett.* **528** 61 (2000)

''A New Algorithm for Computing Statistics of Weak Lensing by Large-Scale Structure'' (with M. White) *Astrophys. J.* **537** 1 (2000)

''Reionization Revisited: Secondary CMB Anisotropies and Polarization'' *Astrophys. J.* **529** 12 (2000)

''Foregrounds and Forecasts for the Cosmic Microwave Background'' (with M. Tegmark, D.J. Eisenstein, and A. de Oliviera Costa) *Astrophys. J.* **530** 133 (2000)

1.3 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 model. 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

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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, **43**, 67.

1.4 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.

1.5 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, and analytical and computational studies of both laboratory and astrophysical fluids and plasmas (especially in the context of stellar convection, stellar magnetic field generation and stellar activity).

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. Most recently, we have been engaged in a major initiative in computational fluid dynamics aimed at combustion and transient nucleosynthesis (as occurs in X-ray bursts, novae and Type Ia supernovae).

PUBLICATIONS

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Litwin, C., Rosner, R., & Lamb, D.Q. (1999) ‘‘On Accretion Flow Penetration of Magnetospheres,’’ MNRAS, 310, 324-30.

Litwin, C., Rosner, R., & Lamb, D.Q. (1999) ‘‘Accretion Streams in Magnetic Binaries,’’ Plasma Phys. Control. Fusion, 41, B343-B350.

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Young, Y.-N., & Rosner, R. (2000) ‘‘Numerical Simulation of Double-Diffusive Convection in a Rectangular Box,’’ Phys. Rev. E, 61(3), 2676-2694.

Rosner, R. (2000) ‘‘Magnetic Fields of Stars: Using Stars as Tools for Understanding the Origins of Cosmic Magnetic Fields,’’ Phil. Trans. R. Soc. Lond. A, 358, 689-709.

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Peres, G., Orlando, S., Reale, F., Rosner, R., & Hudson, H. (2000) ‘‘The Sun as an X–ray Star. II: Using the Yohkoh/SXT-derived Solar Emission Measure vs. Temperature to Interpret Stellar X-ray Observations,’’ ApJ, 528, 537-551.

Fryxell, B., Olson, K., Ricker, P., Timmes, F.X., Zingale, M., Lamb, D.Q., P. MacNeice, P., Rosner, R., Truran, J.W., & Tufo, H. (2000) ‘‘FLASH: A Multidimensional Hydrodynamics Code for Modeling Astrophysical Thermonuclear Flashes,'' ApJ Suppl., in press.

Vainshtein, S., Mikic, Z., Rosner, R., & Linker, J. (2000) ''Evidence for Topological Nonequilibrium in Magnetic Configurations,'' Phys. Rev. E, 62, 1245-51.

Timmes, F.X., Zingale, M., Olson, K., Fryxell, B., Ricker, P., Calder, A.C., Dursi, L.J., Tufo, H., MacNeice, P., Truran, J.W., & Rosner, R. (2000) ''On the Cellular Structure of Carbon Detonations,'' ApJ, in press.

Micono, M., Bodo, G., Massaglia, S., Rossi, P., Ferrari, A., & Rosner, R. (2000) ''Kelvin-Helmholtz Instability in Three-Dimensional Radiative Jets,'' A&A, in press.

1.6 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 understanding 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.

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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.

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Kercek, A., Hillebrandt, W., & Truran, J.W., ''Two and Three Dimensional Simulations of Classical Novae,'' Workshop on Fluid Dynamics, Bordeaux, France, p. 14, 1998.

1.7 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 collisionless 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.

''On a Matrix Method for the Study of Small Perturbations in Galaxies,'' MNRAS, to be submitted.

