University of Hawaii
Institute for Astronomy

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Abstract

The Institute for Astronomy (IfA) is the astronomical research organization of the University of Hawaii (UH). Its headquarters is located in Honolulu on the island of Oahu near the University of Hawaii at Manoa, the main UH campus. The IfA is responsible for administering and maintaining the infrastructure for Haleakala Observatories on the island of Maui and for Mauna Kea Observatories (MKO) on the island of Hawaii. This report covers the period from 1 October 1993 through 30 September 1994.

1 Staff

The scientific staff during this report period consisted of Joshua Barnes, Richard L. Baron, Ann M. Boesgaard, Douglas C. Braun, Yong-Ik Byun (Hubble Fellow), Richard C. Canfield, John Carr, Gianna Cauzzi (solar postdoctoral fellow), Kenneth Chambers, Antoinette Songaila Cowie, Lennox L. Cowie, Constantine Deliyannis (Parrent Fellow), Fred Forbes, Isabella M. Gioia, J. Elon Graves, Thomas P. Greene, Donald N. B. Hall (Director), James N. Heasley, J. Patrick Henry, George H. Herbig, Klaus-Werner Hodapp, Joseph Hora, Esther M. Hu, Hugh Hudson, David C. Jewitt, Robert D. Joseph, Lev Kofman, John Kormendy, Barry J. LaBonte, Edwin Ladd (James Clerk Maxwell Telescope Fellow), Edward Lu (solar postdoctoral fellow), Gerard Luppino, Alexander N. McClymont, Robert McLaren, Karen J. Meech, Thomas Metcalf, Mark Metzger (postdoctoral fellow), Donald L. Mickey, Satoshi Miyazaki (visitor), Malcolm Northcott, Frank Q. Orrall, Aleksei Pevtsov (solar postdoctoral fellow), Tobias Owen, Andrew J. Pickles, Narayan Raja, John T. Rayner, Pui Hin Rhoads, Kathleen Robertson, Claude Roddier, François J. H. Roddier, David B. Sanders, Mark A. Shure, Theodore Simon, Douglas Simons, Bradford Smith, Alan N. Stockton, Tjet Sun, David J. Tholen, Alan T. Tokunaga, R. Brent Tully, Richard J. Wainscoat, Jean-Pierre Wülser, and Gareth Wynn-Williams.

2 Mauna Kea Observatories

The telescopes in operation during the report period were the UH 2.2 m telescope and two UH 0.6 m telescopes; the 3 m NASA Infrared Telescope Facility (IRTF), operated by the UH under a contract with NASA; the 3.6 m Canada-France-Hawaii Telescope (CFHT), operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique of France, and the University of Hawaii; the 3.8 m United Kingdom Infrared Telescope (UKIRT), operated in Hawaii by the Joint Astronomy Centre (JAC) based in Hilo on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom; the 15 m James Clerk Maxwell Telescope (JCMT), a submillimeter telescope operated by the JAC on behalf of the United Kingdom, Canada, and the Netherlands; the 10.4 m Caltech Submillimeter Observatory (CSO), operated by the California Institute of Technology for the National Science Foundation; the Hawaii antenna of the Very Long Baseline Array (VLBA), operated by the National Radio Astronomy Observatory (NRAO); and the 10 m Keck I telescope of the W. M. Keck Observatory (WMKO), which is operated by the California Association for Research in Astronomy (CARA) for the use of astronomers from the California Institute of Technology, the University of California system, and UH.

Construction continued on the 8.2 m Japan National Large Telescope (known as "Subaru") and on the 10 m Keck II telescope. A ground-breaking ceremony for the Gemini 8 Meter Telescope was scheduled for 7 October 1994. The Gemini Project is a partnership of the United States, United Kingdom, Canada, Chile, Argentina, and Brazil.

This report covers in detail only the UH telescopes.

2.1 2.2 meter telescope

During the report period, imaging with CCDs remained the most common use of the telescope, accounting for 42% of the observing time. This comprised mainly wide-field imaging using the Tektronix 2048×2048 CCD at the f/10 focus. Imaging with the 256×256 NICMOS infrared camera was performed for 15% of the observing time, and the new 1024×1024 QUIRC near-infrared camera was used for 6% of the observing time. Near-infrared spectroscopy using KSPEC accounted for 15% of the observing time, and low-resolution optical spectroscopy was performed for 10% of the observing time. Coudé spectroscopy and the OH suppression spectrograph accounted for 5% of the observing time each; the remaining 2% of the observing time involved visitor instruments.

QUIRC, the new infrared camera (see section 4.2), with 1024×1024 pixels, was commissioned on the telescope in July for the impact of comet P/Shoemaker-Levy 9 with Jupiter. This camera has a field of view very similar to that of the 256×256 NICMOS camera with $\times 2$ optics, but has much better sampling, better cosmetics, and lower read-noise, so it has largely replaced NICMOS as the primary near-infrared imaging detector at the 2.2 m telescope.

Work to improve image quality continued, especially on the new f/31 secondary mirror, which is designed to match the primary mirror, thereby giving 80% of the light within 0.2″. At the beginning of this report period, the f/31 top-end was replaced by a new system, which utilizes a hexapod mount for the secondary mirror. This allows the mirror to be remotely tilted in x and y directions, translated in x and y directions, and focused. The new hub is connected to the ring by new spiders that contain damping material.

A new air pressure regulator for the primary mirror support system was installed. This has resulted in an improvement in the mirror support. We are investigating independent servo control of the pressure in the three air bags that support the mirror.

Engineering tests of the tip-tilt secondary system were performed during the second half of the report period. The tip-tilt system was successfully used for the Jupiter/SL9 impact, with one of the Galilean satellites used as the guide "star." Guide stars down to magnitude 12 were successfully used; the camera head will be redesigned for more effective cooling, to permit guiding on fainter guide stars.

A new offset guider was constructed during the report period. This guider uses a Tektronix 512×512 CCD to provide the fast-guide signal for the tip-tilt secondary, and the slow-guide signal for offset guiding. This guider underwent a series of engineering tests during the report period and was scheduled to be installed on the telescope for general use in October 1994.

Equipment to provide a bidirectional video/audio link between Hale Pohaku and the telescope was installed. The video section of the link was tested during the report period. Full usage of this system awaits the installation of some of the audio components. The link is expected to allow remote participation in observations from Hale Pohaku.

Documentation for the telescope is being moved toward a World-Wide Web format. The URL for information relating to the 2.2-meter telescope is

http://www.ifa.hawaii.edu/88inch/88inch.html

Scheduling periods for the telescope are currently 4 month trimesters: December–March (deadline September 30); April–July (deadline January 31); and August–November (deadline May 31).

2.2 0.6 meter decommissioning

On 25 August 1994, the northern 0.6 m ("Planetary Patrol") telescope, which had been in operation since 1969, was removed from the Mauna Kea summit ridge to make way for the Gemini 8 Meter Telescope. The 0.6 m telescope was relocated to Leeward Community College on Oahu, where it will be refurbished for use by undergraduates under the auspices of the Hawaii Space Grant College.

2.3 Site characteristics

The National Radio Astronomy Observatory has installed an atmospheric phase monitor along the road leading to the VLBA antenna, at an elevation of 3220 m. The phase monitor is part of NRAO's program to evaluate potential sites for the proposed Millimeter Array (MMA). Two antennas, 1.8 m in diameter and separated by 200–300 m, receive a 11 GHz signal from a geostationary communications satellite. The changes in phase difference between the signals from the two antennas indicate the degree of wavefront distortion caused by fluctuations in atmospheric water vapor along the two paths. The monitor therefore measures the "seeing" at radio wavelengths. The system is similar to one being operated at the summit by the Smithsonian Astrophysical Observatory. The NRAO phase monitor will operate until 1996; results will be published in the MMA Memo series.

The Federal Aviation Administration, the National Weather Service, and the Department of Defense are engaged in a joint program to install a new generation of sophisticated and powerful Doppler weather radars throughout the United States. The program is called the Next Generation Weather Radar (NEXRAD). Four NEXRADs are planned for Hawaii. Two of them, one on Molokai and one north of Kamuela on the Big Island, have the potential to create serious radio frequency interference (RFI) at the observatories on Mauna Kea and Haleakala. The power density in the main lobe of the radar beam at the observatories is in the range 100 mW m^{-2} to 1 W m^{-2}. The operating frequency is between 2.7 and 3.0 GHz. After extensive negotiations, the IfA has reached agreement with the NEXRAD Program Office, and in particular with the National Weather Service, regarding modification of the scan patterns for these radars. For the Molokai NEXRAD, which became operational in February, the lowest elevation scan is 2°, which avoids illumination of the observatories by the main lobe. In November 1994, the elevation restriction will be replaced by spot blanking, which turns off the transmitter when the antenna is pointed at the observatories. The Kamuela NEXRAD, due to be installed late in 1995, will be fitted with spot blanking from the outset. For both radars, the blanked region will be set so that the peak power density does not exceed 1 mW m^{-2}. As part of the agreement, the Weather Service may suspend the RFI mitigation during periods of severe or threatening weather (e.g., heavy thunderstorms or an approaching hurricane).

2.4 Infrastructure

The UH 2.2 m telescope, CFHT, UKIRT, IRTF, Keck I, CSO, and JCMT, and the Mid-Level Facility at Hale Pohaku are connected through Proteon routers to a fiber distributed data interface (FDDI) token ring. The bandwidth of this local-area communications network is 100 Mbits s^{-1}. The VLBA connects to the network via a leased copper circuit to the local network at the 2.2 m telescope. During the past year, all the Proteon p4200 routers were replaced with Proteon CNX-series units that interface directly to the single-mode fiber, eliminating the need for the multimode–to–single-mode converters, which were used with the older routers. This change solved the problems with failures and low throughput on the FDDI ring. There are four T-1 (1.544 Mbits s^{-1})

circuits leased from GTE Hawaiian Telephone linking telescopes at the summit to base facilities on the island of Hawaii. CFHT and the JAC (UKIRT and JCMT) each have one of these, and Keck has two. From Hale Pohaku there is a leased T-1 to the UH Manoa Computer Center, which carries the off-island Internet traffic for all the Mauna Kea Observatories.

