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1. INTRODUCTION

The astronomy and astrophysics program at the University of Colorado exists within the structure of the Astrophysical and Planetary Sciences Department (APS), with its affiliated units – the Center for Astrophysics and Space Astronomy (CASA), the Joint Institute for Laboratory Astrophysics (JILA), and the Laboratory for Atmospheric and Space Physics (LASP). Previous Observatory Reports provide details on the organizational arrangement.

The APS Department offers an academic program leading to the PhD degree in a variety of areas of astrophysics and planetary sciences. Students obtain basic theoretical knowledge common to these related fields, before specializing. The department has just developed a new undergraduate Astronomy degree, with two tracks (General Astronomy and Astrophysics/Physics). We now have 92 declared undergraduate majors and 44 graduate students. Our 25 faculty and 90 researchers have active research programs funded by NASA, NSF, and DOE.

In this year's report covering 2000-2001, we emphasize new developments and recent publications specifically within APS, CASA and its membership. In astrophysics, particular strengths of CASA lie in hot and cool stars, interstellar and intergalactic matter, high-energy astrophysics, solar physics and UV/Xray/IR/sub-mm instrumentation. Particular strengths of JILA include theoretical studies of black holes and accretion flows, formation of stars and planetary systems, supernovae and supernova remnants, helioseismology, solar and interstellar magnetism, stellar atmospheres, and astrophysical fluid dynamics.

2. SCIENTIFIC DEVELOPMENTS

2.1 Instrumentation

The Far Ultraviolet Spectroscopic Explorer (FUSE) mission was launched in summer 1999. The FUSE spectrograph was designed and built at CASA over a five year effort led by Dr. James Green. Other members of the FUSE science team are CASA astronomers Drs. Cash, Shull, and Snow, and JILA astronomer Dr. Linsky. The mission is an unqualified success, and many CASA professors, researchers, graduate and undergraduate students are deeply involved with the analysis of FUSE data. The CASA hardware team is now progressing well on the development of the Cosmic Origins Spectrograph (COS), to be installed in NASA's Hubble Space Telescope in 2005. The powerful ultraviolet instrument will be built jointly with Ball Aerospace and Technologies Corporation in Boulder. COS will bring the diagnostic power of UV spectroscopy to bear on such fundamental issues as the ionization and baryon content of the intergalactic medium and the origin of large-scale structure in the Universe; the ages, dynamics, and chemical enrichment of galaxies; and stellar and planetary origins. COS will build on the legacies of Copernicus, IUE, GHRS, FOS, STIS, and FUSE, giving HST the greatest possible grasp of faint UV targets, ensuring that Hubble maintains a powerful UV spectroscopic capability through the end of its mission.

CASA also supports three instrumental programs in infrared sub-millimeter, and millimeter-wave astronomy. Dr. Jason Glenn's programs focus on developing bolometer arrays (Bolocam) for mm-wave and sub-mm studies of high-redshift galaxies and star formation, used on the Caltech Submillimeter Observatory and on the Herschel/FIRST satellite later this decade. Drs. Albert Betz and Rita Boreiko work on far-infrared instrumentation for studies of star-forming regions. APS and CASA are also building a near-infrared camera and Fabry-Perot spectrograph (NIC-FPS) for installation on the Apache Point 3.5-meter telescope.

2.2 Space Astronomy

CASA astronomers continue intensive use of NASA spacecraft. In 2001-02, there were awards from the Hubble Space Telescope (HST), FUSE, Chandra, XMM, and Herschel/FIRST. Grants were received from other NASA programs including Astrophysics Theory, Origins of Solar System, Astrophysics Data, Long-Term Space Astrophysics, and High Energy Astrophysics. Several CASA astronomers were awarded FUSE Cycle-3 observing programs for studies of interstellar and intergalactic matter.