2. HISTORY

2.1 Noel M. Swerdlow

My principal project this year has been a book on Renaissance astronomy that has become considerably longer than anticipated. It is to be published by the Burndy Library of the Dibner Institute for the History of Science and Technology through MIT Press and will contain many plates from books in the library so it should be quite a handsome volume. The chapters are on the five principal astronomers of the period: Regiomontanus, Copernicus, Tycho, Kepler, and Galileo, and I have attempted as comprehensive descriptions of their work as I could within the limits of a general survey of this large subject. Nothing before has been done on this scale. As of writing this report, the chapters on Regiomontanus, Copernicus, Kepler, and Galileo are completed, and Tycho is in progress. The chapter on Regiomontanus is particularly interesting as I have used his Epitome of the Almagest to write an exposition of Ptolemy's astronomy as it was understood in this period, which is essential to understanding the work of the later astronomers. I have also included translations of texts that have not before been translated, of which the most important is Regiomontanus's Oration on the Mathematical Sciences given at Padua in 1464, I believe the most important single document on the relation of science and humanism in the Renaissance. The chapter on Copernicus is in large part an exposition of De revolutionibus, the chapter on Kepler of the Astronomia nova and Epitome of Copernican Aastronomy, with briefer treatment of the Mysterium Cosmographicum, Harmonice mundi, and Rudolphine Tables. The chapter on Galileo treats most of his astronomical work, and I have deferred my longer work on Galileo's astronomy and conflicts with the Church, to which I will return when this book is completed.

Two projects which I edited and to which I contributed have finally appeared this year. One is the collection Ancient Astronomy and Celestial Divination published by MIT Press, a collection of papers presented at a conference at the Dibner Institute. The papers are on Babylonian astronomy and astrology and on Greek astronomy. The other, which took many years, is an edition, with Trevor Levere of the University of Toronto, of most of the published papers of Stillman Drake on Galileo and other subjects in the history of science. It is in three volumes running to over 1200 pages, published by the University of Toronto Press. As Drake was the greatest Galileo scholar of our age, the edition will be recognized as an essential contribution to Galileo studies and to the history of science, and of course it can be reprinted indefinitely, a fitting tribute to Drake's work. I am very proud of having worked on this as I believe a collected edition is the greatest honor one can pay to a scientist or scholar.

PUBLICATIONS

Ancient Astronomy and Celestial Divination. Ed. N.M. Swerdlow. MIT Press, 1999.

The Derivation of the Parameters of Babylonian Planetary Theory with Time as the Principal Independent Variable. *Ancient Astronomy and Celestial Divination* (1999), 255-98.

Stillman Drake. *Essays on Galileo and the History and Philosophy of Science.* Ed. N.M. Swerdlow and T.H. Lever. 3 vols. University of Toronto Press, 1999.

Acronychal Risings in Babylonian Planetary Theory. *Archive for History of Exact Science* 54 (1999), 49-65.

Kepler's Iterative Solution to Kepler's Equation. *Journal for the History of Astronomy* 31 (2000), 339-41.

Planetary Theory from Eudoxus to Copernicus. *Encyclopedia of Astronomy and Astrophysics*, 2000.

Ptolemaic Astronomy. *Encyclopedia of the Scientific Revolution*, 2000.

Copernicus. *Encyclopedia of the Scientific Revolution*, 2000.

Review of Thomas Gold, *The Deep Hot Biosphere. Perspectives in Biology and Medicine* 43 (2000), 598-608.

An Essay on Thomas Kuhn's First Scientific Revolution, *The Copernican Revolution.* To appear in a collection of papers on Thomas S. Kuhn.

Review of Lis Brack-Bernsen, *Zur Entstehung der babylonischen Mond theorie, Beobachtung und theoretischen Berechnung von Mondphasen.* To appear in *The Bulletin of the School of Oriental and African Studies.*

Review of Alexander Jones, *Astronomical Papyri from Oxyrhynchus. To appear in Historia Mathematica.*

3. EXPERIMENTATION

3.1 John E. Carlstrom

John Carlstrom continues his research with Caltech graduate student Nils Halverson, Chicago graduate students Gil Holder, Mike Joffre, John Kovac, Sam LaRoque, Daisuke Nagai, and Erik Reese, and research associates Joe Mohr, Erik Leitch, Amber Miller, Clem Pryke and Ramprasad Rao.