In July, a layer of "chip seal" was applied to a 1.4 km section of the paved portion of the Mauna Kea Access Road. Chip seal is a thin layer of asphalt embedded with crushed stone of uniform size, approximately 1.3 cm. The purpose of the application is to make traveling on the road safer when "black ice" conditions occur. Chip seal has been used successfully on a number of mountain roads on the U.S. mainland and elsewhere to improve traction in light ice and snow conditions. The section chosen for this initial chip seal application extends from the 4020 m level down to the 3840 m level and includes all sections where the grade is 15% or greater. The effectiveness and durability of chip seal will be assessed during the coming winter.

Just below the Mid-Level Facility, there is a long-term construction camp available for telescope projects that wish to have their construction workers reside on the mountain during work shifts. During the report period, the camp was used heavily by workers at Keck II and Subaru.

3 Haleakala Observatories

Wayne Lu is the Assistant Director, Haleakala Division, UH IfA, and is based at the IfA Maui headquarters office located in Kula.

3.1 Mees Solar Observatory

The observatory staff consisted of Superintendent Anthony Distasio; System Programmer Elaine Olson; Electronics Technician Les Hieda; Solar Observers Garry Nitta, David Judd, and Jeffrey Douglass; Electronics Engineer Mark F. Waterson; and Electro-Optical Engineer Andrew Sheinis.

During the report period, the Mees staff carried out programs in support of IfA scientists. Mees Solar Observatory continued to support the *Yohkoh* mission, as well as the cosmic ray neutron detector experiment of the University of Chicago's Enrico Fermi Institute.

Major instruments at the Mees Solar Observatory include the Imaging Vector Magnetograph, the Photometric Oscillation Imager, and the White-Light Solar Imaging Telescope System.

3.2 LURE Observatory

LURE is a lunar- and satellite-ranging facility. The mission at LURE was extended more toward providing altimeter information by adding four additional targets needing precise orbit determination for onboard instrumentation calibration. Two Global Positioning System (GPS) satellites carrying cube corner reflectors are now being tracked, along with Russian Space Agency satellite METEOR-3 and the U.S. Department of Defense vehicle MSTI-2. One additional geodynamic satellite (STELLA, launched by the Centre National d'Etudes Spatiales) was also added to the list of targets. The total number of satellites tracked at LURE is now 13.

The accuracy of the measurements continues to provide subcentimeter three-axis positioning for most geodynamic targets. The measurements for LAGEOS-1 and LAGEOS-2 are 0.9 cm rms, while that for STARLETTE is 0.8 cm rms (single shot). Normal points generated by temporal averaging of single-shot data provide 0.2–0.4 cm rms for these targets. Measurements to the altimeter targets vary from 1.8 cm rms for TOPEX/Poseidon to 0.8 cm rms for ERS-1 (single shot).

A follow-on contract to provide satellite tracking data at LURE commenced on 1 February 1994 for the period through 31 January 1999.

The observatory staff consisted of Project Manager Daniel O'Gara, Engineer Ronald Zane, Project Foreman Michael Maberry, and Laser Ranging Technicians Craig Foreman, Karl Rehder, and Timothy Georges.

3.3 Atmospheric Characterization Program

The Haleakala Atmospheric Characterization (HAC) Program, conducted by the UH IfA for the U.S. Air Force Phillips Laboratory, has as its primary goal the measurement and characterization of the atmosphere-induced seeing at this site. This program is in support of the Air Force Advanced Electro-Optical System (AEOS), a 3.6 m telescope that will be built within the Haleakala Observatories Reserve. This program incorporates various instrumentation, including a micrometeorological measurement tower, two optical seeing monitors, and an acoustic sounder.

The UH IfA Haleakala Observatories has a two-year contract, which will run through February 1996, to characterize the atmospheric turbulence at this site and quantify the observed optical seeing effects. Much of the equipment in use was developed by the UH IfA specifically for this program. The instrumentation development phase was nearly completed at the end of the report period. The first measurement and data acquisition campaign of the program had been successfully concluded, and data analysis work was in progress.

Plans included the improvement of some of the instrumentation to provide enhanced data acquisition, management, and analysis. It was projected that at least four data acquisition campaigns will be conducted each year of the program.

4 Instrumentation

4.1 Adaptive optics

During the report period, there was a major effort to develop a flexible control system with real-time diagnostic capabilities that is well adapted to astronomical observations. Two Force CPU-2CE SPARC single-board computers are used on a VME backplane. One processor, called the loop processor, is dedicated primarily to the feedback loop tasks, which include reading signals from a wave-front curvature sensor, doing the feedback loop matrix multiplication, and sending the output to a deformable bimorph mirror. The other processor, called the control/status processor, manages loop data flow to a workstation and transfers new control parameters to the loop processor without stopping the loop. A 1 Mb section of the loop processor memory is mapped onto the VME bus and is accessible for reading and writing from the control/status processor. All communication between the processors is accomplished using this shared memory. An Ethernet link is used for communicating between the control/status processor and a workstation. The software core is based on the Wind River Systems VxWorks real-time operating system running on the Force SPARC computers. Core services currently include the feedback loop, data stream management, and parameter, data, and status passing.

The control system is an integrating type divided into three nested sub-loops: primary, secondary, and tertiary. The primary loop controls the deformable mirror. The secondary loop controls the tip/tilt platform on which the bimorph mirror is mounted. It runs at a lower bandwidth than the primary loop and keeps the bimorph mirror DC tip/tilt component close to zero. The tertiary loop provides guiding information to the telescope control system to keep the tip/tilt platform DC component close to zero.

A graphical user interface has been developed. Pop-up menus are used to display the current status of the system, and sliders allow the modification of the control parameters. A graphic display of the 13 control channels is used to monitor the sensor signals and the output drive values. A pupil display is used for telescope pupil alignment. A Super Mongo graphic display is used for real-time statistical analysis of the sensor AC or DC signals, as well as the mirror drive signals. Before statistical analysis, a matrix transformation can be applied to convert the signals into system modes or Zernike modes.

This new control system was first successfully tested on 5 and 6 December 1993 during an observing run at the CFHT on Mauna Kea. The first astronomical observations were made on the same telescope on 25–27 December 1993. Additional astronomical observations were made on 25–27 January 1994 at the UKIRT. During these observations, the theoretical performance of the system was not yet fully achieved. This is due to a few telescope-related problems that will be avoided in the future. CFHT observations suffered from chromatic aberrations produced by a transfer lens in the coudé train. Observations were limited to the use of narrowband filters, and aberrations produced by the lens (mainly triangular coma) were poorly compensated for. In addition, the sensor suffered from a 2 magnitude loss due to transmission through the coudé train. These problems will be avoided by using the Cassegrain focus. UKIRT observations suffered from strong telescope-produced aberrations that took much of the stroke of the deformable mirror and brought a few actuators close to saturation. Compared with that on the CFHT, the seeing was poorer due to the lack of thermal control in the dome. These problems are now being addressed. The sensor also suffered from a 1 magnitude loss through the built-in dichroic pick-up mirror used for telescope tracking. In spite of these difficulties, in the H band under good seeing conditions at the CFHT, Strehl ratios were improved by a factor of 8.5, producing absolute Strehl ratios of the order of 0.4.

At the CFHT, the instrumentation consisted of the CFHT 256×256 pixel "Red Eye" infrared camera and a 1024×1024 pixel CCD camera from UH. At the UKIRT, only a 256×256 pixel infrared camera from UH was used. Both infrared cameras have NICMOS-type HgCdTe detector arrays. In all cases the pixel size chosen was small enough to sample the images beyond the Nyquist frequency, allowing further deconvolution to be made. This limited the field of view to $6.4'' \times 6.4''$ on Red-Eye and $5.12'' \times 5.12''$ on the UH infrared camera.

A high priority was given to astronomical sources already observed by means of speckle interferometry or COME-ON, an adaptive optics system in France. Most of the sources were young stellar objects (YSOs) known to be double or surrounded with dust. A few evolved stars and protoplanetary nebulae and two galaxy cores were also observed. Standard data reduction procedures were used for flat-fielding, background subtraction, and data interpolation over bad pixels. In several cases individual exposures taken at the CFHT were subsequently derotated by the appropriate amount and co-added. Most of the images have been further deconvolved using the data recorded on stellar point sources. It is found that deconvolution is very effective in restoring the images. Various deconvolution algorithms have been used and compared. These include linear deconvolution methods (Wiener filter), nonlinear methods such as the Lucy-Richardson algorithm, and recently developed blind deconvolution algorithms. In most cases, the Lucy-Richardson algorithm produced the best results.

Scientific results can be summarized as follows: In all cases YSOs known to be double from speckle interferometry observations were clearly resolved. These include T Tau, GG Tau, XZ Tau, Z CMa, and V 380 Ori. Angular distances and position angles were found to be in good agreement with those published in the literature. In several cases (Z CMa, V 380 Ori, T Tau) magnitude differences show evidence for variability. Several objects appear to be marginally resolved. These include FU Ori and the companion of T Tauri. Circumstellar structures are detected around CW Tau, GG Tau, HL Tau, and FU Ori. The two compact sources in the Red Rectangle nebula (AFGL 915) are both resolved and identified with polar outflows from a highly obscured central source. There is marginal evidence for an accretion disk. The central source of the Frosty Leo nebula (IRAS 09371+1212) is double. One of the two components shows evidence for polar outflows. The shape of these protoplanetary nebulae is consistent with the distribution of material ejected by polar outflows from an orbiting binary star. The core of the M31 galaxy was found to be elongated in the H

band, and the core of the Seyfert galaxy NGC 4151 was found to be unresolved at the diffraction limit of the UKIRT in the *H* band.