2.3 Groundbased Astronomy

The Department of Astrophysical and Planetary Sciences, including CASA, has entered into a ground-based telescope consortium (ARC) at the 3.5-meter Apache Point Observatory in southern New Mexico. CU observing programs include studies of clusters of galaxies, stellar outflows, hot stars and the ISM. These and future observing runs on interstellar matter, infrared galaxies, and planets will include undergraduate and graduate students in the observations and analysis. CASA is also developing a near infrared camera to be installed on the telescope in early 2004. APS scientists continue to make extensive use of other national ground-based optical and radio facilities for solar, stellar, interstellar, and extragalactic research.

2.4 Theoretical Astrophysics

Colorado has one the nation's top programs in astrophysical theory. Our research groups are working on such topics as interstellar and intergalactic matter, cosmology (large-scale structure, galaxy formation, reionization by first stars/AGN), formation of stars and planetary systems, black holes and AGN, helioseismology and solar dynamo, plasma astro-

physics, supernovae, and stellar atmospheres. Our faculty and researchers have strong funding for theoretical graduate students and postdocs.

3. SELECTED INDIVIDUAL RESEARCH

Using UV, optical and X-ray observations Dr. Nahum Arav is studying a wide range of AGN outflow phenomena both in terms of luminosity (broad absorption line quasars to Seyfert galaxies) and in the degree of ionization (neutral atoms to X-ray warm absorbers). Arav is particularly interested in determining: the connection between the UV and X-ray warm absorber seen in Seyfert outflows, and the chemical abundances, acceleration mechanism and kinetic luminosity of the outflows. These determinations provide the foundation for the long-range goal of my research program: Establishing the effects of AGN outflows on the growth and evolution of their host galaxies. His approach to research combines a strong theoretical background with detailed technical understanding of the observations to maximize the extraction of scientific knowledge from the data.

Since arriving to CASA Arav is mainly working on the connection between the UV and X-ray warm absorber seen in Seyfert outflows.

Dr. Webster Cash has been concentrating his research on the development of new instrumentation for x-ray astronomy. This includes a) building and testing off-plane reflection gratings for high resolution x-ray spectroscopy in the next generation of x-ray observatories and b) developing x-ray interferometry for the MAXIM Mission with the goal of eventually imaging a black hole.

In the past year, Dr. Joe Collins' research has concentrated on a survey of archival FUSE and HST data for sightlines through high-velocity cloud Complex C. The work attempts to measure metal abundances in Complex C for the purpose of determining its origin. Results from our survey suggest that Complex C is likely a mixture of infalling material from the intergalactic medium and ejecta from the Galactic disk. A FUSE proposal has been submitted for further observations of selected sightlines from the survey. Collins has also submitted a paper on diffuse ionized gas and the disk-halo connection in galaxies. This work presents a ballistic model of halo rotation for comparison to previously obtained spectroscopic data for two edge-on galaxies (NGC 5775 and NGC 891). The data reflect rotation velocity versus height above the disk and indicate a complex coupling between disk and halo rotation. Fabry-Perot data of NGC 5775 are currently under analysis.

Dr. Jason Glenn does millimeter-wave astronomy and instrumentation. His main efforts over the past year have been development of Bolocam and making observations with it, design of Z-spec, design and testing of feedhorn arrays and integrating cavities for SPIRE on the Herschel Space Observatory, and analysis of observations of SiO masers in evolved stars. Bolocam is a large-format, millimeter-wave bolometer camera built by a collaboration including CU, Caltech, the University of Massachusetts, and the University of Wales. We have commenced a survey with Bolocam at the Caltech Submillimeter Observatory for galaxy clusters via the Sunyaev-Zel'dovich effect, a survey for submillimeter galaxies via their dust emission, and a 1 mm map of the Galactic Center. Z-Spec is a millimeter-wave grating spectrometer for measuring the redshifts of submillimeter galaxies and serves as a demonstration of a compact waveguide-coupled grating for a future far-infrared orbital mission. We are building it in collaboration with JPL, Caltech, ISAS in Japan, and CEA in France. Prototype submillimeter feedhorn numerical simulations and testing for the SPIRE bolometer array instrument on the ESA Cornerstone Herschel Space Observatory is nearly complete. We have also just completed a study of the polarization variability of SiO masers in evolved stars, concluding that a single, simple relationship does not exist between maser lifetimes and stellar periods in our sample of 17 stars.

