University of Hawaii Institute for Astronomy

Honolulu, Hawaii 96822

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 1994 through 30 September 1995. More information about the IfA is available at the Institute's World Wide Web site: http://www.ifa.hawaii.edu/.

1. STAFF

The scientific staff during this report period consisted of Timothy Abbott, Joshua Barnes, Richard L. Baron, Ann M. Boesgaard, Yong-Ik Byun (Hubble Fellow), Richard C. Canfield, John Carpenter (James Clerk Maxwell Telescope Fellow), John Carr, Gianna Cauzzi (solar postdoctoral fellow), Kenneth Chambers, Antoinette Songaila Cowie, Lennox L. Cowie, Christophe Dumas, Fred Forbes, Isabella M. Gioia, J. Elon Graves, Thomas P. Greene, Donald N. B. Hall (Director), Olivier Hainaut (postdoctoral fellow), James N. Heasley, J. Patrick Henry, George H. Herbig, John Hibbard (Hubble Fellow), Klaus-Werner Hodapp, William Hoffmann (visitor), Joseph Hora, Esther M. Hu, Hugh Hudson, David C. Jewitt, Robert D. Joseph, Lev Kofman, John Kormendy, Barry J. LaBonte, Sandra Leggett, 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, Konji Ohta (visitor), 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, Bradford Smith, Alan N. Stockton, Tjet Sun, David J. Tholen, Alan T. Tokunaga, R. Brent Tully, William Vacca (Parrent Fellow), 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 the UH 0.6 m telescope; 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 Subaru (formerly Japan National Large) Telescope and on the 10 m Keck II telescope.

This report covers in detail only the UH 2.2 m telescope.

2.1 2.2 Meter Telescope

The main achievement during the report period was bringing the fast-guiding tip-tilt secondary mirror into routine operation. The software was enhanced so that it is simple to use, and so that its usage involves little additional overhead. A bright star or relatively small object is used as a reference or ‘‘guide’’ star, and its image motion is used in a feedback loop to control rapid movement (‘‘tipping’’ and ‘‘tilting’’) of the secondary mirror to stabilize the image. Diffraction-limited images through the K′ filter (0.25″ FWHM) of many hours length have now been obtained for targets that had a guide star close to on-axis. Strehl ratios of up to 0.47 were measured in K′ images obtained during tests in September 1995. These tests showed that the Strehl ratio was approximately doubled by turning on the tip-tilt guiding. Images that appear to be diffraction limited in the *H*-band (FWHM = 0.20″) were obtained in mid-September 1995. Tip-tilt guiding has been successfully used with KSPEC and with the CCD camera (guiding off-axis).

The tip-tilt guiding uses a new offset guider, which employs 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 and was installed on the telescope for general use in November 1994.

During the report period, imaging with CCDs remained the most common use of the telescope, accounting for 44% of the observing time and the bulk of the dark-Moon observing time. This comprised mainly wide-field imaging using the Tektronix 2048×2048 CCD at the f/10 focus. One observing run with the 8192×8192 mosaic CCD camera at the f/10 focus took place in July 1995. Imaging with the new 1024×1024 infrared camera (QUIRC; see § 4.2) was performed for 38% of the observing time, with roughly one third of this time being devoted to high-resolution infrared imaging at the f/31 focus. The large format of this infrared camera has made it an extremely powerful tool for infrared imaging. QUIRC was in high demand and was heavily used during each bright-Moon period. An upgrade to the near-infrared spectrometer KSPEC (see § 4.3) limited its availability, so it was used for only 6% of the observing time. Low-resolution optical spectroscopy was performed for 6% of the observing time. The coudé spectrograph was little used (only 1% of the observing time); the OH suppression spectrograph was used for 3% of the time. The remaining 2% of the observing time was allocated to visitor instruments.

Equipment to provide a bidirectional video/audio link between Hale Pohaku and the telescope was brought into routine operation during the report period. The link is expected to allow remote participation in observations from Hale Pohaku.

Further progress was made in moving documentation for the telescope to the World Wide Web. The URL is http://www.ifa.hawaii.edu/88inch/88inch.html. A telescope newsletter is available at this URL.

Scheduling periods for the telescope are currently four month trimesters: December–March (deadline October 1); April–July (deadline February 1); and August–November (deadline June 1).

2.2 Groundbreakings

The Gemini Project is a six-nation collaboration to build two 8 m optical/infrared telescopes, one on Mauna Kea and the other on Cerro Pachon in Chile. The partners are the United States, the United Kingdom, Canada, Chile, Argentina, and Brazil. Groundbreaking for Gemini Mauna Kea took place on 6 October 1994. By September 1995, the necessary road and utility relocations had been completed (see § 2.4), and the foundations were in place for the support building, the enclosure, and the pier. First light is scheduled for December 1998.

The groundbreaking for the Smithsonian Submillimeter Array (SMA) was held on 8 June 1995. The SMA, which is expected to begin operations in 1997, will initially comprise six 6 m antennas that can be arranged in several configurations on 22 fixed observing pads, with the longest baselines reaching $\sim$500 m. The antennas are moved between the pads by a specially designed transporter with very large tires. Construction of the access roads, the pads, and the cable ducts was well underway by September 1995.

2.3 Site Characteristics

The NRAO has continued to collect atmospheric transparency and radio "seeing" data using monitoring equipment located near the VLBA antenna at an elevation of 3720 m. This is part of NRAO's program to evaluate potential sites for the proposed Millimeter Array (MMA). Results are published in the MMA Memo series and are available on the Internet through the MMA site on the World Wide Web.

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 powerful Doppler weather radars throughout the United States. The program is called the Next Generation Weather Radar (NEXRAD). Four NEXRADs are planned for Hawaii, and two of them have the potential to create serious radio frequency interference (RFI) at the observatories on Mauna Kea and Haleakala unless some mitigating steps are taken. The two in question are the Molokai NEXRAD, which has been in operation since February 1994, and the Kohala NEXRAD (north of Waimea on the Big Island), which is scheduled to start up in October 1996. In accordance with an agreement negotiated by IfA with the NEXRAD Program Office, and in particular with the National Weather Service, spot blanking was implemented on the Molokai NEXRAD in December 1994. Previously, restrictions on scan elevation had provided temporary mitigation. Spot blanking involves turning off the radar transmitter during the portion of the scan when the antenna's main lobe is pointed at the mountain summits. With the blanking enabled, power density levels at the observatories are below 1 mW m^{-2}; without it, the levels are 100–1000 mW m^{-2}. The Kohala NEXRAD will have spot blanking from the outset. As part of the agreement, the National Weather Service may suspend the RFI mitigation during periods of severe or threatening weather (e.g., an approaching hurricane).