Questions on the origins of structure in the universe and on the origins of solar-like stars and planetary systems are being pursued with new observational techniques and instrumentation. They 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 array of telescopes has been proposed. They have also deployed to the Amundsen-Scott South Pole station the Degree Angular Scale Interferometer (DASI), a novel new interferometric array to image the anisotropy in the cosmic microwave background radiation. Analyses of the first year's data is now being completed.

They 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

''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 Observations of Cosmic Microwave Background Anisotropies,'' White, M., Carlstrom, J. E., Dragovan, M., Holzapfel, W. L. 1999, ApJ, 514, 12.

''Imaging the Sunyaev Zel'dovich Effect,'' J. E. Carlstrom, M. Joy, L. Grego, E. Reese, S. Patel, G. Holder, A. Cooray, and W. L. Holzapfel 2000, Physica Scripta, 85, 148, astro-ph/9905255.

''Sunyaev-Zel'dovich Effect Derived Distances to the High Redshift Clusters MS 0451.6–0305 and CL 0016 +16,'' Reese, E. D., Mohr, J. J., Carlstrom, J. E., Joy, M. Grego, L., Holder, G. P., Holzapfel, W. L., Hughes, J. P., Patel, S., 2000, ApJ, 533, 30. astro-ph/9912071

''Galaxy Cluster Gas Mass Fractions from Sunyaev-Zel'dovich Effect Measurements: Constraints on Ω_M,'' Grego, L., Carlstrom, J. E., Joy, M. K., Reese, E. D., Holder, G. P., Patel, S., Cooray, A. R. and Holzapfel, W. L. 2000, ApJ, in press.

''Expectations For an Interferometric Sunyaev-Zel'dovich Effect Survey for Galaxy Clusters,'' Gilbert P. Holder, Joseph J. Mohr, John E. Carlstrom, August E. Evrard, Erik M. Leitch, 2000, ApJ, in press. astro-ph/9912364

3.2 Roger Hildebrand

Measurements of polarization with the University of Chicago polarimeters, Stokes, on the Kuiper Airborne Observatory and Hertz, at the Caltech Submillimeter Observatory have shown a steep drop in the degrees of polarization between 60 and 350 microns (Hildebrand *et al.* 1999). Comparison of these results with those from the instrument SCUBA at the JCMT have shown that the degrees increase again between 350 and 850 microns. We have argued that in the range 60 to 850 microns one should expect a flat spectrum for a homogeneous dust cloud of any grain composition, but that the observed polarization spectrum could be explained in a heterogeneous cloud containing domains at different temperatures where the efficiency of grain alignment is correlated with the temperatures of the various domains (Hildebrand *et al.* 2000). It 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 predictions concerning the polarization spectra and thermal profiles in several astrophysical environments (e.g., a steeply rising spectrum in tenuous clouds). Graduate student, John Vaillancourt, is testing the model we have proposed for the polarization spectrum by comparing polarization spectra and temperature distributions, point by point. To derive the temperature distributions he is inverting flux density spectra from the results of various far-IR and SMM flux maps.

Former student, Darren Dowell, now at Caltech, is using results from Hertz to derive the ratio of the turbulent to uniform magnetic field components in molecular clouds. This investigation, still in an early stage, shows a turbulent component equal to or greater than the uniform component.

We are currently working on the conceptual design of a polarimeter, ''Hale,'' for SOFIA, NASA's airborne observatory now uder construction. 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. The members of the Hale team include Jessie Dotson (Ames), Jackie Davidson (USRA), Darren Dowell (Caltech), Roger Hildebrand (Chicago), Terry Jones (Minnesota), Giles Novak (Northwestern), Ram Rao (Chicago), John Vaillancourt (Chicago), Mike Werner (JPL), and Ellen Zweibel (Colorado).