4.2 Large-format infrared detector arrays

HgCdTe infrared detector arrays, in particular those with a 2.5 μm cutoff wavelength, have found widespread use in ground-based astronomy, even though they were originally developed for space-based applications. The last generation of these arrays, the NICMOS3 devices, was developed for the first infrared instrument (NICMOS) to be installed in the *Hubble Space Telescope* (*HST*).

Since the development of the NICMOS3 detectors in 1989, the fabrication technology for hybrid HgCdTe devices has progressed from the 256 × 256 format of those devices to routine fabrication of devices in a 640 × 480 format. The next step in detector format for astronomical detector arrays could therefore skip that format and go directly to 1024× 1024 pixels.

Based on this idea, the Rockwell International Science Center, under contract with the Institute for Astronomy and with funding provided by the Air Force Phillips Laboratory, developed a new infrared detector array in 1024 × 1024 pixel format named the HAWAII (HgCdTe Astronomical Wide Area Infrared Imager) device. At the IfA, this project involves Hall, Hodapp, Hora, and Metzger.

The multiplexer design was completed by the end of 1993, the first multiplexers were produced in March 1994, the first hybrid devices were fabricated in May, and the prototype device was delivered to the IfA in June 1994.

The first prototype HAWAII devices achieved very good performance. In the camera system, a double-correlated read-noise of 15 e^- was achieved. The dark current at 1 V bias could be confirmed to be below 1 e^-, even though the device was operated above the 77 K operating temperature. The quantum efficiency is above 50% and shows the wavy pattern characteristic of liquid phase epitaxy (LPE)–grown HgCdTe chips. The full well capacity is above 10^5 e^-, limited in this system by the dynamic range of the analog-to-digital (A/D) converter. Data reduction is practically identical to what is used for NICMOS3 256×256 devices. The residual excess dark current problem of the NICMOS3 devices is not fully resolved; however, it appears less serious in the first HAWAII prototype device.

To test the new HAWAII devices, a new infrared camera system, Quick Infrared Camera, or QUIRC, was built by T. Keller and the IfA machine shop staff. The goal was to build a camera in a very short time (7 months) to keep up with Rockwell's aggressive development schedule for the HAWAII devices. Similar to the camera used for the NICMOS3 devices, the new camera is a simple refractive optical system consisting of a field lens and an achromatic reimaging system with approximately a 1:1 reimaging ratio. QUIRC is equipped with a single filter wheel operated by a cryogenic stepper motor, a Portescap motor adapted to cryo operation by replacing the ball bearings with bushings out of MoS_2 impregnated Vespel. In a change from the older camera, a cryogenic pupil mask slide was installed to adapt the camera to different f-ratios. This pupil mask is operated by the same type of stepper motor as the filter wheel. The dewar is an up-looking design with a single large liquid nitrogen can (9 l volume) of a design similar to that of the CCD dewars used at the IfA. The dewar was designed for long periods of cold operation, and its vacuum stability is excellent, having demonstrated in excess of 4 weeks of continuous operation without pumping. The cryogenic hold time is in excess of 36 hours.

The HAWAII arrays are operated by a newly designed controller system intended to combine the best features of the older controllers with the more flexible device operation allowed by a system based on digital signal processors (DSPs). The digital side of this system is based on the CCD controller developed by R. Leach at San Diego State University. It was decided not to use the analog input and D/A pulse shaping capabilities of Leach's system, but rather to optically decouple digital clocking and data processing from any analog signal going in and coming out of the infrared array. For that, a digital interface board that resides on the Leach controller backplane was developed. It uses the same addresses as the Leach analog board for the output of A/D values onto the backplane. Some of the addresses used by Leach to control D/A converters for pulse shaping are used to control the clocks. The analog signal from the devices is preamplified, shifted by manually adjustable offset voltages, and sampled by a 1 MHz analogic A/D converter. The signals from the four independent quadrants of the HAWAII detector array are routed to the same A/D converter by an analog switch.

The DSP used in the Leach system is not used for signal processing due to the limited memory available on that DSP board. All raw data values are transmitted to the host computer (a SPARC LX or SPARC 2) via fiber optics, a fiber optics interface system, and an S-bus interface card, and are processed there.

5 Comet collision observations

All the telescopes at the Mauna Kea Observatories set aside time during July 1994 to study the collision of comet P/Shoemaker-Levy 9 with Jupiter. Only the activities at the University of Hawaii telescopes are covered here; for those on other telescopes see the reports of the individual observatories.

5.1 2.2 meter telescope

Jewitt and collaborators extensively studied doomed comet P/Shoemaker-Levy 9 at the 2.2 m telescope. Images from Mauna Kea in March 1993 were the first to reveal the characteristic "string of pearls" morphology of this comet. Up to 22 fragments were counted in the best images from the 2.2 m telescope. The progressive disintegration of the comet string was measured from monthly imaging observations. Astrometry enabled dynamicists elsewhere to predict the comet impact times accurately. An optical coronagraph was used to examine nuclear fragments as they crossed the inner magnetosphere of the planet immediately prior to impact. Substantial changes in the morphology of each fragment were observed and are presumed to have been caused by the action of the magnetic field on charged cometary dust grains.

Tholen obtained a series of images of comet P/Shoemaker-Levy 9 for purposes of extracting high spatial resolution astrometric data to assist with the accurate prediction of impact times for both ground-based observers and the Galileo project.

5.2 0.6 meter telescopes

In a collaborative effort with researchers from the Massachusetts Institute of Technology, observations of the impact of comet P/Shoemaker-Levy 9 with Jupiter were made using the northern 0.6 m telescope on Mauna Kea. The team consisted of Meech and UH graduate student B. Patten, and H. Hammel, J. Elliot, and graduate student J. Foust (MIT). The observations themselves were carried out by Patten and Foust.

Although the fragments of the comet impacted on the far side of Jupiter, as seen from Earth, two phenomena associated with the impact events were postulated to be visible: the impact flash, reflected off an appropriately placed satellite, and a plume or fireball from the impact site rising over the Jovian limb into direct view from the Earth. To observe these events, they employed a high-speed CCD camera coupled with a Global Positioning System receiver mounted directly at the Cassegrain focus of the telescope. This system allowed them to take five or more images per second with accurate timing information encoded into each frame.

Weather conditions permitted observation of two of the four events potentially visible from Mauna Kea, impacts C and R. High-speed imaging of Io, Europa, and Ganymede during impact C showed no detectable change in the R-band brightness of any satellite due to impact flash. High-speed imaging of the limb of Jupiter during impact R showed no detectable plume or fireball in the B band. A more thorough analysis of these data to search for small ($\sim$1%) brightness variations was still underway.

A campaign of broad- and narrowband visible and near-infrared imaging of Jupiter was also carried out during the period of comet fragment impacts and for one week after the impact of the last fragment to monitor changes in the cloud patterns near the impact sites. A number of new dark "spots" were found to be associated with individual fragment impact sites. These spots were observed to be very long-lived.

Tholen made high-speed photoelectric observations of the flash events with the southern ("Air Force") 0.6 m telescope on Mauna Kea. Four impacts were visible from Hawaii, those of fragments C, G, R, and W. Conditions were photometric for the fragment C impact, and Io was well-placed to produce a reflection. Preliminary analysis of the data, taken in blue light, showed no signal excess >1%. The noise is dominated by scintillation noise, which was at the 0.5–1% level. A little over 20 minutes of data, centered on the nominal event time, were obtained.

For the fragment G impact, intermittent fog and strong moonlight were present throughout the predicted event window, so no observations were attempted. Scattered thin cirrus was present during the fragment R impact, and although fog affected other sites on the mountain, the fog managed to avoid the southern 0.6 m telescope. No obvious flash is present in the data, though the data in the earliest part of the predicted event window were obtained during rapidly changing twilight conditions. A good twilight model will need to be removed from the data before limits on any flash event can be established. The effects of Hurricane Emilia made any observations of the fragment W impact impossible from any of the Mauna Kea sites.

6 Galactic and extragalactic studies

Chambers continued his studies of high-redshift radio galaxies and their environments. He has been conducting a multicolor ultra-deep imaging survey of $z > 2$ radio galaxies to study their color gradients and to search for companions. Chambers and graduate student G. Knopp nearly completed the multicolor photometry of one of these deep fields. Chambers also continued his search for new high-redshift radio galaxies with the Keck I telescope.

Chambers analyzed multifrequency radio observations of a sample of high-redshift radio galaxies that indicate that the Laing-Garrington effect seen in quasars is also seen in radio galaxies. This is contrary to simple orientation scenarios if the depolarizing medium is external to the radio-emitting plasma. A larger sample is being studied with graduate student J. Huang.

Chambers obtained *HST*, *ROSAT X-Ray Astronomy Satellite*, Very Large Array (VLA), and ground-based observations of Minkowski's Object, the best known example of a starburst triggered by a radio jet. Graduate student G. Knopp was analyzing the data.

Chambers obtained initial imaging polarimetery observations of high-redshift radio galaxies with the refurbished *HST*; the first-look data was being analyzed. To complement this data with ground-based data, Chambers began building the Hawaii Imaging Polarimeter for Proto Objects (HIPPO) for use with UH infrared and optical detectors.