2.4 Infrastructure

The IfA has entered into a 10 year Network Service Agreement with GTE Hawaiian Tel to provide high-bandwidth fiber optics communications for MKO. Based on SONET OC-12 (622 Mbit s^{-1}) technology, the system will provide 11.5 DS-3 (45 Mbit s^{-1}) circuits between summit observatories and base facilities in Hilo and Waimea. Hawaiian Tel will use the remaining 0.5 DS-3 in the OC-12 trunk for voice lines. Fiber optic cable will be installed on existing utility poles across the Saddle and up to Hale Pohaku, where it will connect to the existing underground fiber optic trunk to the summit. The IfA is using MKO infrastructure funds to pay the capital cost, resulting in a very favorable monthly rate for the service, which is expected to be available in 1996.

The Gemini Project completed a number of infrastructure changes and improvements along the summit ridge between the UH 2.2 m telescope and the CFHT. First, the access road was relocated to the east, a move that required the installation of a retaining wall 100 m in length. Then, new electrical and communication ducts were installed along the roadway, and new cables were set in place. Finally, the electrical and telephone service, and the fiber optics local area network were switched over to the new and much upgraded infrastructure. Thanks to a combination of good planning and good luck, all of this was accomplished with relatively little disruption of service.

In summer 1994, a layer of chip seal (asphalt embedded with crushed stone) was applied to a 1.4 km test section of the access road. Experience over the 1994–95 winter showed that the chip seal substantially improves traction in light icing conditions, with no significant adverse side effects. In September 1995, chip seal was applied to the previously untreated sections of the access road from the lower parking lot, near the beginning of the pavement (3600 m elevation), all the way up to the UH 2.2 m telescope. Chip seal was also applied to the spur road over to the NASA IRTF and WMKO.

Also in September, the Mid-Level Facility at Hale Pohaku received a new telephone system and new carpeting in the Common Building.

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

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. 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 continues 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

After a successful demonstration in December 1993 at the coudé focus of the CFHT, the experimental adaptive optics system developed at the IfA was dismantled, and a Cassegrain-focus instrument based on the same technique was constructed. The instrument is designed to work at the CFHT f/36 focus and operates with two cameras simultaneously: a 1024 $\times$ 1024 pixel CCD camera and the new infrared camera (QUIRC) built at the IfA (see § 4.2). Compared with the experimental system, the new instrument has better throughput and a larger field of view (36″). It operates with guide stars as faint as mag 16, up to 20″ away from the center of the field. The instrument was operated for the first time during 19–22 December 1994. It performed as expected, delivering stellar images with a typical Strehl ratio of 0.3 in the *H* band. Since this successful observing run, the instrument has been further improved by the addition of various filter wheels, and calibration devices. The control software now provides calibrated seeing data. The instrument was used again during four nights in June and four nights in August 1995. In December 1994, most of the efforts were directed to observations of T Tauri stars, especially HL Tau, GG Tau, and T Tau (see § 7). The August 1995 observing run was dedicated to the observation of Saturn's ring while Earth was crossing the ring plane (see § 8). Data taken in December 1993 have now been fully analyzed, and the results have been published.

4.2 Quick Infrared Camera (QUIRC)

During the report period, the new Quick Infrared Camera (QUIRC) was commissioned at the UH 2.2 m telescope by Hodapp, Hora, Metzger, Electronics Engineer E. Irwin, and Mechanical Designer T. Keller. QUIRC uses a 1024 × 1024 HAWAII (HgCdTe Astronomical Wide Area Infrared Imager) detector array developed by the Rockwell International Science Center under contract from the UH. The commissioning coincided with the impact of comet P/Shoemaker-Levy 9 on Jupiter, and excellent tip-tilt corrected images of that event were obtained. QUIRC uses 1:1 reimaging optics that give platescales of 0.185″ $pixel^{-1}$ at f/10 and 0.06″ $pixel^{-1}$ at f/31.

4.3 Infrared Spectrograph (KSPEC)

KSPEC (*K*-band spectrograph) is a cross-dispersed medium-resolution infrared spectrograph. It was first used at the telescope in October 1992 and was commissioned as a common-user instrument in April 1993. During the report period, Hodapp, Hora, Irwin, and Keller began preparations for upgrading that instrument with a HAWAII array. A spectrograph camera with larger focal length, combined with the smaller pixels of the HAWAII arrays relative to NICMOS3 arrays, will solve the sampling problems of the original version of KSPEC. The addition of a second (ZnSe) prism to the cross-disperser will increase the usable slit length to more than 15″, thus allowing better sky subtraction. The engineering-grade NICMOS3 array previously used for slit-viewing has been replaced by a science-grade device.

4.4 Gemini Near-Infrared Imager (NIRI)

Hodapp is principal investigator and Hora is project scientist for the design of the Near-Infrared Imager (NIRI) for the Gemini Mauna Kea telescope. A preliminary design study done during the report period culminated in a conceptual design review in March 1995. NIRI will use an Aladdin 1024 × 1024 InSb detector array as its science detector and will provide three user-selectable platescales. Besides direct imaging, it will also be capable of coronagraphic work, grism spectroscopy, and polarimetry.

4.5 Camera and Spectrograph for Subaru

Tokunaga (principal investigator) and co-investigators Hodapp, Rayner, Hora; N. Kobayashi and Y. Kobayashi (National Astronomical Observatory of Japan); T. Maihara (Kyoto); and T. Nagata (Nagoya) started the design and construction of a facility instrument for the 8.2 m Subaru telescope at Mauna Kea. The Infrared Camera and Spectrograph (IRCS) will be a high-resolution spectrograph for 1–5 μm ($R=20{,}000$), having a slit-viewer with full imaging capabilities. The camera section will have grisms for low to moderate spectral resolution (up to $R=2000$). The instrument will use 1024 × 1024 InSb arrays, one each for the camera and spectrograph sections. The plans call for the final design to be completed by December 1995, construction to begin in January 1996, and completion in June 1998.

