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The following report covers the Department activities from October 1999 through September 2000.

1. ASTRONOMY AND COSMOLOGY AT PENN

The Department of Physics and Astronomy has been recruiting astrophysicists and cosmologists at an aggressive pace. The Astrophysics Group faculty now comprises C. Alcock, M. Devlin, D. Koerner, C.-P. Ma, and M. Tegmark. B. Jain will join the group in January 2001. Two more faculty appointments are expected in the next few years. In addition, lecturers D. Goldader and J. Goldader assist with the teaching program, and there is a growing cadre of post-doctoral fellows and students.

In addition to the Astrophysics Group, there is active neutrino astrophysics research performed in the High Energy Physics group, notably by E. Beier and D. Cowen. Penn has long been a leading player in neutrino astrophysics, beginning with work on the pioneering solar neutrino experiments, Homestake and Kamiokande, to Penn's present involvement in the Sudbury Neutrino Observatory (SNO) and the Antarctic Muon and Neutrino Detector Array (AMANDA). Penn is also involved in future planned experiments in this field, such as IceCube, the proposed expansion of AMANDA to the kilometer scale, and the first proposed quasi-real-time radiochemical solar neutrino experiment.

2. RESEARCH SUMMARY

2.1 Charles Alcock

C. Alcock joined the faculty in September 2000. He continues his cosmic dark matter work as part of the MACHO Project. Recent advances in this work include new estimates of the gravitational microlensing optical depths towards the Large Magellanic Cloud and towards the Galactic bulge.

C. Alcock, working with groups in California and Australia, is adapting the MACHO Telescope System to survey the ecliptic for exceptionally large Kuiper Belt Objects. This survey will ultimately cover more than 3,000 square degrees, with magnitude limit $V<21$.

C. Alcock is the US PI for the Taiwanese-American Occultation Survey (TAOS), which will search for the occultations of bright stars by small Kuiper Belt Objects. The TAOS team is drawn from the Academia Sinica-Institute for Astronomy and Astrophysics (Taiwan), National Central University (Taiwan), Lawrence Livermore National Laboratory, Mt. Stromlo Observatory, UC Berkeley, NASA Ames, and Penn.

2.2 Eugene Beier

The Sudbury Neutrino Observatory (SNO) group at Penn consists of Profs. E.W. Beier (P.I.), D.F. Cowen, W. Frati and J. Klein, staff physicists F.M. Newcomer and R. Van Berg, postdoctoral researchers S. Oser and R. van de Water, and graduate students C. Kyba, M. Neubauer and V. Rusu. SNO is a second generation dedicated solar neutrino experiment which is extending the results of Penn's earlier work with the Kamiokande II detector by measuring three reactions of solar neutrinos rather than the single reaction measured by the Kamiokande and SuperKamiokande experiments. The collaborative project includes about 100 physicists from Canada, the United Kingdom, and the United States. The experiment is located in an active nickel mine two kilometers underground near Sudbury, Ontario, Canada.

The motivation for the SNO experiment is to study the fundamental properties of neutrinos, in particular the mass and mixing parameters. This will be accomplished by measuring the flux of electron type neutrinos, ν_e, which are produced in the sun, and comparing it to the flux of all flavors of neutrino detected on earth in an appropriate energy interval. Observation of neutrino flavor transformation through this comparison is unambiguous evidence that ν_e's have non-zero mass. Non-zero neutrino mass is evidence for physics beyond the Standard Model of fundamental particle interactions.

Penn has made and continues to make substantial and vital contributions to the SNO experiment. The Penn group designed, implemented, and now maintains SNO's 10,000 channels of custom data acquisition (DAQ) electronics. Significant contributions to the DAQ software, calibration system and simulation and analysis software packages continue to be made, and Penn presently plays a leading role in the analysis of SNO data.

2.3 Douglas Cowen

The AMANDA group at Penn consists of Prof. D.F. Cowen (P.I.), postdoctoral researcher K. Hanson and graduate student I. Taboada. AMANDA is the first functioning large-scale ultrahigh energy (UHE) neutrino detector. Its goal is to discover neutrinos from sources outside the solar system at energies above roughly 10^{14}eV. About 100 physicists from the Belgium, Germany, Sweden and the United States have built the experiment located at the South Pole in Antarctica.

Neutrinos are superb astronomical messengers. Unlike photons or protons, they can travel vast cosmological distances without hindrance, unabsorbed by interstellar matter and undeflected by interstellar magnetic fields. AMANDA's ability to detect UHE neutrinos gives it unique sensitivity to a region of the energy spectrum spanning almost six orders of magnitude, beyond the reach of conventional optical telescopes.

