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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 64 declared undergraduate majors. Faculty have active research programs funded by NASA, NSF, and DOE.

In this report, we emphasize new developments and recent publications specifically within 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.

## 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 a 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 2004. 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.

### 2.2 Space Astronomy

CASA astronomers continue intensive use of NASA spacecraft. In 2000, there were awards from the Hubble Space Telescope (HST), FUSE, Chandra, and XMM. 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-2 and 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. The first CU observations occurred in September 2001, on clusters of galaxies and stellar outflows. These and future observing runs in Nov. 2001 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 mid-2003. CASA scientists continue to make extensive use of other national ground-based optical and radio facilities for solar, stellar, interstellar, and extragalactic research.

## 3. SELECTED INDIVIDUAL RESEARCH

Tom Ayres has been involved in a number of observational and theoretical projects concerning stellar atmospheric structure, coronal phenomena, and the evolution of activity on the Sun and sun-like stars. Solar work has concentrated on joint observations of the quiet Sun with the Infrared Imaging Spectrometer at Kitt Peak ( $5\mu\text{m}$  CO lines) in coordination with long-slit far-UV spectra from *SOHO* SUMER and narrow-band imaging from *TRACE*. A modeling project was undertaken to simulate the solar off-limb emissions of strong  $5\mu\text{m}$  CO lines using the time-dependent 1-D radiation-hydro models of Carlsson and Stein. Another IR CO effort involved a time series of the red giant Arcturus obtained during a five day observing run using the PHOENIX cryogenic spectrometer on Kitt Peak's 2.1 m telescope. A survey of the CO  $5\mu\text{m}$  bands in late-type stars was interleaved with the Arcturus dynamics program.

Also on the stellar side, Ayres has been a Guest Investigator on *HST*, *Chandra*, and *FUSE*. Much of the work has focussed on moderate-mass giants in the Hertzsprung gap; specifically a suspected dramatic change in the coronal structure as such stars enter the "rapid braking zone" (where a solar-like "dynamo" is thought to displace a fossil coronal magnetosphere inherited from earlier evolutionary stages). Other studies have concentrated on the fate of red giant stars in the "coronal graveyard." Recent *HST* and *FUSE* work suggests that high-energy phenomena might be

present on such stars, contrary to previous lore, but hidden from direct view by a “cool absorber.” Collaborations have included studies of R CrB stars, and A-type stars at the edge of convection (and activity). A survey of coronal forbidden lines in the *HST* STIS far-UV interval was based on spectra from a cycle 8 large project (8280) and more recent observations. Additional work on the 8280 material is in progress. Dramatic flare activity was discovered in the clump giant  $\beta$  Cet in a 34 day pointing by the *EUVE* satellite.

Ayres was chair of the Scientific and Local Organizing Committees of the 12th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, held 30 July–3 August 2001 at the University of Colorado, Boulder. The meeting was attended by more than 200 scientists from around the world, and featured an innovative presentation format (designed by co-chair Alex Brown). Topics included: pre-Main sequence evolution, brown dwarfs and exo-solar planets, the Sun, physical processes of stellar activity, and future instrumentation. The proceedings will be released on CD. Ayres is teaching a graduate course APS-5730 (“Stellar Exteriors”) in fall 2001, and continues to supervise 5th-year student Rachel Osten (who is nearing completion of her PhD). He currently is serving as chair of The National Solar Observatory Users Committee and the MAST (Multimission Archive at Space Telescope) Users Committee. Ayres also recently was elected to the AAS council.

John Bally and Bo Reipurth have continued their investigation of outflows from young stars. The first complete optical assay of Herbig-Haro objects in an entire giant molecular cloud was completed. More than 10 square degrees of the Perseus molecular cloud was imaged with narrow band filters in the light of H-alpha and [S II] with the MOSAIC CCD camera at the prime focus of the Mayall 4 meter reflector at Kitt Peak National Observatory.

Bally and collaborators have continued the investigation of irradiated jets and outflows in regions such as the Orion Nebula. Recent results include a complete characterization of the radial velocity fields of outflows in the Orion Nebula with the 10 to 15 km/s velocity resolution of a Fabry-Perot interferometer having an 8' field-of-view on the 3.5 meter Canada-France-Hawaii telescope. At least 6 distinct outflows appear to be emerging from the vicinity of the OMC1-S cloud core located behind the Orion Nebula about 90" south of the OMC1 core.

Bally has continued the investigation of protoplanetary disks (proplyds) embedded in the Orion Nebula with *HST*. Recent results have provided evidence for grain growth in Orion's largest disk, 114-426. The translucent edge of this silhouette disk appears to be completely achromatic between 0.65 and 1.87  $\mu\text{m}$ , indicating that the extinction is dominated by grains larger than about 5  $\mu\text{m}$  in diameter.

Irene Little-Marenin's interests have shifted from late-type stars to archeo-astronomy. She and her husband Stephen J. Little are currently investigating light/shadow interactions on the Great Gallery in Horseshoe Canyon, Utah. They will present their preliminary results at the January 2002 AAS meeting in Washington, D.C. Both are also very involved with out-reach programs. They hold evening observing sessions in Rocky Mountain National Park as well as running

day long seminars on various topics in astronomy through the Nature Association of Rocky Mountain National Park.