4.6 8K CCD Mosaic Camera

During the report period, the IfA developed the world's largest astronomical CCD camera—a mosaic focal plane with 8192 × 8192 pixels. The mosaic is a close-packed (gaps ≤1 mm), 4 × 2 array of three-edge-buttable 2048 × 4096 Loral CCDs with 15 μm pixels. The camera was designed primarily for use at the prime focus of the CFHT, where it offers an unprecedented combination of wide field of view ($0.47° \times 0.47°$ or 0.22 deg^2) with optimal sampling (0.21″ $pixel^{-1}$) of the best Mauna Kea seeing (0.5″). However, with the use of a field flattener, the camera can also be used at the f/10 RC focus of the UH 2.2 m telescope, where the image scale is 0.14″ $pixel^{-1}$ and the field of view is $0.31° \times 0.31°$ (0.1 deg^2). This camera saw first light in March–April 1995 on the CFHT, and it has since been used on both the 2.2 m telescope and the CFHT. The performance during these runs was excellent. On the CFHT, 0.5″ images were achieved over the entire mosaic field. For 1995–96, the camera will be used extensively by UH astronomers for wide-field projects in weak gravitational lensing, the study of the faint galaxy luminosity function in clusters, and the search for solar system comets, asteroids, and Kuiper Belt objects.

5. GALACTIC AND EXTRAGALACTIC STUDIES

Chambers is continuing 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, and he has continued the search for identifications and redshifts of faint ultra-steep spectrum sources. Chambers and graduate student G. Knopp are carrying out multicolor photometry of deep fields around four of these objects.

Chambers is also analyzing data obtained from imaging polarimetry observations of high-redshift radio galaxies with the refurbished *HST*. To complement these data with ground-based data, Chambers built the Hawaii Imaging Polarimeter for Proto Objects (HIPPO) for use with UH infrared and optical detectors. Knopp has been measuring the polarization of bright high-redshift radio galaxies.

Gioia and Henry used both the UH 2.2 m and the CFHT to continue the study of the NEP (North Ecliptic Pole) region of the All-Sky Survey of the *ROSAT X-ray Astronomy Satellite*. The goal of this program is to make identifications in the deepest region of the All-Sky Survey to study the evolution of the X-ray luminosity function of clusters, evolution first detected in the Einstein Observatory Medium Sensitivity Survey (EMSS) sample. The fraction of sources observed and identified as of this writing is over one third, with the following optical identifications: 50 clusters of galaxies, 75 active galactic nuclei, 4 BL Lac objects, and 100 stars. During the summer 1995 observing season, a region of sky containing 56 X-ray sources was identified completely. When added to the 55 sources identified the previous year, these sources increase to ∼100 the total number of objects in a complete sample usable for statistical studies. The mix of sources in the two complete regions leads to an estimate that ∼100 clusters total will be found in the NEP, about 40–50 of which will be at a redshift of $z>0.3$. Twelve such high-z clusters have already been found, 6 with $z>0.5$. Among the serendipitous discoveries of this year is the most distant cluster of galaxies yet found in the NEP at $z=0.82$.

Gioia and Luppino, in collaboration with J. Annis (Chicago) and F. Hammer and O. Le Fèvre (Observatoire de Paris-Meudon), completed the observational program to search for arcs and arclets in a sample of 40 X-ray-luminous ($L_x>2\times10^{44}$ erg s^{-1}) and distant ($0.15<z<0.83$) clusters of galaxies drawn from the EMSS. The program used both the UH 2.2 m telescope and the CFHT. The main results are (1) high X-ray luminosity does indeed identify the most massive clusters, and thus X-ray selection is an advantageous method for finding rich clusters at intermediate and high redshifts; (2) there is evidence for compact mass density profiles in clusters; (3) the geometry of the arcs suggests the presence of mass substructure in the central 0.5 Mpc cluster cores. The abundance of massive, high-z clusters present in the lensing survey sample prompted Luppino and Gioia to discuss the cosmological implications of the very existence of these clusters in the framework of hierarchical structure formation theories. Such clusters are not expected to have existed in significant numbers according to the standard cold dark matter model.

Gioia, Luppino, and collaborators obtained *HST* images of two of the clusters with giant arcs. Spectroscopic measurements of the arcs' redshifts and of the velocity dispersions of the cluster galaxies are being obtained to facilitate the lens modeling. For these two clusters, and other X-ray-selected clusters, *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*) and *ROSAT* High Resolution Imager (HRI) observations are in progress. They will provide the necessary information (temperature and structure of the hot gas) to determine the cluster mass, which will be compared with the mass obtained from the lensing.

Luppino, Metzger, Miyazaki, Gioia, and N. Kaiser of the Canadian Institute for Theoretical Physics (CITA) have used the newly constructed UH 8192 × 8192 CCD mosaic (see § 4.6) at the prime focus of the CFHT to image a number of X-ray clusters selected to cover a range in redshift. The goal of this ongoing program is to measure the weak gravitational distortion of faint background field galaxies behind rich clusters at large radii. These observations will supply a direct measurement of the two-dimensional projected mass density, with no assumptions about the dynamical state of the cluster, to a precision better than 20% for the most massive clusters. The technique can be applied at all radii, and it promises to be a very powerful direct tool to measure the mass distribution on supercluster scales.

Graduate student D. Clowe, Henry, and Gioia are investigating how to use the brightest cluster galaxies (BCGs) as standard candles to create a Hubble diagram to measure the deceleration of the universe. The results have shown that BCGs do serve as reasonable standard candles and provide a measure of q_0 that is consistent with that determined from radio galaxies.

Graduate student K. Jim continued to make K-band observations of the most X-ray luminous clusters of the EMSS sample to search for possible distant "red arcs" and to investigate the nature of the arc sources. He has also used the tip-tilt technique to obtain the highest possible resolution of the lensed objects from a ground-based telescope.