Penn has responsibility for the most important AMANDA calibration task, the determination of the relative time offsets of the AMANDA PMTs. Correct measurement of these constants is vital to event reconstruction. Penn is also a lead institution in the study of ν_e-induced cascade signals, with searches for cascade signals from diffuse sources and gamma ray bursters in progress.

2.4 Mark Devlin

M. Devlin led the development and deployment of MAT: The Mobile Anisotropy Telescope. MAT is a 1 meter telescope designed specifically to search for anisotropy in the Cosmic Microwave Background. MAT observes from a high plateau (17,000 ft) in the Atacama region of Chile. At this site the atmosphere is stable and integration times can be extended for as long as desired (two months or more).

Collaborating with L. Page at Princeton University, this group completed its first observing season from October to December of 1997 and another from September to December of 1998. With the HEMT and SIS-based receiver a large amount of high-quality data was collected. The analysis of these data has provided some of the most exciting results to date. The data leave little doubt that the Doppler peak falls at small angular scales. The location of the peak as determined by these data indicates that there is no spatial curvature to the Universe.

M. Devlin is the PI for BLAST: a Balloon-borne Large Aperture Telescope. Penn is the lead institution in a large international collaboration which makes up BLAST. The design of BLAST incorporates a 2.0 m mirror that will be replaced with a 2.5 m mirror in the 4th and 5th years of the project. The telescope will operate on a Long Duration Balloon (LDB) platform with large format bolometer arrays at 250, 350, and 500 microns. BLAST will address some of the most important galactic and cosmological questions regarding the formation and evolution of stars, galaxies and clusters. It will conduct large-area sensitive galactic and extragalactic surveys which will: (i) identify large numbers of distant high-redshift galaxies; (ii) measure cold pre-stellar sources associated with the earliest stages of star and planet formation; (iii) make high-resolution maps of diffuse galactic emission from low to high galactic latitudes. This project was funded at the end of 1999 and reflects a broadening of the group's interests while maintaining strong ties to cosmology.

M. Devlin and his team is developing the Penn Bolometer Array (PBA). The PBA is a direct result of CMB receiver development efforts. The receiver originally built for MAT will be outfitted for 3 millimeter observations on the Green Bank Telescope (GBT) in West Virginia. A feasibility study of the implementation of this work has been completed in collaboration with NRAO. The science potential of a 3 millimeter array on a 100 m dish is astounding, ranging from actually mapping SZ clusters to searching for planetary disks in star-forming regions in the Galaxy. In August of 2000 a proposal was submitted to NSF with the full endorsement of NRAO to complete this work. If funded, the array should be in on the GBT in 2002.

2.5 David Koerner

The prevalence and character of extra-solar planetary systems is the focus of research by D. Koerner. Steps which lead to the formation of planetary systems are investigated by means of high-resolution imaging of protoplanetary disks around young stars in different stages of early evolution. Techniques include mm-wave aperture synthesis imaging of cold dust and gas, Keck thermal infrared imaging of warm dust, and both Keck and HST observations of light scattered by disk surfaces. Theoretical simulations of the radiation from dust and gas are used to analyze images with a view to ascertaining the range of properties - e.g., size, mass, temperature, density, kinematics, and chemical composition - in the circumstellar disks from which planets form. Koerner is also active in searches for sub-stellar companions to nearby stars. An ongoing Keck survey of companions to L dwarfs will potentially reveal images of giant jupiters. Thus far, it has resulted in the discovery of a small sample of brown dwarf binaries.

2.6 Deborah Goldader

D. Goldader is investigating the nature of cluster galaxies through analysis of near-IR data. At $z>0.2$, evidence for a steep relationship between redshift and fraction of optically blue galaxies continues to accumulate (i.e. the Butcher-Oemler Effect). Goldader is testing the idea that the galaxies responsible for the effect have experienced recent bursts of star-formation or enhanced AGN activity. The infrared signature of both effects is to redden the galaxies with respect to the E/SO sequence (for star formers, due to enhanced RGB and supergiants, for AGN, a hot dust component). So far, no significant population of galaxies bluer or redder than the E/SO sequence has been observed in clusters surveyed at $z>0.2$. This places constraints on the duration and strength of the activity. Future analysis will include a morphological investigation and radial corrolations.