PUBLICATIONS

Polarimetry and Magnetic Fields. R. H. Hildebrand. In Millimeter-Wave Astronomy: Molecular Chemistry & Physics in Space, 115-126. W. F. Wall et al. (eds.), Klewer Academic Publishers (1999)

The Far-Infrared Polarization Spectrum: First Results and Analysis. R. H. Hildebrand, J. L. Dotson, C. D. Dowell, D. A. Schleuning, and J. E. Vaillancourt. 1999, ApJ, 516: 834

Summary of Results from Far-Infrared Polarimetry. J. L. Dotson, C. D. Dowell, D. A. Schleuning, & R. H. Hildebrand. 2000, ApJS, 128, 335 - 370

Submillimeter Polarimetric Observations of the Galactic Center. G. Novak, J. L. Dotson, C. D. Dowell, R. H. Hildebrand, T. Renbarger, & D. A. Schleuning. 2000, ApJ, 529, 241-250

Probing the Magnetic Field Structure in the W3 Molecular Cloud. D. A. Schleuning, J. E. Vaillancourt, R. H. Hildebrand, C. D. Dowell, G. Novak, J. L. Dotson, & J. A. Davidson.2000, ApJ, 535, 913

A Primer on Far-Infrared Polarimetry. R. H. Hildebrand, J. A. Davidson, J. L.Dotson, C. D. Dowell, G. Novak, and J. E. Vaillancourt. 2000, PASP, 112, 1215

Interstellar Magnetic Fields and Infrared-Submillimeter Spectropolarimetry. R. H. Hildebrand. In ''Astrophysical Spectropolarimetry'' Cambridge University Press (2001) (In press)

3.3 Edward Kibblewhite

In 1998-99, the Chicago Adaptive Optics system (ChAOS) was removed from the 3.5-meter ARC 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 coronographic upgrade has been designed with a consortium based at New Mexico University. The sum frequency laser was transfered 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 coefficents 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 μK 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

The 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). 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 do laboratory experiments in physics.

Important discoveries have come from this work. These include, among others (1) that the gravitational N-body problem is chaotic, (2) that galaxies oscillate in normal modes with surprisingly large amplitudes, (3) 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, (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 strong contractions evident in galaxy collisions are normal modes of oscillation.

Recent work includes: (1) A return to the problem of interpreting $n-$body integrations when the underlying process is chaotic. The $n-$body equations of motion appear to provide no constraints beyond seeking maximum phase volume while conserving the ten first integrals, according to the standard tests normally used to compare various computer models. (2) Dynamical 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 to permit the quantitative measures that allow alternatives to be tested against observation. Developing them is 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 is continuing his collaboration with S. Majewski (Virginia) and his team 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. In the past year studies of the faint globulars Pal 12 and Pal 13 were completed in this long-term program. We found the space velocity of Pal 12 to be most consistent with this cluster having been tidally captured from the Sagittarius dwarf galaxy, rather than from the Large Magellanic Cloud as previously suggested by others. Pal 13, on the other hand, is apparently being disrupted by the Galaxy, but its kinematics are not clearly identified with any other Milky Way satellite of known orbit.

K. and H. Cudworth continued the Yerkes Space Explorer program which they started a few years ago. This is an educational outreach directed toward middle-school students in communities near Yerkes Observatory. The student's activities this year were primarily related to telescopes and deep-sky objects.

PUBLICATIONS

''The Absolute Proper Motion of Palomar 12: A Case for Tidal Capture from the Sagittarius Dwarf Spheroidal Galaxy'' Dinescu, D. I., Majewski, S. R., Girard, T. M., & Cudworth, K. M. 2000, AJ (in press)

''Pal 13's Last Stand'' Siegal, M. H., Cudworth, K. M., Majewski, S. R., Takamiya, M. 2000, (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).

L.M. Rebull has completed her thesis research, which 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), for which Duncan is a Visiting Scholar.