Joseph, Sanders, graduate student J. Goldader, and R. Doyon (Montreal) continued their study of a complete sample of galaxies with infrared luminosities $>2\times10^{11}L_\odot$. The sample includes the 13 "ultraluminous" galaxies with infrared luminosities $>10^{12}L_\odot$. They have obtained 2 μm infrared spectra for $\sim$60 galaxies. Emission lines due to H II, He I, H_2, and a number of stellar absorption features are detected in most galaxies. The spectra fail to reveal any broad-line Seyfert 1 nuclei that were not previously recognized by optical spectroscopy, even though the extinction is 1/10 of that at optical wavelengths. Simple starburst models with cutoffs to the initial mass function at $\sim$1 $M_\odot$ and $\sim$30 $M_\odot$ can account for far-infrared and Brγ luminosities, and the CO indices.

Joseph began a new program to study an optically selected, magnitude-limited sample of $\sim$150 spiral galaxies chosen from the revised Shapley-Ames catalog. Near-infrared images are being obtained at the IRTF, while mid- and far-infrared images and photometry for this sample will be obtained using the *Infrared Space Observatory*.

Kormendy and D. Richstone (Michigan) wrote "Inward Bound: The Search for Supermassive Black Holes in Galaxy Nuclei" for the *Annual Review of Astronomy and Astrophysics*. This paper summarizes the state of the black hole search and contains preliminary CFHT spectroscopy of the black hole candidates M31, M32, NGC 3115, and NGC 4594 using the Subarcsecond Imaging Spectrograph (SIS). In each case, the detection of a central dark object of mass $\sim10^7$ to $10^9M_\odot$ becomes more secure as the spatial resolution is improved.

Kormendy continued work on *HST* photometry of the cores of early-type galaxies, as part of a team including E. Ajhar (National Optical Astronomy Observatories [NOAO]), Y. Byun, A. Dressler (Carnegie Observatories), S. M. Faber (PI; California, Santa Cruz), C. Grillmair (Santa Cruz), K. Gebhardt (Michigan), T. R. Lauer (NOAO), D. Richstone (Michigan), and S. Tremaine (CITA). V-band photometry of 45 early-type galaxies using the *HST* Planetary Camera was reported in a paper by Lauer and collaborators. Kormendy reviewed the results at an Aspen Workshop, "Physics of Dense Stellar Systems" and at International Astronomical Union (IAU) Symposium 171, "New Light on Galaxy Evolution."

Graduate student A. S. Evans and Sanders, in collaboration with J. M. Mazzarella (Infrared Processing and Analysis Center [IPAC]), P. M. Solomon (State University of New York at Stony Brook), D. Downes and C. Kramer (Institut de Radio Astronomie Millimétrique [IRAM]), and S. J. E. Radford (NRAO), completed a two year search for CO emission in a sample of high-redshift powerful radio galaxies (HzPRGs) The upper limits obtained for the best-studied sources imply that high-redshift radio galaxies as a class do not have more star-forming molecular gas than the most gas-rich galaxies observed locally.

Evans and Sanders, in collaboration with Radford, R. Cutri (IPAC), Solomon, Downes, and Kramer, obtained upper limits on the molecular gas masses of IRAS 09104+4109 ($z=0.4$), IRAS 15307+3252 ($z=0.9$), and the optically selected, infrared luminous quasi-stellar object (QSO) PG 1634+706 ($z=1.3$). Near-infrared spectroscopy of the two *IRAS* (*Infrared Astronomical Satellite*) galaxies, covering the restframe wavelength range 0.4–1.1 μm, shows that the *IRAS* galaxies have Seyfert II-like optical/near-infrared emission-line spectra. The CO and near-infrared observations of the *IRAS* galaxies indicate that their extreme infrared luminosities are primarily reprocessed active galactic nuclei (AGN) light.

Evans and Sanders are conducting a near-infrared spectroscopic survey of $z\sim2$ powerful radio galaxies. The restframe optical emission lines from these galaxies are redshifted to the J, H, and K bands, making emission-line diagnostics and extinction determinations of these galaxies possible.

Evans and Sanders, in collaboration with Mazzarella, are continuing CO(1→0) and CO(2→1) observations of $0.02<z<0.2$ powerful radio galaxies (PRGs). Three of the six PRGs previously detected in the (1→0) line at the NRAO 12 m telescope were detected in the (2→1) line with the JCMT on Mauna Kea. Tentative detections of CO emission from two Fanaroff-Riley class II radio galaxies with the NRAO 12 m and JCMT still need to be confirmed. As the first CO detections of FR II PRGs, these results would represent an important confirmation of the hypothesis that PRGs are rich in molecular gas, and that there may be an evolutionary connection between PRGs and other classes of molecular gas-rich objects such as luminous infrared galaxies and infrared selected QSOs.

Sanders and graduate student D.-C. Kim, in collaboration with S. Veilleux (Maryland), Mazzarella, and B. T. Soifer (Caltech), completed a long-slit optical ($\lambda\lambda=3750$–8000 Å) spectroscopic survey of a complete sample of luminous infrared galaxies (LIGs) using the UH 2.2 m telescope. These data were combined with previous optical spectroscopic data obtained at the Palomar 5 m telescope to generate a complete sample of ''warm'' *IRAS* galaxies in order to investigate the properties of the line-emitting gas and underlying stellar population in and out of the nucleus. These observations show that the fraction of LIGs with AGN spectra and the fraction of Seyferts among the AGN increase with infrared luminosity, reaching values of 62% and 54%, respectively, for ultraluminous infrared galaxies (ULIGs: $L_{\rm ir}>10^{12}L_\odot$, $H_0=75$ km s^{-1} Mpc^{-1}). The fraction of LINERs (low-ionization nuclear emission-line regions) remains relatively constant at $\sim27\%$.

D.-C. Kim carried out a study of a complete sample of 115 ULIGs for his Ph.D. dissertation. The maximum redshift and luminosity were $z=0.27$ and $L_{\rm ir}=10^{12.84}L_\odot$, respectively. The space density of ULIGs appears to be $\sim$5–7 times larger than that of optically selected QSOs at comparable bolometric luminosities. A maximum likelihood test suggests strong evolution for the sample. Assuming density evolution proportional to $(1+z)^\alpha$, $\alpha=7.5\pm3.1$. Optical and near-infrared imaging of the complete sample shows that all of these objects appear to be strongly interacting/merging systems. Optical spectroscopy shows that nearly half of these objects are of type Seyfert 1 or 2, with an additional $\sim30\%$ of LINER type.