Dr. Nick Gnedin continued his work on numerical simulations of early universe. With Mike Shull and Massimo Ricotti he studied formation of the very first galaxies in the universe and their effect on the intergalactic gas. With C. Carilli and F. Owens from NRAO, and with S. Shandarin from the University of Kansas, Gnedin proposed two novel approaches for investigating the structure of the intergalactic medium during the early stage of galaxy formation, prior to cosmological reionization.

Dr. Graham Harper is a Guest Investigator with FUSE studying the outer atmospheres of late -K and M evolved stars. These observations have led to the identification of new Fe II and Cr II fluorescence emission in the FUV, and to an understanding of the controlling factors which ionize Ca II in cool stellar winds. In collaboration with Edward Guinan (Villanova University) and Ignasi Ribas (Universitat de Barcelona), Harper is involved with the Sun-in-Time program where the evolution of solar activity is derived through the study of solar proxies of different ages. The history of the solar irradiance will help understand the development of planetary atmospheres in the early solar system. Harper has served on the FUSE Observer's Advisory Committee for several years and is now the Chair.

VLA and ATCA radio studies of single evolved late-type stars and the zeta Aurigae eclipsing binary conducted by Harper and Brown, indicate that the wind acceleration in the evolved primary of zeta Aurigae is different from that of single stars with similar spectral types. This confirms previous UV spectral line analyses and highlights the need for detailed single star spectroscopic analyses. Harper and Brown have also continued to develop the spatially resolved semi-empirical atmosphere for Betelgeuse, using the new high spatial resolution VLA and Pie Town configuration. These data show that the wind acceleration region is non-axisymmetric and revisions to existing models are required. An M supergiant reference model atmosphere is being constructed which will be used to study the potential of the forthcoming NASA SIRTF and SOFIA missions to contribute to our understanding of the, as yet unknown, mass loss mechanisms.

Dr. Philip Maloney continued research on the effects of ionizing radiation on neutral gas in astrophysical environments. New work shows that disk galaxies can truncate their neutral hydrogen disks, provided that the disks are warped and that a sufficient fraction of ionizing photons escape the

disk. In collaboration with Mary Putman (CU), Maloney demonstrated that the cosmological, dark-matter-dominated model for compact high-velocity clouds is untenable, as ionization by the extragalactic background radiation field has dramatic effects on the neutral gas fractions. In addition, he continued work with Imanishi (NAO, Japan) and Dudley (NRL) on probing the energy sources of ULIRGs using 3-4 micron spectroscopy. Further work on X-ray powered masers and new models of CO emission from high-redshift galaxies is in progress.

Dr. Jon Morse continued research on processes in the interstellar medium, including HST studies of protostellar jets, oxygen-rich supernova remnants, and Eta Carinae.

Morse is the Project Scientist for the Cosmic Origins Spectrograph (COS) for the Hubble Space Telescope, currently scheduled to be installed in early 2004. He is responsible for coordinating and executing the COS GTO science program.

Dr. Mary Putman continues her involvement with the HI Parkes All-Sky Survey (HIPASS) by investigating the distribution of the Magellanic Stream and high-velocity clouds (HVCs) along the sightline to the Sculptor Group. She has also been working with P. Maloney to determine if the small compact HVCs could exist at large distances from the Galaxy when subject to an extragalactic ionizing radiation field. This work, together with her work on the Halpha emission from HVCs, is showing that the majority of the HVCs are within 200 kpc of the Galaxy. Her collaboration with SINGG (Survey for Ionization in Neutral Gas Galaxies) has revealed high latitude H II regions which appear to be a unique type of halo object, and she is obtaining optical spectra of these objects with Ken Freeman, Gerhardt Meurer and Emma Ryan-Weber. Putman has been working with J. Rosenberg and others at Colorado on a large survey of the distribution of HI galaxies around low-redshift Lyα absorbers. She is also exploring the link between the HI gas content of groups and their x-ray emission with John Mulchaey and David Barnes.