2.7 Jeffrey Goldader

J. Goldader continued his work on ultraluminous infrared galaxies (ULIRGs), to see if they are indeed the local counterparts to the sub-mm selected far-IR luminous galaxies discovered at high redshifts. UV images of a sample of local ULIRGs, taken with the HST, show that they are faint in the ultraviolet. The local ULIRGs also do not obey the same correlation between UV color and the far-IR/UV flux ratio that exists for local, UV-bright starbursts. This can be understood if the UV light escaping ULIRGs comes from low optical depths, and represents only a tiny portion of the bolometric energy. Preliminary results show that local ULIRGs would be very faint and generally difficult or impossible to detect in current deep optical imaging surveys, if placed at the same redshifts as the sub-mm galaxies. This may explain the great difficulty in finding the optical counterparts to the sub-mm galaxies.

2.8 Chung-Pei Ma

C.-P. Ma and collaborator J. Fry (U of Florida) have made some recent breakthroughs in using analytical methods to understand the nonlinear properties of gravitational clustering, which is the most fundamental physical process in cosmology. In a series of three papers, they proposed an analytic model that is capable of predicting the clustering statistics of dark matter and galaxies over a wide range of length scales from the linear to the highly nonlinear regime. The model is based on properties of dark matter halos, each of which is the site for one or a group of luminous galaxies. Their tests have shown close agreement between this model and high resolution numerical simulations. The significance of this analytic model includes (1) it offers a highly efficient way to carry out complex nonlinear calculations; (2) it provides a deeper physical insight into the fundamental question of ''how does matter cluster''; and (3) it is a new tool for studying the asymptotically nonlinear properties of gravitational collapse which is beyond the reach of simulations. Ma is currently extending the model to include baryons.

C.-P. Ma has been using gravitational lensing as a tool to investigate the inner mass structure of elliptical galaxies and clusters of galaxies. With collaborator M. Metzger (Caltech), they obtained optical data of the cluster Abell 697 with the Keck II telescope and identified unusual disturbed structure in the central cD galaxy and a previously unknown faint gravitational lens arc. From the observed position and orientation of the arc, they built numerical models for the inner cluster potential and found that the dark matter profile is likely to be quite elliptical. This suggests that the cluster may have undergone a recent merger and is in the process of forming its central dominant galaxy.

C.-P. Ma and graduate student D. Rusin have recently completed a study of the inner mass profiles of lensing galaxies. The study is based on the lensing property that a shallow mass distribution produces a relatively bright odd image that is easily detectable, whereas the odd images in nearly all lensed systems are too faint to be seen. This allowed them to place a lower limit on the power-law slope of the central mass density using a sample of six doubly-lensed quasars from the CLASS radio survey. They found that the inner mass profiles of lensing galaxies must be nearly isothermal or steeper, and that adding a central black hole does not significantly change the constraint.

C.-P. Ma has been a member of the AMiBA (Array for Microwave BAckground) project, whose aim is to study the cosmic microwave background (CMB) at small angular scales with an interferometer array at 90 GHz. The main science goals are to detect the CMB polarizations and to map cosmic baryons via the Sunyaev-Zeldovich effect. The project has received full funding from the National Science Council and the Ministry of Education in Taiwan and involves an international team of scientists.

2.9 Angelica de Oliveira-Costa

Together with M. Tegmark, the Tenerife collaboration and the WHAM collaboration, A. de Oliveira-Costa made quantitative models of microwave foreground contamination by cross-correlating various microwave background observations with templates for dust, synchrotron and free-free emission. This provided new evidence for a novel emission component corresponding to spinning dust grains.

2.10 Max Tegmark

Together with A. Hamilton (Boulder) and N. Padmanabhan (Stanford), M. Tegmark developed new techniques for analyzing galaxy redshift surveys. These were applied to both the CfA/SSRS UZC and the PSCz surveys, giving accurate measurements of galaxy clustering and so-called redshift space distortions.

Together with M. Zaldarriaga (IAS) and A. Hamilton (Boulder), M. Tegmark used the latest cosmic microwave background (CMB) and galaxy clustering measurements to constrain cosmological parameters. This included developing a method for separating physical radiative transfer processes to accelerate the CMBfast power spectrum software by a factor of 1000.

Together with A. Cooray and W. Hu (Chicago), M. Tegmark quantified the ability of upcoming CMB experiments to measure the diffuse Sunyaev-Zel'dovich effect caused by large-scale structure, finding that this technique may emerge as yet another powerful probe of the dark matter distribution over the next few years.

C. Alcock