In the past year, Philip Maloney (in collaboration with C. Reynolds, UMD, and M. Nowak, CXC-MIT), showed, using ASCA X-ray observations, that the low-luminosity AGN in NGC 4258 has a narrow iron K alpha line, in contrast to many high-luminosity AGN which exhibit relativistically broadened Fe lines. We also found clear evidence for a change in the X-ray flux. Maloney and Reynolds also showed, using new ASCA data, that in the extremely luminous Seyfert 1 galaxy Mrk 231, which has always been claimed to be X-ray weak, we almost certainly do not see the central X-ray source directly, but only via scattering, and hence that the intrinsic X-ray luminosity is much higher than the observed luminosity. Maloney and Bland-Hawthorn (AAO) demonstrated that, at least in the case of Abell 1795, the extremely luminous EUV emission claimed to be present from *EUVE* observations would produce such a large concomitant ionizing photon flux that all cluster galaxies within 10' radius would be glowing in H alpha, at levels much higher than observed. With Imanishi (NAO, Japan) and Dudley (NRL), Maloney reported results of 3-4 micron spectroscopy of the ULIRG UGC 5101, which strongly argue that the bolometric luminosity of this galaxy is dominated by an AGN and not by star formation. With the WHAM group from the University of Wisconsin, Maloney presented observations of the outer disk of M31, in which H alpha emission was clearly detected in the HI layer outside the optical disk; if due to the cosmic ionizing background, this implies that the cosmic photon flux is about 16,000 photons per square cm per second. Maloney and Neufeld (JHU)

are at work on new models of X-ray powered maser emission, with particular emphasis on transitions other than the 22 GHz line that will be observable with ALMA. Maloney gave an invited review talk at the ASA meeting in Australia (June 2001), on Powerful Extragalactic Water Masers.

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 G TO science program.

Michael Shull's interests lie in both observational and theoretical studies of interstellar and intergalactic matter. His research group includes 3 grad students, 4 postdocs, and 2 undergraduates working with Hubble Space Telescope, FUSE, and theoretical or computational studies of the low-redshift IGM, molecular hydrogen in the Galaxy and Magellanic Clouds, galaxy formation, the first stars and quasars, and reionization of the IGM in both hydrogen and helium. The last year marked the first publication of many new FUSE results.

Using Hubble spectrographs (GHRS and STIS), the Colorado IGM group surveyed the low-*z* Lyman-alpha absorbers toward 31 AGN, measuring the absorber distribution relative to large-scale structure, their physical properties, and their metallicities. Penton, Stocke, & Shull (2000a,b, 2001) wrote

3 papers describing the Hubble survey of the low- $z$  IGM. Ricotti, Gnedin, & Shull (2000) pioneered a technique to use the distribution of Ly-alpha line widths as a probe of the IGM effective equation of state and the history of IGM reheating. Using both Ly-alpha (Hubble) and Ly-beta (FUSE) absorption to correct for line saturation, Shull *et al.* (2000) began a quantitative baryon census of the low- $z$  IGM.

Our group also wrote two papers using Hubble absorption-line data to measure heavy-element abundances in high velocity clouds in the Magellanic Stream (Gibson *et al.* 2000) and Cloud Complex C (Gibson *et al.* 2001). Complex C appears to be infalling gas with metallicity ranging from 10-40% times solar abundance. Using FUSE, Shull also studied the molecular content of gas in the Magellanic Stream (Sembach *et al.* 2001a). Additional FUSE papers included studies of the 3C 273 sightline (Sembach *et al.* 2001b), diffuse O VI emission from the ISM (Shelton *et al.* 2001), studies of escaping Lyman continuum radiation from starburst galaxies (Deharveng *et al.* 20001), and hot O VI in the Galactic disk (Sembach *et al.* 2000) and halo (Savage *et al.* 2000).

In a major article in *Science*, the FUSE IGM group (Kriss, Shull, *et al.* 2001) announced the first detection of the He II Ly-alpha forest at redshifts  $z = 2.3-2.9$ . The data are consistent with theoretical expectations of an IGM photoionized by both quasars and starburst galaxies.

Shull, Tumlinson, Browning, and colleagues wrote several papers on the FUSE molecular hydrogen surveys. Initial FUSE H<sub>2</sub> results were described by Shull *et al.* (2000), while a major survey of H<sub>2</sub> in the LMC and SMC (Tumlinson, Shull *et al.* 2001) confirmed theoretical expectations about the lower molecular content and elevated UV radiation fields in the Magellanic Clouds. The dominant effects appear to follow from the reduced metallicities and lower grain formation rates of H<sub>2</sub> in the LMC and SMC.

On the theoretical side, Tumlinson & Shull (2000, 2001) published two papers modeling the first, zero-metal stars and their ionizing effects on the surrounding gas. These stars are smaller and hotter than their Pop I counterparts, and they may be detectable through redshifted He II emission lines, owing to their prodigious emission of He II (ionizing) radiation.