A. Cowie, L. Cowie, Hu, and J. Gardner (Durham) completed a spectroscopic survey of $K < 20$ galaxy samples from the Hawaii Survey. The sample was chosen using K selection to minimize sensitivity to galaxy-type mix, and is substantially complete at $K < 18$, with $\sim$70% completeness at $K = 19 \rightarrow 20$. From the magnitude-distance relation at K, it is possible to rule out any significant positive luminosity evolution out to $z = 1$. Evolution of the amplitude of the 4000 Å break and Balmer line equivalent widths indicates that galaxies were undergoing significantly more star formation at

$z = 1$ than at the present time. These data are being used to study the K-band luminosity function and its evolution.

Although most survey objects have redshifts $z \lesssim 1$, an unusual galaxy at $z = 2.35$ was found. This object (HAW-167) shows a spectrum of both low- and high-ionization absorption lines in the rest-frame ultraviolet, a characteristic of post-starburst galaxies. However, near-infrared spectroscopy by graduate student E. Egami shows broad, redshifted Hα emission and no detected emission in other Balmer lines, [O II] λ3727, or [O III] λ5007.

L. Cowie, A. Cowie, Hu, Pickles, and Wainscoat, in collaboration with UH students Egami, Huang, and S. Ridgway, and R. Weymann (Carnegie Observatories) combined imaging and spectroscopic observations at optical and near-infrared wavelengths to show that HAW-167 closely resembles the most extreme member of the class of Mg II–absorbing broad absorption line quasars (BAL QSOs), though HAW-167 is possibly more heavily reddened, as indicated by the strong Balmer decrement. This similarity suggests there may be an evolutionary sequence or other close connection with the BAL QSOs, which will be explored in future investigations.

Gioia continued her participation in the *Einstein Observatory* Einstein Medium Sensitivity Survey (EMSS) project. The third paper of the EMSS series presents optical images for all 835 sources extracted from digitized Schmidt plates, together with an update of the source identification. The images, $5.6' \times 5.6'$ centered on the X-ray source position and containing the indication of the optical counterpart of the X-ray source, are intended as finding charts for observers interested in carrying out further observations of the sources. The fundamental goals of the EMSS are to provide a detailed accounting of the classes of discrete sources that make up the faint X-ray sky and to provide large and complete samples of X-ray–selected objects for statistical and individual studies. The data have been used to study and discuss statistical properties (counts, luminosity functions, evolution) of AGN, Bl Lac objects, clusters of galaxies, and galactic stars.

Gioia and Henry continued the study of the NEP (North Ecliptic Pole) region of the *ROSAT* All-Sky Survey. The goal of this program is to use the deepest region of the All-Sky Survey to extract a sample of distant clusters to study the evolution of their X-ray luminosity function, evolution first detected in the EMSS sample. To date about 170 sources have been observed. Preliminary data reduction has revealed the presence of ~45 clusters, ~50 AGN, 4 BL Lac objects, and ~50 stars. The spectroscopic program is carried out in parallel using both the UH 2.2 m telescope and the CFHT. During the summer 1994 observing season, a region of sky containing 55 X-ray sources was completely identified. The identification rate was as follows: 63% active galactic nuclei (AGN) or emission-line galaxies, 17% clusters of galaxies, and 20% stars. This mix of sources leads to an estimate of finding of the order 100 clusters total in the NEP, some at high redshift (12 clusters with $z > 0.3$, and 3 clusters with $z > 0.5$ already found).

The low-redshift groups of galaxies were the first surprise of the NEP Survey. These objects are extended in X-rays and, from a small volume-limited sample, the first measurement of the ensemble properties of X-ray–selected groups of galaxies were made. Their X-ray luminosity and temperature function were derived and found to be a smooth extrapolation from rich clusters of galaxies. A paper on the results was submitted to *The Astrophysical Journal*. Among the serendipitous discoveries of the survey are (1) the most distant X-ray–selected QSO at a redshift of 4.32 (paper published), and (2) a cluster at 0.327 showing an arc in a 10 min I exposure that is bright enough to be observed spectroscopically with some hope of success (paper in preparation).

Throughout the report period, Gioia and Luppino, in collaboration with J. Annis (Fermilab), and F. Hammer and O. Le Fevre (Observatoire de Paris-Meudon and CFHT), continued the observational search for arcs and arclets in a complete sample of 40 X-ray–luminous ($L_x > 2 \times 10^{44}$ ergs s^{-1}) and distant ($0.15 < z < 0.8$) clusters of galaxies drawn from the EMSS. The program uses the UH 2.2 m telescope, the CFHT, and the Keck I telescope. All clusters were imaged at least once in the R band and in excellent seeing conditions ($0.8''$–$0.9''$). A paper describing the results has been published in *The Astrophysical Journal Supplement Series*.

A few selected clusters were also imaged in B, V, and I bands. The survey has yielded eight giant arcs, two arclets, and six candidate lensing systems, resulting in the highest lensing frequency ever found in a complete sample. The main results (submitted to *The Astrophysical Journal*) indicate that (1) high X-ray luminosity does indeed identify the most massive clusters, and thus X-ray selection is the preferred method for finding rich clusters at intermediate and high redshifts; (2) there is evidence for compact cluster mass density profiles; (3) the geometry of the arcs suggests the presence of mass substructure in the central 0.5 Mpc cluster cores; (4) the data support the view that standard $\Omega = 1$ CDM (cold dark matter) cannot account for the abundance of massive, high-redshift clusters present in the lensing survey sample. Next, the CFHT and the Keck I telescope will be used to determine the redshift for the arcs and cluster velocity dispersion to confirm that these arcs are indeed images of distant galaxies gravitationally distorted by the massive foreground clusters. When the 8 K $\times$ 8 K CCD mosaic, now under fabrication at IfA, is ready, it will be used at the prime focus of the CFHT to image EMSS clusters selected to cover a range in redshift. The goal of these observations is to measure the weak gravitational distortion of faint background field galaxies behind rich clusters at large radii.

The most X-ray luminous clusters were also being observed in the K band (with graduate student K. Jim) to search for possible distant "red arcs" and to investigate the nature of the arc sources. Two of the most spectacular arc systems were being observed with the *HST*.

ROSAT High Resolution Imager (HRI) and *ASCA* (*Advanced Satellite for Cosmology and Astrophysics*) data were also forthcoming.

Hu and R. McMahon (Cambridge) continued their investigation of Lα candidate emitters in $z > 4$ quasar fields with spectroscopic follow-up studies. These objects, which are selected on the basis of deep narrow-band filter imaging at the wavelengths of the quasar's redshifted Lα emission and at neighboring continuum bands, are potentially emission-line galaxies at very high redshift, which enables them to sample epochs when the universe was 1–2 Gyr old. Observations made with the LRIS spectrograph on the Keck I telescope in multislit mode show a number of objects with prominent emission only near the quasar Lα wavelength. In contrast to many previous searches for Lα companions to high-z quasars, where detected candidates lay within $\sim 6''$ of a (radio-loud) quasar, these objects have typical separations of $\sim 80''$ from each other and from the quasar. The separations approximate the characteristic galaxy-galaxy correlation scale at these redshifts, suggesting that the objects do, indeed, correspond to a high-redshift population of field galaxies, and that we are sampling emission from field galaxies unrelated to the radio emission mechanism of the quasar.

Hu and L. Cowie continued their study of deep ($\sim$40,000 s) *ROSAT* X-ray images taken with the HRI on fields within the Hawaii Galaxy Survey. The fields have low hydrogen column density and lie at high ecliptic and galactic latitudes. The high spatial resolution of the HRI, with a positional error box $\sim 3''$ in radius, allows for unambiguous source identification, and identifications are complete to an X-ray flux limit of 2.5×10^{-14} ergs cm^{-2} s^{-1}. From this sample, it is seen that although 10 of the 14 objects above the flux limit are quasars or Seyferts, the remaining 4 are much more commonplace galaxies, including a normal Sb galaxy, and very tiny $L = 10^{-5} L_*$ dwarf Im galaxy. With graduate students T.-S. Kim and Ishida, work is proceeding to identify different classes of galaxy populations at fainter flux levels by cross-correlating the X-ray data with the multicolor optical and infrared image data for these fields.

Graduate student Huang, L. Cowie, and R. Ellis (Cambridge) are conducting a wide-area, multicolor galaxy survey in the optical and infrared. The goal is to obtain multicolor imaging and spectra for large samples (many thousands) of objects. In contrast to the $K < 20$ spectroscopic survey, which sampled fields of $\sim$100 arcmin^2, this survey is using the new large-format infrared arrays to cover degree-size areas down to a K magnitude of 16. The fields are equatorially positioned, to be observable from both northern and southern hemispheres. Spectroscopic studies will be carried out with Autofib II, a multifiber spectrograph at the Anglo-Australian Telescope (AAT).

Stockton and graduate students S. E. Ridgway and M. Kellogg used the LRIS spectrograph on the Keck I to obtain deep spectroscopy of the radio galaxies 3C 65 and 3C 368, and the quasar 3C 2, all at $z \sim 1$. For 3C 368, they confirmed previous suggestions that the apparent "nucleus" is actually a projected Galactic M5 star, and they found a striking complexity in the velocity field of the emission lines. While the actual data has a spatial resolution (FWHM) of $\sim 0.85''$, the signal-to-noise in the [O II] λ3727 line is sufficient to allow deconvolution of the two-dimensional spectrum to better than $0.3''$. They found no evidence for an old stellar population either in the summed continuum along the body of the galaxy or in the bright continuum peak near the N radio lobe. The situation is quite different in 3C 65. Stockton, Kellogg, and Ridgway found, contrary to previous reports, that after a careful subtraction of the emission-line spectrum, both the 4000 Å break and absorption lines characteristic of an old stellar population are clearly present. This is the first clear detection of stellar absorption lines in a high-redshift radio galaxy.