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 L.M. Hobbs

During the year that began on July 1, 1998, and with a variety of collaborators, I have carried out studies of (1) lithium and boron in the Galactic center and of lithium in nearby metal-poor stars, and of (2) the nearby interstellar medium. These investigations 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 $Li/H < 3.9 \times 10^{-8}$ and $B/H < 2.7 \times 10^{-6}$. 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(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 $-2.0 < [Fe/H] < -0.9$. No positive detections of the 6Li isotope were found, at upper limits in the range $0.02 < {}^6Li/{}^7Li < 0.08$. With a goal of determining the evolution of the 6Li abundance in the early Galactic gas in order to understand the nucleosynthetic origin of this isotope, we further collected and analyzed the accumulated ^{6}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}Li that was initially present in the surface layers of most halo stars appears to provide an important barrier to more frequent detections of the lighter isotope. Both ^{6}Li and Be are expected to have been produced principally by the reactions of cosmic rays with the interstellar gas. The relatively high ^{6}Li/Be ratios measured in the two very old stars in whose spectra ^{6}Li has been detected are consistent with this prediction and indicate that most of the ^{6}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 included 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. Differing values of 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}Li in Halo Stars,’’ ASP Conference Series, 171, 23 (invited paper).

L. M. Hobbs, J. A. Thorburn, L. M. Rebull 1999, ‘‘Lithium Isotope Ratios in Halo Stars. III,’’ ApJ, 523, 797.

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, 124, 465.

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 and formal observing activities and have collected imaging data for over 1700 square degrees of sky. Several fundamental discoveries have been made, including the detection of weak gravitational lensing, additional L and T dwarf stars, substructure in the Milky Way halo, and tidal stripping of a globular cluster. The spectroscopic systems have been fully commissioned, and spectroscopy is now reaching full operation status. Over 30,000 redshifts of galaxies and quasars have been obtained, including a record of over 4000 spectra in one night. Stephen Kent continues as head of the Experimental Astrophysics Group at Fermilab.

PUBLICATIONS

''Discovery of a Field Methane Dwarf from Sloan Digital Sky Survey Commissioning Data ,'' Strauss, M. A., Fan, X., Gunn, J. E., Leggett, S. K., Geballe, T. R., Pier, J. R., Lupton, R. H., Knapp, G. R., Annis, J., Brinkmann, J., Crocker, J. H., Csabai, I., Fukugita, M., Golimowski, D. A., Harris, F. H., Hennessy, G. S., Hindsley, R. B., Ivezic, Z., Kent, S., Lamb, D. Q., Munn, J. A., Newberg, H. Jo, Rechenmacher, R., Schneider, D. P., Smith, J. A., Stoughton, C., Tucker, D. L., Waddell, P., York, D. G., Astrophysical. Journal. Letters, 552, L61, 1999.

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''Identification of A-colored Stars and Structure in the Halo of the Milky Way from SDSS Commissioning Data,'' Yanny, B., Newberg, H. J., Kent, S., Laurent-Muehleisen, S. A., Pier, J. R., Richards, G. T., Stoughton, C., Anderson, J. E., Annis, J., Brinkmann, J., Chen, B., Csabai, I., Doi, M., Fukugita, M., Hennessy, G. S., Ivezic, Z., Knapp, G. R., Lupton, R., Munn, J. A., Nash, T., Rockosi, C. M., Schneider, D. P., Smith, J. A., York, D. G., Astrophysical Journal, (in press), 2000.

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. Among other tasks, Kron has helped define and monitor performance metrics for the operations at Apache Point Observatory; these metrics aid in assessing the progress in mapping the sky on a continuing basis.

Kron, Fermilab astrophysicist James Annis, and graduate student Brian Wilhite have begun to look at images of selected large galaxies in the Sloan Digital Sky Survey from the perspective of stellar populations, using the color maps (color versus intensity for each pixel) as a diagnostic of age distribution, dust content, and other attributes of the population.