Dr. Brian Rachford has been involved in several observational projects related to the interstellar medium. The primary focus has been studies of molecular hydrogen (H2) in heavily reddened lines of sight with FUSE, in collaboration with Ted Snow, Mike Shull, and others. This work investigates relationships between H2 and various gas and dust parameters in a sample of ''translucent'' clouds. The main result is that most of the putative translucent clouds are, in fact, collections of classical diffuse clouds and do not represent a new chemical or physical regime. Snow and Rachford also completed a study of iron abundances in a subset of these lines of sight, finding surprisingly uniform depletion of iron out of the gas onto the grains. Other collaborative ISM studies include a rare detection of molecular hydrogen absorption in a supernova remnant at moderately high velocity (+65 km/s relative to the Local Standard of Rest), and a combined IUE/FUSE study of dust extinction which will eventually involve nearly 100 lines of sight.

Dr. Jessica Rosenberg's research has focused mainly on the connection between galaxies and Lyman-alpha absorbers. In collaboration with Stephen Schneider (University of Massachusetts) she has worked to predict the properties of low redshift damped Lyman-alpha absorbers using a sample of low redshift, gas-rich galaxies selected by their 21cm emission (Rosenberg & Schneider 2003). Rosenberg has also become involved in a study of an intriging pair of quasars on the edge of the Virgo Supercluster which exhibit 10 absorbers in the velocity range of the cluster. In Rosenberg *et al.* (2003) they show that these sightlines, only one of which seems to have a nearby galaxy, indicate that there may be many small clumps of metal-enriched gas that are coherent along a filament stretching over at least 350 kpc.

To study the relationship between Lyman-alpha absorbers and gas-rich galaxies, Rosenberg and Putman have initiated a search for gas-rich galaxies near low redshift absorbers. They have taken several hundred hours of 21cm observations using Arecibo, the VLA, Parkes, and the ATCA telescopes around the sightlines towards 30+ nearby Lyman-alpha absorbers to derive a statistically significant sample for investigation. Rosenberg has also worked with R. McEntaffer and John Stocke on a similar VLA study of the galaxies near a single nearby absorber in a filament which was part of McEntaffer's comprehensive exam project. McEntaffer *et al.* (2003) found 4 gas-rich galaxies in the vicinity of the low redshift absorber, but all of the galaxies were at least 190 kpc from the absorber.

In August 2002, Rosenberg and Putman organized a meeting held at CU-Boulder on ''The IGM/Galaxy Connection: The Distribution of Baryons at z=0.'' This meeting brought astronomers from around the world to Boulder to discuss the IGM/Galaxy Connection, a focus of many of the astronomers in the department. The meeting highlighted the work of astronomers on campus as well as providing a forum for interaction with other groups investigating similar questions.

Dr. Michael Shull's research group works on a wide range of theoretical and space-observational topics connected with the interstellar medium (ISM), intergalactic medium (IGM), and galaxy formation. With students and postdocs, his recent work includes theoretical models of the first stars and quasars and their effects on reionizing the IGM in hydrogen and helium, and on radiation feedback from galaxy formation. Shull, Gnedin, and recent PhD Massimo Ricotti have investigated the radiative feedback from galaxy formation through the formation/destruction of H2 by the first stars. Shull and recent PhD Jason Tumlinson studied the structure and ionizing radiation from the first stars. With postdoc Aparna Venkatesan and Tumlinson, we studied the effects of high-redshift quasars and low-metallicity stars on IGM reionization. With colleagues John Stocke and Steve Penton, Shull has investigated the baryon census of the IGM associated with the low-redshift Lyman-alpha forest. With Mark Giroux (CASA and East Tennessee State) and Tumlinson, Shull is investigating He II reionization, multi-phase intergalactic gas, and the metallicity of the IGM.

Shull's observational work includes studies with Hubble Space Telescope and FUSE on a variety of topics: interstellar molecular hydrogen, hot interstellar gas (O VI), interstellar deuterium, metallicity of high-velocity clouds, the distribution, baryon content, and metallicity of low-redshift Lyman-

alpha forest, and intergalactic He II absorption at redshifts z = 2-3.