Stockton and Ridgway received their first *HST* Wide Field Planetary Camera 2 (WFPC2) image in their program of deep imaging of a complete sample of $z \sim 1$ 3C galaxies and quasars. This program is an extension of Ridgway's doctoral thesis program, which includes ground-based optical and infrared imaging of a larger complete sample of 3C quasars, along with similar observations of a sample of quasars with a similar redshift distribution but lower radio luminosity. The observations for this program were completed in 1994, and the data are now being modeled. One of the goals of both projects is to determine whether the host galaxies of quasars in this complete sample are consistent with projections of the radio galaxies from the same sample, as predicted by the unified scenario.

Stockton, Hu, graduate student T.-S. Kim, and J. MacKenty (Space Telescope Science Institute) continued their study of the physical conditions in the luminous extended emission region around the quasar 4C 37.43 ($z = 0.3708$). The Lα flux, obtained from an *HST* Faint Object Spectrograph measurement, together with fluxes in Hα and Hβ, obtained from ground-based observations, indicate the presence of a moderate amount of dust in the emitting regions. The electron density, obtained from the [O II] λ3727 doublet ratio, is $\sim$300 e^- cm^{-3}; since the emission region is some 20 kpc from the quasar nucleus, this high density indicates that the emitting gas is probably either shocked or gravitationally confined. Detailed measurements of the velocity field of the ionized gas were also obtained; maximum velocities in the local frame were $\sim$400 km s^{-1}.

Tully collaborated with E. J. Shaya (Maryland) and P. J. E. Peebles (Princeton) on a project to reconstruct the development of the region around the Local supercluster. An extension of the *Nearby Galaxies Catalog* provides a description of the present distribution of galaxies within 3000 km s^{-1}. A variational principle analysis allows orbits to be constructed for choices of the two free parameters: mass-to-light assignments and the age of the universe. Model distances are compared with observed distances to discriminate between alternative parameter choices. Their current best model constrains the density parameter to be $\Omega_0 = 0.2 \pm 0.2$ (95% probability).

7 Interstellar matter

Graduate Student J. Deane, with Sanders and Ladd, mapped the W3 Giant Molecular Cloud (GMC) in $^{12}CO(1\to0)$ and $^{13}CO(1\to0)$ with 50″ resolution, an improvement in resolution of $\sim4\times$ over their previous maps of the region. A local thermodynamic equilibrium (LTE) analysis deterimined the distribution of column density throughout the GMC. This mass distribution was compared with the far-infrared luminosity, as determined from the *IRAS* Infrared Sky Survey Atlas (ISSA) images. A model of the background emission from the Galactic plane was removed from the ISSA images to isolate the emission from the GMC itself. Maps were constructed of the ratio of far-infrared luminosity to molecular gas mass throughout the cloud. The spatial variations of this $L_{\rm fir}/M_{\rm H_2}$ ratio are greater than the cloud-to-cloud variations among samples of molecular clouds in the Galaxy. One-third of the cloud's mass, contained in the three most massive cloud cores, generates 85% of the total cloud far-infrared luminosity and has elevated L/M ratios indicative of heating by embedded sources. The high activity in these regions does not seem to influence the L/M ratios in the rest of the cloud, which is relatively inactive, with $L_{\rm fir}/M_{\rm H_2}$ ratios ($\sim$2) characteristic of simple heating by the interstellar radiation field. Analysis of a similar data set of large-scale CO maps and ISSA images of the NGC 7538 GMC was begun to determine whether W3 is typical in its L/M properties.

Deane and Ladd completed a survey of eight dense cores in the NGC 7538 GMC in $^{13}CO(2\to1)$, $C^{18}O$ $(2\to1)$, and $^{13}CO(3\to2)$ at the CSO. Core properties such as size, linewidth, and excitation conditions are being determined for comparison with the local star-forming conditions, indicated by the $L_{\rm fir}/M_{\rm H_2}$ ratio. A similar core survey is underway for the W3 GMC.

Greene completed a mid-infrared photometric survey of young stellar objects (YSOs) in the ρ Ophiuchi dark cloud. This work was performed in collaboration with B. Wilking (Missouri St. Louis), P. André (Saclay, France), E. T. Young (Arizona), and C. J. Lada (Smithsonian Astrophysical Observatory [SAO]), and it was $\sim3\times$ more sensitive than the previous *IRAS*-based study of these YSOs. This new study identified many more Class II YSOs in the embedded cluster, and several new low luminosity ($L < 1L_\odot$) embedded (Class I or flat spectrum) YSOs were also found. The suspected luminosity segregation between embedded and Class II YSOs in the cloud is reinforced with these new results, and a new embedded phase lifetime of $2 \pm 1 \times 10^5$ yr was calculated. An empirical technique for estimating Class II and III luminosities from dereddened J-band data was developed, and this technique was used to derive luminosities and estimate masses (using stellar models) for these members of the YSO population. Nearly all these young stars have masses $0.2M_\odot < M < 2M_\odot$ with an average mass of $1.0M_\odot$ if the typical observed T Tauri age of 10^6 yr is assumed for the cluster.

Greene, in collaboration with Hora, M. Meyer (Massachusetts Amherst), and C. J. Lada, has also conducted a survey of ρ Oph YSOs with the UH KSPEC spectrometer. Preliminary results indicate that the embedded ρ Oph cluster is indeed quite young; results of spectral typing these data demonstrate that most Class II YSOs are younger than the D'Antona and Mazzitelli 10^6 yr stellar model isochrone and fall within the mass range $0.3M_\odot < M < 2M$. Greene and Lada have also used KSPEC to study the evolution of circumstellar material of YSOs as they evolve from embedded to pre–main-sequence (PMS) phases. Preliminary results suggest that flat-spectrum YSOs are in evolutionary states intermediate between embedded protostars and Class II PMS YSOs, since their photospheric absorptions are intermediate in strength between those of these classes.

Herbig's investigation of the young cluster IC 348 and its vicinity has continued. Color-magnitude data derived from $BVRI$ CCD photometry at the UH 2.2 m telescope are now available. Special attention has been paid to the Hα-emission stars, some as faint as $R = 20$, that were found in the earlier 2.2 m grism survey, and to *ROSAT* discoveries in the same area. Similar material has been obtained for several other star-forming regions, notably IC 5146, IC 1274-5, and IC 5070.

Herbig and graduate student M. Krismer are also working on the Hα grism material for NGC 2264. A substantial number of new emission-line stars, most of them much fainter than the limit of the classical surveys near $R = 16$, have been found in this young cluster. These new detections not only extend to a much fainter magnitude limit, but also to much weaker Hα equivalent widths than were previously possible. The conventional surveys halted near W(Hα) = 10 Å, while the new 2.2 m material extends into the domain of the WTTS (weak-line T Tauri stars), to about W(α) = 3 Å. It is expected that *ROSAT* detections in this area will ultimately become available.

Hodapp completed the analysis of the K'-band imaging data of all sources of molecular outflow on Fukui's list. The image data files will be published in the AAS CD-ROM series and are also available via anonymous ftp. The project of obtaining low-resolution infrared spectroscopy of stars in young embedded clusters continued with observations in the GGD 12-15 and L 1654 clusters.

Hodapp also began a project to measure column densities of dust in star-forming regions by measuring the reddening of background stars using the NICMOS3 camera. It is now being continued with the 1024 × 1024 QUIRC camera. The first target objects were Serpens NW and B 335.

Hora, along with W. Latter (NRAO) and L. Deutsch (Five College Astronomy Department/Univ. of Massachusetts), completed a spectral survey of planetary nebulae (PN) using KSPEC on the UH 2.2 m telescope. The 1–2.5 μm spectra of approximately 40 objects were obtained using a 1″ × 6″ slit, which allowed them to examine the different components of the PN, such as the central star, the ionized ring or lobes, and the halo region. By sampling various parts of the PN, more detailed data about the structure and conditions within the nebulae were obtained. For example, in the bipolar proto-PN AFGL 2688, an analysis of the H_2 line ratios showed that the molecule is collisionally excited throughout the nebula. In the bipolar PN M 2–9, the H_2 emission had a significant fluorescently excited component, and evidence for higher temperature shocks was seen in the ansae, where several lines of [Fe II] were observed.

With W. Hoffmann (Arizona), G. Fazio (SAO), and Deutsch, Hora used the MIRAC mid-infrared camera at UKIRT to observe the emission from three bipolar protoplanetary nebulae (PPN), AFGL 915, AFGL 618, and AFGL 2688. Short (0.1 s) exposure times were used, and the data were combined using a shift-and-add technique to achieve nearly diffraction-limited resolution at wavelengths from 8 to 20 μm. In all three PPN, the sources showed a bright unresolved core and fainter extended emission, primarily along the same axis as the optical and near-infrared nebulae. No direct evidence for structures such as disks perpendicular to the bipolar axis were seen. In AFGL 915 (the "Red Rectangle"), the mid-infrared emission features at 7.7 and 11.2 μm were seen concentrated along the edges of the bipolar "cone," with mainly continuum emission from the bright unresolved central source.

Ladd, with collaborators P. Myers (Harvard-Smithsonian Center for Astrophysics), G. Fuller (NRAO), R. Padman (Cambridge), and F. Adams (Michigan), published their study of the environs of one nearby embedded young star, L1551-IRS 5, in the submillimeter continuum and in rare isotopes of CO. They have found a nonaxisymmetric distribution of gas and dust on 3000 AU size scales and have attributed it to the effects of the powerful bipolar outflow from this source.

With Fuller, Ladd extended the study of rare CO isotope emission to a small sample of young sources in the Taurus-Auriga dark cloud complex. They have found that toward many of these sources, emission from even the very rare $C^{17}O$ isotope is optically thick, suggesting that the gaseous envelopes surrounding these sources have higher column densities than previously believed.