Wilhite has contributed to the performance evaluation of the automated SDSS spectroscopic analysis software by direct and systematic checks of the redshift determinations and object type classifications. Kron, in collaboration with B. Holden (LLNL) and M. Ulmer (Northwestern U.) and others, has used the ARC 3.5-m telescope to detect faint cluster galaxies (SDSS i and z bands) at the locations of extended X-ray sources as part of a larger project to find X-ray emitting rich clusters at large redshift. So far one out of four candidate sources plausibly fits that description, based on red colors and positional coincidence, but a spectroscopic redshift is required to secure the case.

PUBLICATIONS

Romer, A. K.; Nichol, R. C.; Holden, B. P.; Ulmer, M. P.; Pildis, R. A.; Merrelli, A. J.; Adami, C.; Burke, D. J.; Collins, C. A.; Metevier, A. J.; Kron, R. G.; and Commons, K. (2000), The Bright SHARC Survey: The Cluster Catalog. The Astrophysical Journal Supplement Series, Volume 126, Issue 2, pp. 209-269. (ApJS Homepage)

4.7 Takeshi Oka

We have observed $H_3 3^+$ in dense molecular clouds toward six young stellar objects (1). The observation provides information on fundamental properties of the cloud, the path length, numberd ensity and temperature.

We have observed $H_3 3^+$ also in the diffuse interstellar medium toward the Galactic Center and Cygnus OB2 No.12 (2). The observed high column densities of $H_3 3^+$ had not been anticipated and introduce an enigma on the chemistry of the diffuse interstellar medium.

Much of these results have been discussed in a discussion meeting in February 2000 whose proceedings has been published (3).

We have also observed C_2, CO, CH, and CN in the diffuse clouds to obtain information on the chemistry of such medium.

We have studied diffuse interstellar bands attributed to C_7^- in order to test the extremely good match between the observed absorption and laboratory data (4).

PUBLICATIONS

B. J. McCall, T. R. Geballe, K. H. Hinkle, and T. Oka, ''Observations of H_3^+ in Dense Molecular Clouds,'' Astrophysical Journal, 522, 338 (1999).

T. R. Geballe, B. J. McCall, K. H. Hinkle, and T. Oka, ''Detection of H_3^+ in the Diffuse Interstellar Medium: The Galactic Center and Cygnus OB2 No. 12,'' Astrophysical Journal, 510, 251(1999).

''Astronomy, Physics, and Chemistry of H_3^+,'' Philosophical Transactions of the Royal Society of London, Series A, 358, 2351 (2000).

B. J. McCall, D. G. York, and T. Oka, ''Observations of Diffuse Interstellar Bands Attributed to C_7^-,'' Astrophysical Journal, 531, 329 (2000).

4.8 Patrick Palmer

In the past year I have had two goals: to finish analysis of data obtained on comet Hale-Bopp and to begin some studies of Galactic masers.

Really great comets are rare. Therefore the work on Hale-Bopp in 1997, was carried out with a large number of collaborators and used a number of telescopes, but primarily the VLA and the BIMA array. Several papers (listed at the end) were published this year; and, more recently, we have finished papers on a re-determination of the photo-dissociation lifetime of CS, and a comparison of the morphology of optical CN lines with radio HCN lines to access the argument that CN in comets originates from photo-dissociation of HCN. There is still more of this data to analyze.

Other solar system studies this year were: finishing analysis of a radar study of the asteroid 6489 Golevka, and observations of Comet LINEAR (C/1999 S4) with both the VLA and the BIMA array. However, this comet turned out to be a disappointment – it was much fainter than predicted.

A number of transitions of several interstellar molecules are known to form interstellar masers. One of the most uncommon and puzzling of these of these is formaldehyde. Only three Galactic sources are known to show these masers despite extensive searches by ourselves and others. Therefore the next step was to make more precise measurements of the known sources. This Fall, Miller Goss (NRAO) and I we used the Very Long Baseline Array to measure the angular sizes of these sources. This data is currently being processed.