Shull is a member of the Science Teams for FUSE, the Cosmic Origins Spectrograph on Hubble, and the SPIDR Small Explorer Mission (to study diffuse emission from the ISM and IGM). He also a member of study teams for the Constellation-X (X-ray spectroscopy) and Space Ultra-Violet Observatory (SUVO) missions.

Dr. Stephen Skinner's research focuses on observational studies of star-forming regions, Wolf-Rayet (WR) stars, and solar-like stars using a variety of space and ground-based telescopes. Skinner spent the first half of 2002 on a visiting appointment at Paul Scherrer Institute (PSI) in Zurich. He continues to serve as editor of COOLNEWS, a monthly electronic research newsletter on cool stars and the Sun distributed to more than 700 astronomers and institutions worldwide.

In the area of star-formation, Skinner is currently analyzing recently obtained high-resolution Chandra X-ray observations of the NGC 2024 star-forming region in Orion and the young southern cluster NGC 6193 in the Ara OB1 association. These data provide the first deep X-ray census of NGC 2024 and reveal about 280 X-ray sources, most of which are highly-variable and heavily absorbed members of the embedded young stellar population. Chandra grating spectra of the central ionizing O star (HD 150136) of NGC 6193 are providing stringent tests of X-ray emission models in massive stars. These models have traditionally attributed the X-ray emission of single massive OB and WR stars to shocks that are distributed throughout their winds. However, several recent X-ray observations are in conflict with model predictions. For example, radiative wind shock models predict only soft X-rays, whereas two putatively single WR stars (WR6 and WR 110) observed recently with XMM-Newton by Skinner and collaborators clearly show both a soft and hard X-ray component. These results suggest that either putatively single WR stars with prominent X-ray emission are in fact close binaries whose companions have escaped detection (binary wind interaction could then produce the hard X-rays) or that theoretical models of X-ray emission in massive single stars are in need of revision. Skinner continues to collaborate on several Chandra and XMM-Newton observations of solar-like stars with M. Guedel (PSI, Zurich) and M. Audard (Columbia). In the past year, Proxima Centauri (the nearest star to the Sun) was observed with XMM-Newton, providing sensitive X-ray monitoring and simultaneous optical data from XMM's onboard optical telescope. Because of its high sensitivity, XMM-Newton was able to temporally resolve the X-ray emission into a nearly continuous sequence of weak flares, challenging the very concept of a 'quiescent corona' and giving support to the idea that low-level flaring may play an important role in heating the coronae of magnetically active stars. Strong correlations between X-ray and optical variability were detected, providing solid evidence for flare-induced evaporation of chromosperic material up into the corona, much as occurs in the Sun.

Dr. Ted Snow's research activities continue to be focused on interstellar medium problems, with particular interest in the physical and chemical conditions in the densest interstellar clouds that are still sufficiently transparent to allow absorption-line measurements. Some of Snow's research involves observations obtained at the ARC 3.5-m telescope, as part of a group headed by D. G. York of the University of Chicago to study the unidentified diffuse interstellar bands (DIBs); while other work has been based on ultraviolet spectra obtained with the HST and FUSE, much of it collaboration with Colorado colleagues such as B. Rachford and various students. In addition, Snow continues to head a laboratory astsrophysics program in collaboration with V. Bierbaum of Chemistry at Colorado, aimed at measuring chemical reaction rates in molecular ions of astronomical interest.

Major studies completed and published in 2001 include: a FUSE survey of molecular hydrogen (Rachford *et al.* 2001, 2002); a new analysis of the profile of the 4430 DIB, demonstrating that it is almost certainly formed by a molecular carrier (Snow 2002; Snow, Zukowski, and Massey 2002); and new laboratory and theoretical studies of molecular ions, particularly carbon chains and polycyclic aromatic hydrocarbons or PAHs (Barckholtz *et al.* 2001; LePage, Snow, and Bierbaum, 2002, 2002).