With H. Chen and P. Myers (Harvard-Smithsonian Center for Astrophysics), Ladd completed a comparative survey of the young stars in the Taurus and Ophiuchus star-forming complexes. They have found that the distributions of bolometric temperature and luminosity differ between the two complexes, and have suggested that these differences can be attributed to a difference in the average age of the young stars in each complex.

M. Hanner and T. Brooke (JPL), and Tokunaga undertook a 10 μm spectral survey of young stellar objects (YSOs) in the Ophiuchus molecular cloud. The objective was to determine if compositional similarities could be found in the 10 μm spectra of YSOs and that of comets. They were particularly interested in finding in the spectra of YSOs the 11.3 μm spectral signature of olivine seen in comets. In a sample of 14 sources, they found no evidence for olivine in the spectra of YSOs. Since the standard silicate emission and absorption band is seen in the YSOs, the lack of any olivine signature suggests that substantial thermal annealing of silicates in their line of sight has not yet occurred. Similar results were obtained in observations of YSOs in Taurus. A particularly interesting source in Taurus, Elias 1, was studied in detail. This object shows emission of both silicates and aromatic hydrocarbons and is peculiar in this respect.

J. Lacy (Texas), R. Knacke (Pennsylvania State, Erie), T. Geballe (UKIRT), and Tokunaga used the CSHELL to detect the S(0) H_2 quadrupole absorption at 2.22 μm in NGC 2024/IRS2. In conjunction with a nondetection of the S(1) line at 2.12 μm and observations of the CO 2-0 overtone band at 2.35 μm, an H_2/CO ratio of 3700 (+3100, −2600), with 2 σ limits, was obtained. This was the first directed measurement of the H_2/CO ratio. For NGC 2264/IRS, a limit of $H_2/CO < 6000$ was obtained. These ratios are lower than the ratio of 1 to 2 $\times\ 10^4$ determined from other methods. Ratios of other sources need to be determined, but this is made difficult by the high signal-to-noise required ($\geq$300) and the contamination by foreground H_2 emission that is very common in star-forming regions.

Tokunaga, graduate student J. Surace, Greene, and Carr (now at Ohio State) have begun a spectral survey using the KSPEC (1−2.5 μm cross-dispersed spectrograph) on the UH 2.2 m telescope. Their objective is to search for YSOs' spectral signatures that can be used to classify them and also to search for spectral signatures that can be observed at high spectral resolution to be used as probes of physical conditions close in to the star. This work is in progress.

8 Stellar astronomy

Graduate student J. King (now at Texas) and Boesgaard examined the differences in oxygen abundances obtained from the [O I] line at 6300 Å and the O I triplet at 7774 Å. With solar intensity spectra of the λ7774 triplet obtained at Haleakala Observatory, they confirmed previous results that indicate a discrepancy between the observed equivalent widths of Altrock (1968) and the values predicted by LTE and recent non-LTE models. However, this disagreement does not seem to affect the solar O abundance derived from *flux* spectra. They derived O abundances for a selection of relatively metal-rich F and G dwarfs from both [O I] 6300 Å and O I 7774 Å triplet, and they described the various uncertainties that enter into the analyses. After minimizing the possible systematic effects, they found that for $T_{eff} \leq$ 6200–6300 K there is no systematic difference between the 6300 and the 7774 abundances. For $T_{eff} \geq$ 6200–6300 K, however, the 7774 abundances are systematically higher than those from 6300. The agreement in O abundances from the two features at the cooler temperatures conflicts with other results; they suggest that the discrepancy may be due to the different model atmospheres utilized. If, as recently proposed, hotter T_{eff} values for metal-poor dwarfs are correct, then there appears to be no discrepancy between the 6300 Å O abundances in metal-poor giants and dwarfs and the 7774 Å abundances for dwarfs. This would seem to rule out substantial LTE departures or atmospheric inhomogeneity effects that skew metal-poor O abundances from the 7774 Å line (for cooler stars that have lower metallicity anyway). Given the repeated inability of different investigators to reproduce each others' O abundances from the [O I] 6300 Å line, and the uncertainty in its solar equivalent width, King and Boesgaard question the belief that O abundances from the forbidden line are more reliable than those from the permitted triplet.

King's dissertation work dealt with the general problem of stellar oxygen abundances. He also found two causes of the 7774 Å O I discrepancy in halo dwarfs: (1) the 7774 Å equivalent widths measured by some investigators apparently are systematically too large, and (2) the current $T_{\rm eff}$ scale for metal-poor dwarfs may be $\sim$150 K too low. Using improved equivalent widths and new photometric $T_{\rm eff}$ relations, he determined [O/Fe] ratios for a handful of halo dwarfs. The mean value, [O/Fe] $\sim$+0.52, is in good agreement with values determined from ultraviolet molecular features and optical forbidden lines in metal-poor stars. Additionally, the trend of [O/Fe] with $T_{\rm eff}$ seen by others disappears. King agreed that the effects of non-LTE and atmospheric inhomogeneities are relatively small for the stars considered.

King also considered possible cosmological implications of a hotter $T_{\rm eff}$ scale for metal-poor dwarfs and subgiants. Such higher values are in good agreement with those inferred from both the Victoria and Yale group's isochrone color-$T_{\rm eff}$ conversions. He concluded that no significant downward revision of globular cluster ages would result for those clusters having [Fe/H] near -1.3. Although a similarly strong conclusion cannot be reached for clusters of other metallicities, it seems that no substantial age reductions (>1 Gyr) due to uncertainties in color-$T_{\rm eff}$ relations are necessary. The good agreement between the newest Yale isochrones (which are redder than the Victoria isochrones for $0.45 < (B-V) < 0.75$) and the observed lower main sequence of M92 may be consistent with the upward revision of the temperature scale. However, this is not a very secure conclusion given the uncertainties in low-mass stellar models. The higher $T_{\rm eff}$ values lead to a mean ^{7}Li abundance of 2.28 ± 0.09 (1 σ) in hotter halo dwarfs. King infers a primordial value of $N({\rm Li}) = 2.35$. Stretching both observational and theoretical uncertainties, consistency with standard models of big bang nucleosynthesis is still achieved in the range $0.012 < \Omega_b < 0.017$ (for $H_{\rm o} = 100$ km s^{-1} Mpc^{-1}). The higher $T_{\rm eff}$ scale also raises the observed B/Be ratio in HD 140283 from 10 to 12. This value is more comfortably consistent with the production of the observed B and Be by ordinary spallation processes.

King also examined the question of the location of the break in the [O/Fe] vs. [Fe/H] relation. Fitting simple functions to a homogeneous data set, he found that the quality of fit does not currently favor any unique break point in the range $-1.7 <$ [Fe/H] < -1.0. Using existing ^{9}Be data as a proxy for O results in the same conclusion. However, other evidence suggests that the break occurs near [Fe/H] ~ -1.0 rather than at the values ([Fe/H] ~ -1.7) claimed by others. Implications of this result were considered with particular attention to the possibility of significant delays between the end of halo formation and the beginning of star formation in the disk. A gap in the observed [O/H] distribution, seen by others and found to persist in his sample, may indicate such a hiatus. More work is required to determine whether this gap might be related to a G dwarf problem instead. King argues that present data indicate that [O/Fe] is constant in the halo for [Fe/H] > -3.0. For [Fe/H] > -1.0, ordinary least-squares regressions indicate that the slope in the [O/Fe] vs. [Fe/H] relation is -0.35 to -0.40, significantly less than the usually assumed value of -0.5. However, other regressions, which may be more appropriate for determining the relation between [O/Fe] and [Fe/H], yield steeper slopes (-0.7). Until a consensus can be reached on which regression is applicable for what purposes, the constraints provided by an "observed" [O/H]-age relation (which does not use true O abundances, but adopts O abundances based on Fe abundances) for several issues of Galactic chemical evolution should be regarded with caution.

Deliyannis (now at Yale), with S. Ryan (AAT), T. Beers (Michigan State), and J. Thorburn (Chicago), reported lithium detections in two cool halo dwarfs, Gmb 1830 and HD 134439. Li abundances in halo stars, when interpreted correctly, hold the key to uncovering the primordial Li abundance, Li(p). However, whereas standard stellar evolutionary models imply consistency in standard big bang nucleosynthesis (BBN), models with rotationally induced mixing imply a higher Li(p), possibly implying an inconsistency in standard BBN. The present observations provide the coolest and lowest Li detections in halo dwarfs to date, and are consistent with the metallicity dependence of Li depletion in published models. If the recent report of a beryllium deficiency in Gmb 1830 represents a real Be depletion, then the rotational models would be favored. Tests to reduce critical uncertainties were proposed.

Deliyannis and Ryan studied Li abundances in short-period binaries to test internal stellar mixing. Some late-type short-period binaries are Li rich compared with similar single stars. This had been predicted as a signature of Li preservation if rotational mixing (related to angular momentum loss and redistribution) was a cause of Li destruction in warm and cool dwarfs. Understanding stellar Li depletion is important not only for constraining stellar evolution models but also for determining Li(p). Seven short-period halo and disk binaries were examined to discern the conditions under which Li-rich binaries may be found. A halo dwarf and a halo subgiant with periods of 12.4 and 7.6 days have Li abundances on the Spite halo Li plateau; these orbits probably synchronized too late to prevent mixing-induced Li depletion. A 5.6

day period halo subgiant, however, does have a higher Li abundance than otherwise similar stars. They found an intermediate metallicity 1.8 day subgiant with a measurable Li abundance at a T_{eff} where most stars yield only low upper limits. The remaining three disk stars, with 3.3 to 6.6 day periods, yielded only Li upper limits, and suitable single stars against which to compare them were lacking. High Li abundances were also found for an intermediate metallicity dwarf, and also for some previously studied binaries in the Hyades, which is old enough for its single stars to be depleted, as well as in the much older M67, but not in the younger Pleiades, as predicted. High Li short-period binaries have thus been observed in a variety of contexts, consistent with the Yale rotational models combined with tidal theory: young cool disk and old intermediate metallicity dwarfs, young and old Li peak dwarfs, and old cool intermediate halo subgiants. Some synchronized binaries with periods less than about 6 days may be better able to preserve their Li abundances, in line with Yale rotational model predictions. Suitable short-period binaries in the region of the halo Li plateau still await identification and observation.