Sanders, with graduate student E. Egami, S. Lipari (Space Telescope Science Institute), I. F. Mirabel (Centre d'Etudes de Saclay), and Soifer, published Part II of the *IRAS* Bright Galaxy Survey, which extends the original survey to southern declinations ($\delta<-30°$) and low Galactic latitudes ($5°<|b|<30°$). The survey extension contains 288 sources with 60 μm flux densities S(60) $>$ 5.24 Jy.

Graduate student S. Ridgway and Stockton completed the initial analysis of a large body of *HST* and ground-based imaging of a complete sample of 3CR sources with $z\sim1$. The sample includes five galaxies and five quasars. After careful point-spread function subtraction, the deep Wide Field Planetary Camera 2 (WFPC2) images show luminous extensions around all of the quasars, and four of the five show some detailed correlation between the radio and optical structure, including the first clear examples of the alignment effect in quasars. 3C212, in particular, shows one of the most striking examples among high-z objects of the alignment effect. The quasar 3C2 shows detailed agreement between the optical and radio structure in its north radio lobe, and the optical/infrared spectral-energy distribution forms a smooth extension of that in the radio, with a somewhat steeper spectral index. Because the radio galaxies do not show the same degree of coincidence between radio and optical structure, beaming of the optical radiation appears to be more common in the quasars, in agreement with the qualitative prediction of unified models. Finally, there appears to be an enhancement of linear or ''chain'' galaxies in the immediate vicinities of the radio galaxies and quasars in this sample. If these galaxies are in the process of formation, powerful radio sources at this epoch may be associated with preferentially young environments. Much of this project comprises part of Ridgway's Ph.D. thesis.

Stockton and graduate students Ridgway and M. Kellogg used CGS4 on UKIRT to obtain very deep near-infrared spectroscopy of the nucleus of the powerful radio galaxy Cygnus A. No evidence for broad wings on the Pa-α line has been found, indicating extremely high extinction to the center if a quasar nucleus is present. There is, however, some evidence that the coronal lines [Si VI] λ1.962 μm and [S XI] λ1.920 μm are broader than the lower ionization lines, which could be evidence for a transition region between the classical narrow-line region and a hidden broad-line region.

Tully, E. J. Shaya (Maryland), and P. J. E. Peebles (Princeton) reconstructed the orbits of $\sim$1200 galaxies and groups within $z=0.01$ with the Least Action variational principle methodology. The modeling is constrained by 900 galaxies with measured distances. If it is assumed that matter is strictly confined to halos about visible galaxies, then they measure $\Omega_0=0.14\pm0.05$, where the very low error estimate is a 1σ uncertainty *if mass follows light*. The Least Action methodology has been applied to a $\Omega_0=1$ cold dark matter N-body simulation supplied by Kofman and J. R. Bond and D. Pogosyan (CITA) (see § 10.1). To recover the known value of Ω in the simulation, it is necessary to relax the assumption that mass is distributed like the galaxies and a suitable trick is to soften the force law on scales

<400 km s^{-1}. When the same trick is played on the real data, the χ^2 fit is improved by 1σ and $\Omega_0=0.25\pm0.1$ is determined. The uncertainty is dominated by the model-dependence associated with mass biasing. $\Omega_0=1$ can probably be excluded unless there is a very hot mass component that is poorly correlated with observed galaxies.

Graduate student C. Dudley and Wynn-Williams are continuing their 8–13 μm spectroscopic studies of luminous infrared galaxies using CGS3 on UKIRT. They are finding that most galaxies in the luminosity range 10^{11} to $10^{12}L_\odot$ have spectra dominated by polycyclic aromatic hydrocarbon (PAH) emission features, indicating a starburst origin for the galaxy's power. A minority, including the ultraluminous galaxy IRAS 0857+3915, show strong silicate absorption that is interpreted as indicating the presence of an obscured active nucleus.

Dudley and Wynn-Williams have measured the 8–13 μm spectrum at several places in the central region of the nearby starburst galaxy NGC 253. They have found variations in the relative strength of the PAH and continuum emission that echo those found earlier at 3.3 μm. There is no need to invoke absorption by silicate grains to explain the spectrum at any location in NGC 253.

Graduate student J. Jensen, Sanders, and Wynn-Williams are continuing their K-band studies of galaxies selected from the *IRAS* Bright Galaxy Survey. They are preparing an atlas of K-band images of these galaxies that they will publish in collaboration with Mazzarella, who has complementary R-band data. They find that galaxies with high 60–100 μm color temperatures have high ratios of far-infrared to K-band luminosity. This result confirms earlier suggestions that the dust in starburst galaxies is hotter than dust in quiescent galaxies.

6. INTERSTELLAR MATTER

A. Sakata, S. Wada, and T. Narisawa (Univ. of Electro-communications), and Tokunaga continued their work on understanding the nature of quenched carbonaceous composite (QCC), a laboratory analog to the carbonaceous material in the interstellar medium. Ultraviolet spectra of the QCC show that this material has a 220 nm absorption that is close in wavelength to that seen in the interstellar medium. This work supports the idea that QCC, a carbonaceous composite made from a hydrocarbon plasma, is a plausible candidate to explain the UV absorption and the infrared emission features seen at 3.3, 6.2, 7.7, 8.6, and 11.3 μm.

Herbig obtained a series of spectrograms of reddened OB stars with the HIRES spectrograph at Keck I, at a resolution of about 45,000. This material covers the region from about 3050 to 4100 Å , and is intended to settle the question of whether interstellar C_{60} and free coronene exist at detectable levels in diffuse clouds. It may also be useful in a search for diffuse interstellar bands in this relatively unexplored spectral region.

Herbig wrote an extensive review of the diffuse band problem, as it appeared in mid-1994, that has been published in the *Annual Review of Astronomy and Astrophysics*.