Dr. Aparna Venkatesan's research interests lie primarily in theoretical cosmology, with a focus on the evolution of cosmic stellar activity and its feedback on the intergalactic medium (IGM) and the cosmic microwave background (CMB). Venkatesan, in collaboration with Jason Tumlinson (now the E.P. Hubble Scientist at The University of Chicago) and J.M. Shull, recently wrote two papers on the cosmological consequences of the evolving spectra of the first metal-free stars, which have unusually hard ionizing spectra. The study by Venkatesan, Tumlinson & Shull (2003) is the first to examine the effects of metal-free stars on the hydrogen and helium reionization of the IGM. Venkatesan, with Mark Giroux and J.M. Shull, has also studied the role played by an early X-ray background in the heating and ionization of the high-redshift IGM. In Venkatesan (2002), she proposed the use of an independent measurement of the reionization epoch, as well as of a reionization model, to break degeneracies in CMB parameter extraction and to improve constraints from data from the MAP satellite. Venkatesan recently began a 3-year NSF Astronomy and Astrophysics Postdoctoral Fellowship at CU-Boulder. In August 2002, Venkatesan was on the Local Organizing Committee for a meeting held at CU-Boulder on ''The IGM/Galaxy Connection: The Distribution of Baryons at z=0.'' Her current research collaborations include: ongoing projects with Tumlinson and Shull on reionization by early stars; studies with Keiichi Wada (National Astronomical Observatory of Japan) on the feedback from the first supernovae on the metal re-incorporation timescales in high-redshift protogalaxies; work with Andrea Ferrara and Raffaella Schneider (Astrophysical Observatory of Arcetri, Florence, Italy) on the evolution of the first stars' nucleosynthetic products in QSO emission-line regions; and, a project on the nucleosynthetic and ionizing photon signatures of the first stars in the IGM with Jim Truran (The University of Chicago).

Dr. Venkatesan has had a long-standing interest in education and public outreach, and has recently become active on

issues pertaining to the representation of women in science. As part of the outreach component of her NSF postdoctoral fellowship, Venkatesan teaches summer courses on astronomy for the University of Colorado Upward Bound (CUUB) Programs. CUUB targets Native American high school students from economically disadvantaged backgrounds, typically from schools which are on or near major reservations across the nation. In recent years, as many as eighteen Native American tribes and ten states have been represented. Venkatesan is also an associate member of the Science Integration Institute (SII), based in Portland, Oregon. SII is a nonprofit organization dedicated to helping people use the scientific process and its insights to be an integral part of their daily lives. Venkatesan was recently selected to be on the US delegation to the IUPAP International Conference on Women in Physics, held at UNESCO headquarters in Paris, France, March, 2002, and attended by representatives from 67 countries. For press related to this event and publications that Venkatesan has co-authored on the status of women in physics, as well as more general press, please see her CASA webpage.

4. PERSONNEL CHANGES DURING 2001

New Faculty: Dr. Jack Burns (University of Missouri-Columbia).

New Research Associates:

Dr. Nahum Arav (University of California-Berkeley); Dr. Doug Duncan (University of Chicago); Dr. Cynthia Froning (Space Telescope Science Institute); Dr. Patrick Motl (University of Missouri-Columbia); Dr. Nathan Smith (University of Minnesota), Dr. Mark Vincent (New Mexico State University).

Research Associate Departures:

Dr. Rachel Osten (National Radio Astronomy Observatory); Dr. Massimo Ricotti (University of Cambridge), Dr. Ka Chun Yu (Denver Museum of Nature and Science).

CASA Visiting Scientists: Dr. Blair Savage (University of Wisconsin-Madison); Dr. Keiichi Wada (National Astronomical Observatory of Japan).

New Graduate Students: Emily Baker, Catherine Boone, Sean M. Doyle, Meredith Drosback, Lieko Earle, Fred Hearty, Amalia Hicks, Brian Keeney, Katharina Kohler, Nate Murphy, Joshua Walawender.

5. PUBLICATIONS DURING 2000/2001

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