Last summer, F. Yusef-Zadeh (Northwestern) and I began reductions and analysis of data we obtained in a study of the hydrogen recombination lines in the Orion Nebulae with the VLA. This data has angular resolution of 10″ over the inner 10′ of the nebula. It is very well suited for comparison with previous radio studies we made as well as with HST images of Orion obtained by C. R. O'Dell.

PUBLICATIONS

''An Interferometric Study of HCN in Comet Hale-Bopp (C/1995 O1)'' 1999, Veal, J. M., Snyder, L. E., Wright, M., Woodney, L. M., Palmer, P., Forster, J. R., de Pater, I., and Kuan, Y.-J. 2000, Ap. J., 119, 1498.

''Water Emission from Comets'' Graham, A. P., Butler, B. J., Palmer, P.and Strelnitski, V. 2000, Ap. J., 119, 2465.

''Radar Observations and Physical Modeling of Asteroid 6489 Golevka'' 2000, Hudson, R. S., Ostro, S. J., Jurgens, R. F., Rosema, K. D., Giorgini, J. D., Winkler, R., Rose, R., Choate, D., Cormier, R. A., Franck, C. R., Frye, R., Howard, D., Kelley, D., Littlefair, R., Slade, M. A., Benner, L. A. M., Thomas, M. L., Mitchell, D. L., Chodas, P. W., Yoemans, D. K., Scheeres, D. J., Palmer, P., Zaitsev, A., Koyama, Y., Nakamura, A., and Harris, A. W., 2000, Icarus (accepted 6/7/00).

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.

4.9.1 P.C. Frisch

Frisch and collaborator Dr. Jon Slavin (Smithsonian), have modeled elemental ionization and abundances in the warm diffuse interstellar material closest to the Sun (the 'Local Fluff'). Local Fluff ionization levels provide key information for determining the chemical composition of interstellar matter (ISM) from observations of pickup ions and anomalous cosmic rays. They also help interpret data for more distant clouds, where the spatial isolation of individual 'cloudlets' is difficult. The CLOUDY photoionization code is used, combined with the double constraints of column densities towards nearby stars (e.g. H I, C II, C II*, N I, O I, Mg I, Mg II), and interstellar neutrals observed as pickup ions inside of the heliosphere (He, N, O, Ne). Together, the data and models place tight constraints on photoionization in the Local Fluff and gas-phase elemental abundances. In particular, column densities constrain overall cloud properties, while the pickup ion data constrain interstellar cloud properties at the entry point to the heliosphere. The results of these calculations are being prepared for publication in the Astrophysical Journal.

Frisch has continued collaborations with others to look at the properties of interstellar dust within the solar system in order to better understand the properties of interstellar dust in the Local Fluff, the coupling between dust and gas in the Local Fluff, the chemical composition of the Local Fluff, and the total gas-to-dust mass ratio in the Local Fluff. These collaborations have resulted in several publications [1],[3]. The gas-to-dust mass ratios found for interstellar dust within the solar system, versus values determined astronomically for the cloud around the solar system, suggest that large and small interstellar grains have separate histories and that large interstellar grains preferentially detected by Ulysses and Galileo spacecraft are not formed exclusively by mass exchange with nearby interstellar gas. An in situ value for the gas-to-dust mass ratio of $R_{g/d}=94(+46,-38)$ is found, where this ratio is dominated by the larger near-micron-sized grains. This ratio is reduced when excluded smaller grains are included. The gas-to-dust mass ratios are also derived by combining spectroscopic observations of the gas-phase abundances in the nearest interstellar clouds. Measurements of interstellar absorption lines formed in the cloud around the solar system, as seen in the direction of epsilon CMa, give $R_{g/d}=427(+72,-207)$ for assumed solar reference abundances and $R_{g/d}=551(+61,-251)$ for assumed B star reference abundances (and using Gry *et al.* data). These values exceed the in situ value suggesting either that grain mixing or grain histories are not correctly understood or that swept-up stardust is present. The cloud surrounding the solar system exhibits enhanced gas-phase abundances of refractory elements such as Fe II and Mg II, indicating the destruction of dust grains by shock fronts. The good correlation locally between Fe II and Mg II indicates that the gas-phase abundances of these elements are dominated by grain destruction, while the poor correlation between Fe II and HI indicates either variable gas ionization or the decoupling of neutral gas and dust over parsec scale lengths. These abundances, combined with grain destruction models, indicate that the nearest interstellar material has been shocked with shocks of velocity 150 km s^{-1}.