Herbig completed an extensive investigation of IC 349, a small, fan-shaped nebula in the Pleiades that was discovered by Barnard in 1890. Although it is an order of magnitude brighter than any other part of the conventional Pleiades nebulosity, IC 349 has received little attention because it is only about 30″ from 23 Tauri, of $V=4.2$. The color and spectrum show that IC 349 is a pure reflection nebula. Since the general Pleiades nebulosity is the result of the chance encounter of the star cluster with the outer fringe of the Tau-Aur molecular clouds, it is proposed that the semi-stellar object at the apex of IC 349 is part of that cloud, and that it is being dissipated in the radiation field of 23 Tauri as the two approach one another. The shape of the fan is compatible with a model in which small dust particles from the nucleus are being swept back by the combined effects of radiation pressure and drag exerted by intercluster gas. It is not known whether the nucleus is a dust-shrouded pre–main-sequence star or a dust concentration of dust and gas several hundred AU in diameter.

Carpenter, with R. Snell and P. Schloerb (Massachusetts Amherst), completed their study of the molecular gas and stellar content of the Gemini OB1 molecular cloud complex. They found that most of the molecular gas in this complex is contained in cold, diffuse, low column density molecular material ($T_{\rm kin}<10$ K, N(H_2) $<3\times10^{21}$ cm^{-2}). The embedded star formation sites are confined to the high column density regions (N(H_2) $>10^{22}$ cm^{-2}) within the cloud. One of the more striking structural features in the Gem OB1 cloud complex is the rings and arcs of molecular gas found on spatial scales ranging from 1 pc to more than 35 pc in diameter. These structures appear to be shells of molecular gas created from stellar winds and expanding H II regions. The massive dense cores in the Gem OB1 complex, as traced by CS emission, are preferentially found along these arclike structures. Furthermore, most of these massive cores contain a significant population of embedded stars, as traced by radio continuum emission, *IRAS* point sources, and near-infrared images. These results suggest much of the current star formation activity in the Gem OB1 complex has been "triggered" by past star formation events, and that star formation occurs rapidly after the formation of massive dense cores.

Carpenter began a molecular line survey of massive dense cores to determine how basic core parameters (masses, sizes, densities, temperatures) are related to the embedded stellar content. The intent is to survey a sample of objects spanning 4 orders of magnitude in far-infrared luminosity.

Carpenter obtained strip maps of the L1498 and Gem OB1 molecular clouds in the $J=2\rightarrow1$ and $J=3\rightarrow2$ transitions of ^{12}CO and ^{13}CO. The goal of the project is to determine if the clumpy cloud model can account for the relative intensity and shapes of the various rotational transitions. A three-dimensional Monte Carlo radiative transfer code is being developed for the data analysis.

Hora, with collaborators N. Ladd (Massachusetts), Wynn-Williams, W. Hoffmann (Arizona), L. Deutsch (Five College Astronomy Department [FCAD]), G. Fazio (Center for Astrophysics [CfA]), IfA graduate student J. Deane, and Sanders, used the MIRAC2 mid-infrared camera at the IRTF to map the W3 and S235 molecular clouds. In W3, a $3'\times1.5'$ area was mapped at a 1 σ sensitivity of 20 and 54 mJy arcsec^{-2} at 11.7 and 20.6 μm, respectively. Several new faint sources were detected at 20.6 μm. A ratio image appears to show a temperature gradient in IRS1 between the inner (warmer) and outer (cooler) regions, and in IRS4 between a warm unresolved core and cooler extended emission. These images will be used along with existing images at 2.2, 450, and 800 μm and radio maps at 6 cm to determine the relative importance of O stars and protostars to the luminosity of the H II region/molecular cloud complex, and to put constraints on the properties of the infrared-emitting dust. No extended emission was detected in the 1′ area around S 235.

Hora and W. Latter (NASA/Ames), using QUIRC (see § 4.2), extended their near-infrared imaging study of planetary nebulae to obtain deep narrowband images of several nebulae. In Hubble 12, the extended emission was observed to be dominated by H_2. The bipolar structure was seen to extend to about 35″ N–S at 2.12 μm, and a ring or cylindrical shell of emission was resolved around the core. The H_2 spectrum in the equatorial region was confirmed to match models of fluorescent excitation, but an area in the ring was observed to have strong [Fe II] emission at 1.257 and 1.643 μm, indicating the presence of shocks or a dense clump of material in the ring. Additional spectra of the faint bipolar lobes were obtained using KSPEC (see § 4.3) to determine the excitation mechanism of the H_2 in the outer regions of the nebula.

The project to measure column densities of dust in star-forming regions by measuring the reddening of background stars was continued by Hodapp and Carpenter. They used QUIRC at the UH 2.2 m telescope and IRCAM3 at UKIRT to obtain deep imaging of B 335 in *H* and *K*.

Bipolar outflows of very young stars (class 0 and class I) were imaged in the S(1) line of molecular hydrogen by Hodapp and Ladd. The objects were NGC 1333, L1634, and IRAS 08076−3556. In all these cases, evidence for multiple outflows was found. This shows that even on the short time scales involved in those very early phases of star formation, stars tend to form in small groups.

Sanders, Carpenter, and Deane are carrying out a "matched-beam" (20″) survey of the galactic mid-plane in the (1→0), (2→1), and (3→2) lines of CO and ^{13}CO using the IRAM 30 m telescope in Pico Veleta, Spain, the JCMT, and the CSO, respectively. The survey includes ~1000 positions at 12′ spacing in longitude, from $\ell = -10°$ to $\ell = +120°$, all at $b = 0°$. The survey is designed to eliminate the effects of beamsize on the measured line ratios in response to previous suggestions that beamsize may be responsible for the different findings by various groups concerning the presence or absence of a galactocentric gradient in both the CO isotope ratios and the line ratios for CO and ^{13}CO. In addition to determining the radial distribution of emissivity in all six lines, these new data will be used to compile a list of several thousand clouds in the inner galaxy, and to study their internal properties (e.g., excitation temperature, density, volume filling factor).

Ladd, Wynn-Williams, graduate student J. Surace, and Sanders have re-reduced the *IRAS* data for about 80 Galactic H II regions using the HIRES algorithm. The new maps, which have significantly better spatial resolution than the originals, are being compared with radio maps of the same regions published by Fich and colleagues. The primary goal is to search for radio-quiet infrared sources that indicate the presence of embedded O stars.