Deliyannis, King, Boesgaard, and Ryan found Li in a short-period, tidally locked binary (SPTLB) in the open cluster M67. In open clusters, late F stars show a maximum of Li abundance. This maximum occurs at lower abundance as cluster age increases, a trend that could be due to either stellar depletion or galactic enrichment. Any SPTLBs that synchronized in the early pre–main sequence would avoid the rotational mixing that may be responsible for Li depletion with age in cluster dwarfs; they would thus be expected to show the original cluster Li abundance and about a factor of 3 or more above the mean Li peak region abundance in M67. The initial Li/H abundance for M67 would then be as high as 3×10^{-9}. This high M67 SPTLB Li abundance, and those in the Hyades, supports a combination of Zahn's tidal circularization and the Yale rotational mixing theories. This may indicate that the halo Li plateau (analogous to the Li peak region) abundance has been depleted from a higher primordial value.

Deliyannis, with R. Malaney (Canadian Institute for Theoretical Astrophysics [CITA]), studied the possibility that flares might produce the ^{6}Li isotope in halo dwarfs near turnoff. Motivated by the recent report of a ^{6}Li detection in the atmosphere of HD 84937, they coupled stellar evolution calculations with light isotope production via stellar flares. They found that as a consequence of their small convective envelope mass near the turnoff, low-metallicity dwarfs and subgiants may possess observable amounts of ^{6}Li arising from such flare activity. There is an observational test that could discriminate between flare-produced ^{6}Li and protostellar ^{6}Li: In the T_{eff} range 6000 to 6600 K, the ^{7}Li/^{6}Li ratio on the subgiant branch should increase as a function of T_{eff} if flare production is important, whereas the same ratio should be constant if a protostellar origin is the source of the observed lithium. The absence of a flare-produced variation in the ^{7}Li/^{6}Li ratio would allow for a more reliable inference of the cosmologically important atmospheric depletion mechanisms in stars.

9 Solar system studies

9.1 Planets

Tholen, in collaboration with M. W. Buie (Lowell Observatory), continued acquiring imaging data on the Pluto-Charon system with the *HST*. All together, they obtained 60 observations, with emphasis on good rotational coverage, during the 15 months between 1992 May and 1993 August. Work was underway to extract from the data the individual light curves of Pluto and Charon, as well as an improved orbit for Charon around Pluto.

In collaboration with S. A. Stern (Southwest Research Institute), Tholen used the JCMT to measure any rotational variation in the thermal emission from Pluto. The noise level of the data prevents any definitive statements about variations in the thermal radiation.

9.2 Asteroids and trans-Neptunian objects

Graduate student J. Chen started a thesis project aimed at the detection of objects in 1:1 resonances with the outer gas giant planets. Such "Trojan asteroids" are expected in association with each of the four gas giant planets but have been observed only in connection with Jupiter.

Jewitt and J. Luu (Harvard) continued their investigation of the outer solar system using deep-imaging techniques on Mauna Kea. Trans-Neptunian object 1992 QB1 was discovered in late 1992. Three additional trans-Neptunians (1993 FW, RO and RP) were found in 1993. Two of these objects (RO and RP) are sufficiently close to the orbit of Neptune that their orbital stability on billion year timescales is in question. These bodies might be stabilized against Neptune perturbations by Pluto-like mean-motion resonances, and additional astrometric observations were underway to test this possibility.

In collaboration with A. Barucci (Observatoire de Paris-Meudon), M. Lazarin, C. Barbieri (Padova, Italy), and M. Fulchignoni (Istituto Astronomico, Rome), Owen continued his studies of small, primitive bodies in the outer solar system. This particular investigation involved observations with the UH 2.2 m telescope of the near-infrared spectra (J, H, and K bands) of nine dark asteroids. The spectra proved to be featureless. There was no evidence of the 2.2 μm absorption reported by other workers and ascribed to X-CN and no hint of the prominent absorptions found in this wavelength region in the spectrum of 5145 Pholus.

This apparently negative result is still consistent with the possibility that these bodies are dark because their surfaces are covered by a carbon-rich coating of some mixture of organic compounds, e.g., the terrestrial substance known as kerogen, as well as coal and charcoal; all show featureless reflection spectra in this wavelength region.

At the COSPAR meeting in July 1993, Owen reported on this work, as well as on K-band region observations of the dark side of Iapetus and comet Schwassmann-Wachmann I made with T. Geballe (JAC), D. P. Cruikshank (NASA Ames), and C. de Bergh (Observatoire de Paris) at the UKIRT. Like the dark asteroids, Iapetus and the comet also show featureless spectra. Further work on all these objects, including the all-important extension to the 3 μm region, is planned for the coming year.

Tholen continued a project to survey the physical properties of planet-crossing asteroids. The newly discovered trans-Neptunians objects are being included in the survey in addition to the near-Earth objects. Particular emphasis was given to (1620) Geographos, in anticipation of the encounter by the Clementine spacecraft in late 1994. Light curves were obtained in both 1993 December and 1994 February, along with a series of astrometric observations intended to help navigate the spacecraft to its target.

Observations of the newly discovered Centaur object 1993 HA2 revealed extraordinarily red colors shared by only one other object in the solar system, namely (5145) Pholus, another Centaur object, which suggests that the material producing the unusual color may be rather common in the outer solar system.

Tholen, in collaboration with B. Zellner (Computer Sciences Corporation), used the *HST* to look for binary asteroids. Special emphasis was given to the asteroid (243) Ida after the Galileo spacecraft returned images showing the existence of a small satellite around Ida. No other binaries have turned up so far.

9.3 Comets

Jewitt and graduate student M. Senay used the JCMT to study (2−1) rotational line emission from carbon monoxide in comets. The 1.3 mm line was detected in distant comet P/Schwassmann-Wachmann 1, with an inferred CO production rate of order 2 tonnes s^{-1}. This prodigious rate of gas release is sufficient to drive the observed activity in this comet. This new observation provides the first direct evidence that activity in distant comets is powered by the sublimation of CO.

In collaboration with Meech, graduate student T. Farnham continued his thesis work to model the development and dynamics of cometary dust tails. This work is an analysis of the dust tail structure and morphology, which is being used to infer properties of the dust (specifically roughness and scattering properties) and the mechanisms of dust production on active comets. The modeling is based on Finson-Probstein–type techniques of the kinematic and fluid-dynamic coupling of the dust and gas as it escapes from the nucleus. During the report period, they made major strides in computer programming for the inversion of the light curves to obtain the velocity and particle size distributions of the dust and the onset of activity.

Meech continued to search for observable differences between the physical or chemical nature of the periodic (old) comets and those of the Oort comets (comets passing through the inner solar system for the first time) by studying their brightness as a function of heliocentric distance, R. The scientific objectives of this study are to search for physical differences in the behavior of the dynamically new (Oort) comets and the periodic comets, and to interpret these differences, if any, in terms of the physical and chemical natures and the evolutionary histories of the two groups of comets. Observations of approximately 50 comets over a range of R neared completion. The data will be compared to models of the level of activity (brightness and extent of coma) as a function of distance to interpret the observations in terms of possible evolutionary or aging processes, or as differences in primordial source regions. The proposed final observations for this program will use the Keck I telescope on Mauna Kea and the *HST*.

Observations of cometary comae of the dynamically new comets at large heliocentric distances clearly indicate that there is a strong difference between the brightness curves of the Oort comets and those of the periodic comets. The dynamically new comets and the short-period comets are believed to have formed in different regions, with the short-period comets forming at lower temperatures, and the differences in activity levels seen between the comet classes are almost certainly due to evolutionary or aging effects. An important result of the work is that the brightness limits for the Oort cloud comets suggest that the nuclei are relatively small and not the giant nuclei that some have suggested. Meech was continuing work on placing these distant comet observations into the context of the formation of the early solar system material.

Meech analyzed *HST* observations of the unusual object Chiron made during February and March 1993 and discovered a gravitationally bound dust coma close to the nucleus. Combined with estimates of the coma dust particle sizes, which constrain the mass of Chiron, it has been possible to combine these measurements with recent occultation radii and thermal infrared measurements of the radius of Chiron to infer a density, thus giving one of the first relatively direct measurements of comet nucleus densities.

Meech, with graduate students G. Knopp and Farnham, and D. Green (Center for Astrophysics), completed a major study of the dynamically new comet Wilson, which split into two fragments. An orbital analysis of the fragments suggests the splitting took place 2–3 AU from the Sun, coincident with a brightness outburst observed in the database. A brightness limit when the comet was at 12.65 AU constrains the primary nucleus to have a maximum radius of between 5 and 7 km. Finson-Probstein dust modeling showed that the cometary activity began at distances larger than 6 AU, which implies that a material more volatile than water was responsible. The dominant grain sizes in the coma were in the range from 1 μm to a few 100 μm.

To analyze data from Mauna Kea and *HST*, Meech developed a new technique for placing limits on the amount of possible outgassing from objects in comet-like orbits. It will be used to search for cometary emissions on 5145 Pholus, an outer solar-system object in a Chiron-like orbit.