Frisch has continued her investigation into the journey of the Sun, and the influence of the galactic environment of the Sun on the interplanetary environment and heliosphere properties. The dynamical interaction between the heliosphere and interstellar material (ISM) establishes the physical characteristics of the interplanetary environment. The physical properties of interstellar matter through which the Sun has passed show that the heliosphere has been relatively large for the past few million years.

Frisch and Dr. Garry Zank (Bartol Research) continued an investigation of the influence of an encounter between a dense cloud and the heliosphere. The possibilities of interstellar matter affecting terrestrial climates has attracted interest since the late 1920s. Recent models describing the solar wind-local interstellar medium (LISM) interaction self-consistently have provided the tools for accurately evaluating these interactions. Zank and Frisch modeled the interaction between the heliosphere and an interstellar cloud with the same properties as currently, except that the H I density is increased from the present value of n(H I) 0.2 cm^{-3} to 10 cm^{-3}. The interplanetary environment at the orbit of the Earth was found to changes dramatically, with the density of interstellar H I increasing to 2 cm^{-3}. The termination shock itself experiences periods where it disappears, reforms, and disappears again, and Rayleigh-Taylor-like instabilities appear in the nose region. The calculation presented here supports past speculation that the Galactic environment of the Sun moderates the interplanetary environment at the orbit of the Earth and possibly also the terrestrial climate.

In addition, several other papers have been published (e.g. Welty, Frisch, *et al.*) and papers were presented at several meetings.

PUBLICATIONS

P. C. Frisch, J. M. Dorschner, J. Geiss, J. M. Greenberg, E. Gruen, M. Landgraf, P. Hoppe, A. P. Jones, W. Kraetschmer, T. J. Linde, G. E. Morfill, W. Reach, J. D. Slavin, J. Svestka, A. N. Witt, G. P. Zank, ''Dust in the Local Interstellar Wind,'' Astrophysical Journal, vol. 525, pages 492-516, 1999.

P. C. Frisch, ''The Galactic Environment of the Sun,'' Journal Geophysical Reviews, vol. 105, pages 10279-10290, 2000.

P. C. Frisch, ''Foreword,'' Journal Geophysical Reviews, vol. 105, pages 10237-10238, 2000.

G. P. Zank and P. C. Frisch, ''Consequences of a Change in the Galactic Environment of the Sun,'' Astrophysical Journal, vol. 518, pages 965-973, 1999.

G. P. Zank and P. C. Frisch, ''The Interaction of the Solar Wind with a High Density Cloud,'' In Proceedings: AIP Conf. Proc. 471: Solar Wind Nine, pages 831+, 1999.

D. E. Welty, P. C. Frisch, G. Sonneborn, D. G. York, ''Interstellar Abundances in the Magellanic Clouds. II. The Line of Sight to SN 1987A in the Large Magellanic Cloud,'' Astrophysical Journal, vol. 512, pages 636-671, 1999.

P. Frisch, ''Galactic Environments of the Sun and Cool Stars,'' In *Planetary Sciences – The Long View*, (Publisher: Editions Frontieres), Editors: L. M. Celnikier and J. Tran Than Van pages 3-10, 1999.

P. C. Frisch, ''The Galactic Environments of Nearby Cool Stars'' To be published in the Proceedings of NStars Workshop, NASA Ames Publication, 2000.

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/