Deane, with Sanders and Ladd, examined the spatially resolved infrared luminosity to molecular gas mass ratios in the NGC 7538 and W3 Giant Molecular Clouds (GMCs). Large-scale (~2.5 square degrees) ^{12}CO(1→0) and ^{13}CO(1→0) maps were used to determine molecular gas ($M(H_2)$) distributions, and 8–1000 μm infrared luminosities (L_{ir}) were determined from *IRAS Infrared Sky Survey Atlas* (*ISSA*) images, including careful background subtraction to isolate the GMC emission from the strong galactic plane background. The NGC 7538 GMC has a lower cloud-integrated $L_{ir}/M(H_2)$ ratio ($\sim 3 L_\odot / M_\odot$) than does W3 (8 $L_\odot / M_\odot$), due to the former's lower infrared luminosity and greater total mass. Interestingly, the internal $L_{ir}/M(H_2)$ variations within each cloud are comparable to the dispersions in GMC mean values from previous surveys of the Galactic disk. Most of the molecular material has low $L_{ir}/M(H_2)$ ratios suggestive of moderate mean dust temperatures (12–25 K). NGC 7538 shows evidence of limb brightening due to external heating, and elevated temperatures toward the highest column-density regions of both GMCs reveal the effects of heating by their known embedded stellar clusters. In both W3 and NGC 7538, a small fraction of the total mass is responsible for most of the total luminosity. The $L_{ir}/M(H_2)$ ratios throughout most of each cloud resemble those of GMCs without active, massive star formation.

Deane and Ladd used isotopic CO observations at the CSO to continue their survey of dense cores in the W3 and NGC 7538 GMCs. Core properties such as size, linewidth, and excitation conditions are being determined for comparison with the local star-forming conditions indicated by $L_{ir}/M(H_2)$ ratios.

7. STELLAR ASTRONOMY

Greene, with C. Lada (Smithsonian Astrophysical Observatory) and M. Meyer (Massachusetts Amherst), has been conducting a number of near-infrared spectroscopic observations of very young stars in dark clouds. Greene and Meyer completed their survey of the ρ Ophiuchi young stellar population with the KSPEC near-infrared spectrograph (see § 4.3). This study produced accurate spectral types and stellar luminosities for approximately 20 cluster members. Comparisons of their positions in the H-R diagram to pre–main-sequence (PMS) evolutionary tracks reveal that the cluster is approximately 3×10^5 yr old and is forming stars with a mass function similar to that of the solar neighborhood. Greene and Lada are continuing their work on characterizing the young stellar object (YSO) populations in dark clouds based solely on their near-infrared spectra. Greene and Lada also completed a near-infrared spectroscopic study of the YSO IRAS 04239+2436 in the Taurus dark cloud. They discovered that this YSO has near-infrared CO emission and a very strong H I emission spectrum. At 1.3 $L_\odot$, it is the lowest luminosity YSO, by nearly an order of magnitude, yet detected to have infrared CO emission. This emission must be excited by collisional processes in the dense circumstellar environment of this young star. Greene and Lada have also started a high spectroscopic resolution rotation study of

YSOs in the ρ Oph cloud. They are using the IRTF CSHELL spectrograph to investigate whether the spectral lines observed in low surface gravity YSOs may be forming in either circumstellar disks or embryonic photospheres.

With graduate student M. Nassir, B. Wilking (Missouri St. Louis), and the MIRAC mid-infrared camera team, Greene started a survey of dense cores in the ρ Ophiuchi dark cloud for very low luminosity ($L < 1 L_{\odot}$) Class I protostars using the IRTF telescope. This survey will be useful for comparing the accretion characteristics and mass function of protostars in the ρ Oph cloud to those of the Tau-Aur clouds.

Herbig's color-magnitude investigation of the young cluster IC 348, comprising *BVRI* photometry of about 250 stars, is now complete. Multislit spectroscopy of a substantial fraction of the photometric members of the cluster was obtained with the MOS arrangement at CFHT, and he plans to carry out *JHK* photometry as well during the 1995–96 season. A portion of this material is discussed in a 1995 article in *Astronomy and Astrophysics* by T. Preibisch, H. Zinnecker, and Herbig about an investigation of the X-ray sources in IC 348 detected by *ROSAT*.

In December 1994, the C. Roddier, F. Roddier, Northcott, Graves, and graduate student K. Jim used the adaptive optics system on the CFHT (see § 4.1) to observe T Tauri stars, especially HL Tau, GG Tau, and T Tau. The *C*-shaped dust cloud, discovered by the *HST*, that hides HL Tau in the visible is clearly seen on the *J*-band images together with the star itself. The star becomes more prominent at longer wavelengths. All four components of the quadruple star GG Tau could be imaged together in the $36'' \times 36''$ field. Comparison with data taken in 1993 and other published data shows that the northern close binary rotates clockwise. The fast observed motion indicates that it must be near periastron. Photometry shows that it consists of a K7-M0 star with an M4 companion. Masses inferred from dynamical motion are larger than the spectral type suggests. The companion appears to be younger than the main star. Both stars seem to be surrounded with a warm unresolved disk. Images reveal a circumbinary ring also recently detected at millimetric wavelengths. The ring seems to be produced by light scattered by the edge of a cavity inside a much larger disk. At the cavity edge, the disk thickness is estimated to be one tenth of the cavity radius. Light that illuminates this cavity edge appears to be reddened by absorption through the inner disks. Azimuthal variations of the illumination indicate that the inner disks must be lumpy. A paper on GG Tau was submitted for publication in *The Astrophysical Journal*. An arc of dust, similar to that observed in the visible by the *HST*, is also seen in the infrared near T Tau. The bright southwest condensation seen on the *HST* image appears in the *J* band as a bright spot close to the south companion, detected for the first time at this wavelength. The bright spot disappears at longer wavelengths.

Simon, S. A. Drake (NASA/Goddard and University Space Research Association), and summer undergraduate student researcher P. D. Kim (MIT) completed a survey of X-ray emission from bright field main-sequence A stars. In a sample of 74 A stars having deep pointings with the *ROSAT* Position Sensitive Proportional Counter, they found 19 stars that are positionally associated with soft X-ray sources. The inferred X-ray luminosity values cover nearly 4 orders of magnitude. In most cases the observed emission is suspected to come from unknown or unresolved binary companions of the A stars.