Graduate student M. Nassir worked with Meech on the analysis of the rotational light curve data of comet P/Kopff, which has been found to have a substantial light curve with a period near 12 hr. Further observations were planned for this object to refine the period and to model the development of activity in the comet.

10 Solar physics

The solar research program includes *Yohkoh* data analysis, Mees Solar Observatory data analysis, and theory. Results other than those discussed in this section and section 11 (Theoretical Studies) are described in the articles and books listed in section 12 of this report.

Metcalf continued a study of linear polarization in the Hα line during solar flares observed with the Mees Imaging Vector Magnetograph. This linear polarization is a possible signature of 100 keV proton beams. Preliminary results show that the linear polarization is present during the impulsive phase of flares. Relationships between the linear Hα polarization and hard and soft X-rays observed with *Yohkoh* are being explored. Metcalf developed a new technique for resolving the 180° ambiguity in solar vector magnetograms. Metcalf also worked on a new technique for synthesizing hard X-ray images from the *Yohkoh* Hard X-ray Telescope data.

11 Theoretical studies

11.1 Structures theory

Barnes and graduate student C. Ishida studied the collapse of spherically symmetric perturbations in an expanding universe. Self-consistent simulations showed that spherical collapses—including some published self-similar solutions—are subject to a dynamical instability similar to the one seen by Henon in generalized polytropes. This instability causes radial pulsations that considerably modify the phase-space structure of spherical collapse solutions. Ishida is using the Zeldovich approximation to generate consistent initial conditions and is following their evolution with an N-body code optimized for nearly spherical systems to delimit the domain of this instability.

Building on the above, Barnes is simulating collapses of binary systems and groups by imposing multiple perturbations. These experiments are intended to pave the way for a project to study the dynamical evolution of groups by using X-ray gas as a tracer of the gravitational potential. Toward this end, Barnes received a grant from NASA to implement a combined N-body/SPH code optimized for simulation of hot gas in groups. X-ray images of the simulated groups will be directly compared with Henry's *ROSAT* observations of groups in the NEP region (see section 6).

Barnes ran experiments to study relaxation in N-body systems. These showed that potential fluctuations in N-body simulations of stable systems such as King models are of order $N^{-1/2}$ as expected from Monte-Carlo statistics, but that much larger fluctuations can occur in systems which are nearly unstable. Among such nearly unstable systems are disk galaxy models, which can strongly swing-amplify sampling fluctuations.

Using spherical symmetry and the Jeans equations as basic assumptions, Barnes began a project to build near-equilibrium N-body models of composite galaxies. With fairly simple techniques it proved possible to construct galaxy models with realistic density profiles spanning a range of $\sim 10^{-2}\ R_e$ to more than 10 R_e in radius. The basic procedure has been extended to approximate systems including flattened, self-gravitating disks; a more general treatment of oblate systems is also possible.

Barnes collaborated with T. de Zeeuw (Leiden) and L. Hernquist (California, Santa Cruz) on fitting separable potentials to N-body systems, with a particular application to remnants of major mergers. Numerical tests showed that relatively simple fitting procedures can obtain good matches to triaxial potentials with finite cores, but density profiles diverging as $r \to 0$ give less satisfactory results. Nonetheless, this fitting method should improve existing analysis of merger simulations by providing estimates of integrals and actions at wholesale prices.

Barnes and Hernquist continued studying the formation of bound objects in tidal tails. Although the idea that dwarf galaxies might form in this manner was first advanced by Zwicky, it may not be widely realized that the basic concept resembles Jeans's tidal theory for the formation of the solar system. Following Jeans's footsteps, they think it is possible to constrain the parameters of tidal dwarf galaxies by considering the Jeans length in the outer regions of spiral galaxies.

Hierarchical N-body codes that separately traverse the tree for each particle perform many unnecessary computations; Barnes noticed that a single sweep through the entire tree could achieve the equivalent task for all particles at once. A new algorithm based on this idea takes ~60% of the CPU time required by the standard algorithm for an equivalent calculation and yields better error performance as well. Large gains are expected on vector and parallel machines since the new algorithm can easily exploit either.

Barnes gave four lectures on "Interactions and Mergers in Galaxy Formation" at the Canary Islands Winter School, The Formation of Galaxies. He used the occasion to attempt a synthesis of the most recent numerical and observational results. The written lectures are available by anonymous ftp and will be published by Cambridge University Press. He presented an invited review, "Dynamics of Interacting Galaxies," to the Activity in the Central Parts of Galaxies discussion at the IAU meeting in The Hague, and he gave an invited talk, "Formation of Dwarf Galaxies during Galaxy Interactions," at N-Body Simulations of Stellar Clusters and Planetary Systems.

Kofman investigated properties of the cosmological density and velocity probability distribution functions (PDFs). The galaxy probability distribution function manifests significant non-Gaussian features. Cosmic density PDF emerging from complicated gravitational dynamics is derived in different analytical approximations, as well as from N-body simulations. It is found that density PDF deviates from a normal distribution early, and it develops a shape remarkably similar to a lognormal distribution. In contrast, the velocity PDF is fairly time invariant. When these results are applied to observational data, the velocity and density PDF is consistent with Gaussian initial fluctuations.

Kofman and Bernardeau (CITA) demonstrated a mutual agreement in the PDFs derived by different methods. They suggested the methods to build cosmic PDFs out of a limited number of moments (the Edgeworth expansion). They also explained that the lognormal PDF is not a universal form of the cosmic density PDF due to the nonlinear dynamics, but is rather a convenient fit for the particular region in the parameter space of cosmological models. Fortunately, this particular region includes the CDM-type models at moderate variances of density fluctuations.

In general relativity (GR) the equations of cosmological gravitational instability contain the electric part of the Weyl tensor represented by the local terms, and the nonlocal magnetic part. If the magnetic part (which has no Newtonian limit) is ignored, then the Newtonian limit of the basic relativistic equations without the magnetic part consists of the closed set of the local Lagrangian equations. Recently, this fact has drawn much attention, since the gravitational instability in that form would greatly simplify the study of cosmic structure formation.

Kofman and Pogosyan (CITA) resolved the contradiction between the Newtonian theory and GR versions adopted in some recent papers. They showed that dropping the magnetic part from the basic relativistic equations is *incorrect*. The correct Newtonian limit is derived by the $1/c$-expansion of the GR equations and the Bianchi identities for the Weyl tensor. The last ones begin with $\sim 1/\mathrm{c}^3$ order; therefore in this case one *must* take into account the magnetic part in the first nonvanishing post-Newtonian order $\sim 1/c^3$, which contains nonlocal terms. Finally, the basic GR equations with the magnetic part are reduced *precisely* to the canonic Newtonian *nonlocal* equations.

Kofman, Linde (Stanford), and Starobinsky (Moscow) developed the theory of reheating of the universe after inflation. They found that typically at the first stage of reheating the classical inflation field ϕ rapidly decays into ϕ-particles or into other bosons due to broad parametric resonance. Then these bosons decay into other particles, which eventually become thermalized. Complete reheating is possible only in those theories where a single massive ϕ-particle can decay into other particles. This imposes strong constraints on the structure of inflationary models. On the other hand, this means that a scalar field can be a cold dark matter candidate even if it is strongly coupled to other fields.

11.2 Solar theory

Lu continued his studies of the statistical mechanical properties of nonequilibrium-driven dissipative systems. He has originated the use of cellular automaton models in studying the energy release process in magnetically dominated plasmas. This work has provided an explanation for the observed scale invariant distribution of solar flares, which spans more than 6 orders of magnitude in flare energy release. Together with R. Hamilton (Chicago), he showed how the distribution of solar flares can arise from a few simple properties of local magnetic instabilities. This theoretical framework allows for the first time the calculation of the large-scale long-term behavior of such systems. This work also provides an explanation for the distributions of stellar flares and flares in binary systems.

As part of this work, Lu showed how certain continuum systems can be approximated by cellular automaton models. This provides an explanation not only for why solar flares can be modeled in such a manner, but also for why such natural phenomena as earthquakes and river flows can be modeled using this method. This work is potentially far reaching and may prove applicable to a wide variety of physical systems.

Lu also showed that a class of energy storage and release models for astrophysical transients proposed by R. Rosner (Chicago) can be ruled out for the case of solar flares.

Graduate student Y. Fan (now at NOAO/National Solar Observatory) and McClymont, with G. Fisher (California, Berkeley), studied the buoyant rise of magnetic flux tubes from the base of the convection zone to the photosphere. They introduced a correction to the equation of motion used in previous studies and found that as a loop of flux erupts to form a new active region, the magnetic field in the leading leg is twice as strong as in the following leg. The loop is also tilted, with the leading leg closer to the equator, which is in agreement with observations. Both these asymmetries are produced by the Coriolis force. The difference in field strength offers a natural explanation for the difference between the well-organized leading polarity of an active region and the fragmented, disorganized following polarity.

McClymont, in collaboration with D. Gómez (Instituto de Astronomia y Fisica del Espacio, Argentina), studied heating of the corona by dissipation of the currents generated through intertwining of magnetic field lines by turbulence in the photosphere. They completed a study of energy transfer in a simplified system consisting of three modes, a process that can be regarded as the building block for a more complex energy cascade capable of enhancing the dissipation rate. A numerical code to study the full energy cascade has been developed.

McClymont, in collaboration with I. Craig (Waikato, New Zealand), applied both analysis and numerical simulation to the problem of magnetic reconnection. The present goal is to understand the effect of gas pressure on the reconnection rate.

McClymont collaborated with Z. Mikic (Science Applications International Corporation, San Diego) to develop methods for computing force-free coronal magnetic fields from active region magnetogram data. They concluded a study of active-region AR 5747 (20 October 1989) and computed a coronal field for active region AR 7260, a large well-observed and flare-productive region.

12 1993 publications list

The following articles and books were published during calendar year 1993:

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