Shull and colleagues made several in-depth theoretical investigations of the “radiative feedback” from galaxy formation, primarily the effects of ionizing radiation produced by the first massive stars. Venkatesan, Giroux, and Shull (2001) studied the IGM heating and ionization from an early X-ray background produced by AGN. Ricotti and Shull (2001) modeled the escape fraction of Lyman continuum radiation from high- $z$  spheroidal galaxies, while Dove, Shull, and Ferrara (2000) modeled the escape from disk galaxies with superbubble breakthrough. Ricotti, Gnedin, and Shull (2001a,b) wrote two papers presenting self-consistent numerical simulations of the formation and radiative feedback from the first galaxies. A key new result is the “positive feedback” of the ionizing radiation in producing molecular hydrogen, a key coolant for Population III objects. These objects are low-mass galaxies with virial temperatures less than 10,000 K. The robust re-formation of molecular hydro-

gen far outweighs the photo-dissociation of H<sub>2</sub> by far-ultraviolet radiation. Thus, low-mass (dwarf spheroidal) galaxies may be quite common during early epochs, at redshifts  $z = 15-30$ .

Stephen Skinner’s research is currently focused on observational studies of star-forming regions and Wolf-Rayet (WR) stars using a variety of space and ground-based telescopes. Recent observations with the Chandra X-ray observatory have revealed variable X-ray emission from very young embedded stars in the Rho Oph and Orion molecular clouds. Current work is directed toward identifying the physical processes by which such young stellar objects produce X-rays. The first high-resolution X-ray spectra of WR stars were obtained with Chandra and XMM-Newton during 2000. Chandra grating spectra of the nearest WR binary system Gamma Velorum (WC8 + O7) are rich in emission lines, and the spectral properties place tight constraints on theoretical wind-shock models used to explain WR X-ray emission. The high angular resolution Chandra images also reveal a second X-ray source lying only 4.8 arc-seconds from Gamma Vel that is very likely a late-type pre-main-sequence star. This discovery, along with earlier ROSAT images, supports the idea that the massive Gamma Vel system is quite young and is surrounded by a population of low-mass pre-main-sequence stars.

Ted Snow continued his interstellar medium research, concentrating on problems related to the interaction of gas and dust in interstellar clouds, the connection between interstellar and interplanetary dust, and the longstanding question of the unidentified diffuse interstellar bands (DIBs). These research programs involve both observational and laboratory studies.

During the past year, Snow’s observational programs were largely focused on results from the Far Ultraviolet Spectroscopic Explorer (FUSE), particularly the survey of molecular hydrogen abundances and excitations in translucent interstellar clouds. In addition, Snow was active in several ground-based studies of interstellar absorption lines and dust extinction. Among these are a general survey of molecular hydrogen in dense clouds and a study of the relationship between H<sub>2</sub> and the carriers of the as-yet unidentified diffuse interstellar bands (DIBs).

Snow has also been involved in optical ground-based studies of the DIBs, with two new results regarding the strongest DIB, which is centered near 4428Å; (1) this DIB is devoid of fine structure, suggesting that it is produced by electronic absorption followed by rapid internal conversion, or else is a composite of many unresolved rotational lines in a molecular band; or (2) the band is shallow because it consists of individual lines that may be individually saturated but are unresolved, thus leading to a broad featureless feature (See Snow 2002, *ApJ*, in press).

Snow’s FUSE observational study of molecular hydrogen in translucent interstellar clouds has given rise to fundamental questions about the nature of these clouds as well as the origin and excitation of molecular hydrogen, the most abundant interstellar species. The basic results and conclusions of this survey will be reported by Rachford *et al.* (2002, in preparation).

Finally, within the past two years Snow's ongoing laboratory study of candidate carriers of the DIBs has led to new results on ionized polycyclic aromatic hydrocarbons (PAHs; LePage, Snow, and Bierbaum, 2001, *ApJ Supp.* 132, 233); and carbon chain anions (Barckholtz *et al.* 2001, *ApJL*, 547, L161). Our laboratory chemistry program will continue to focus on carbon chain ions reacting with neutral atoms such as H, and will then move on to studies of reactions of atomic cations such as C<sup>+</sup> with neutral PAH and carbon chain molecules.

#### 4. PERSONNEL CHANGES DURING 2000

*New Faculty:* Dr. Jason Glenn (California Institute of Technology).

*New Research Associates:* Dr. Joseph Collins (University of New Mexico); Dr. Mary Putman (Australian National University); Dr. Jessica Rosenberg (University of Massachusetts); Dr. Stephen Skinner (JILA/University of Colorado); Dr. Aparna Venkatesan (University of Chicago).

*Research Associate Departures:* Dr. Brad Gibson (University of Melbourne); Dr. Mark Giroux (University of Tennessee); Dr. Bo Reipurth (University of Hawaii).

*New Graduate Students:* Matthew Browning, Nathaniel Cunningham, Benjamin Knowles, Randy McEntaffer.

*New Staff:* Brooks Rownd.

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