Simon and graduate student B. Patten are continuing their study of the evolution of rotation rates and coronal activity levels for solar-type stars in young open clusters. Much of this work is an integral part of Patten's dissertation. Their efforts have been focused on the 30 Myr old southern clusters IC 2391 and IC 2602, where solar-type stars have just arrived (or are just arriving) on the zero-age main-sequence (ZAMS). A *ROSAT* survey of IC 2391 in 1992 revealed a number X-ray sources associated with previously uncataloged stars. Patten has concluded a program of photometric and spectroscopic observations of these stars using the Cerro-Tololo International Observatory 0.9 m and 1.0 m telescopes. These observations have been used to identify many new candidates for cluster membership among the *ROSAT* X-ray sources. Patten also used those telescopes to measure photometric rotation periods for two dozen solar-type stars in IC 2391 and IC 2602, the latter cluster in collaboration with J. Stauffer and C. Prosser (CfA).

Among the solar-type stars in both clusters, a factor of ~ 25 spread is observed in the distribution of rotation periods, and a factor of ≈ 10–20 spread in the distribution of X-ray luminosities. These results show conclusively that solar-type stars arrive on the ZAMS with a wide range of rotation rates and coronal activity levels. When compared with data from older clusters like the Pleiades and the Hyades, Patten and Simon's data show that although there is an overall decline in the median rotation rate and X-ray luminosity with age, the spread in the distribution of X-ray luminosities actually grows larger. This is because the young, rapidly rotating stars lie along a plateau of magnetic saturation, where L_X has a weak dependence on rotation period, while for the older, more slowly rotating stars the weaker L_X has a strong dependence on rotation period. The abrupt turnover in the Rossby diagram near log $N_R = -0.5$ suggests there may be a fundamental change in the nature of the dynamo for rapidly rotating stars.

8. SOLAR SYSTEM STUDIES

In August 1995, members of the IfA Adaptive Optics group (C. Roddier, F. Roddier, Northcott, Graves, Electronics Engineer D. O'Connor, and graduate student K. Jim; see § 4.1), collaborators from the Observatoire de Paris (A. Brahic, C. Ferrari, L. Perret, P. Thebault, and C. Dumas, who is now at IfA), Owen, and graduate student B. Han observed Saturn's ring while Earth was crossing the ring plane. Unique images of the ring disappearance that reveal the presence of faint satellites were obtained. The objective of this project is to improve knowledge of the motion of the known satellites and perhaps discover new ones. These images should also provide new and more accurate information on the rings structure and thickness. A precise timing of the event should help improve data on the precession of the ring plane and Saturn's internal structure. High angular resolution *H* and *K* images of Titan ($0.7''$ diameter) were obtained both in

December 1994 and in August 1995. They all show well-resolved features. In all cases, the southern hemisphere appears brighter than the northern one. These infrared images contrast with the featureless images obtained in the visible by *Voyager*. Clearly, the foggy atmosphere becomes more transparent at longer wavelengths. However, it is still unclear whether the features seen are atmospheric or ground structures. *K*-band images of Uranus and Neptune were also obtained during the August run. In these images, the most prominent features are the ring of Uranus and the atmospheric bands of Neptune.

Joseph and collaborators S. Miller, H. Lam, and J. Tennyson (University College London) are continuing to investigate the physics of the Jovian aurorae using infrared spectroscopy of the H_3^+ molecular ion. They found evidence that the collision of comet P/Shoemaker-Levy 9 with Jupiter produced an enhancement of the northern aurora and a depression in the southern aurora. One explanation would be that particulates from the impact sites drifted southward into the auroral regions in the ionosphere, thereby lowering the conductivity and the current flow, and thus cooling the H_3^+.

Meech continued to search for observable differences in the physical or chemical nature of the periodic (old) comets compared to 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 has been continuing for several years and is nearing 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 final observations for this program are proposed to use the Keck I telescope and the *HST*. Highlights of the work are as follows:

• Observations of cometary comae at large heliocentric distances are now routine for the dynamically new comets, and this clearly indicates that there is a strong difference between the brightness curves of the Oort comets and those of the periodic comets. While 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, 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. Work is continuing on placing these distant comet observations into the context of the formation of the early solar system material.

• Observations of the possible extinct comet nucleus 3200 Phaethon were made during January 1995, when it was at its minimum geocentric distance, to place stringent limits on any possible activity. The rotational period has been measured, and a pole solution will be attempted by combining this data with other observations.

• Graduate student M. Nassir has been working with Meech on the analysis of the rotational lightcurve data of comet P/Kopff, which has been found to have a substantial lightcurve, with a period near 12 hr. An additional seven nights of data have been obtained on this comet, and analysis is underway.

• An observing campaign to follow 2060 Chiron as it approaches its 1996 perihelion is underway using the UH 2.2 m telescope and the Kitt Peak National Observatory (KPNO) 0.9 m telescope. The goal is to get nearly nightly observations of Chiron to look both at its long- and short-term brightness variations and coma extent. The color of the coma dust is being monitored in an attempt to correlate this with the level of activity. This will be important information for modeling the size distribution of the optically dominant scatterers in the coma.

• Work on 2060 Chiron continues. In conjunction with the ground-based observing campaign, Meech, M. Buie (Lowell Observatory), and M. Belton (KPNO) have been awarded Cycle 5 *HST* time to confirm their reported discovery during Cycle 2 observations of the exopause boundary at 1200 km. There is a straightforward relationship between the extent of this bound atmosphere (the exopause), the size of the dust grains in the coma, and the size of Chiron's nucleus and its mass, and the *HST* observations imply a very low nucleus density for Chiron. Because we have recent occultation measurements that give a good estimate of Chiron's size, for the first time we can get an estimate of a comet nucleus density, which has fundamental implications for the condensation processes in the early solar nebula. Even after the P/Halley spacecraft encounters, the nucleus density was not well constrained. In addition, development of a sophisticated bound atmosphere model is planned.

Graduate student T. Farnham has continued his thesis work in collaboration with Meech to model the development and dynamics of cometary dust tails. This work is an analysis of the dust tail structure and morphology that is being used to infer properties of the dust and the mechanisms of dust production on active comets. The models are expanding upon an elegant method of comet dust-tail modeling, originally developed by M. Finson and R. Probstein, that calculates the surface brightness of a cometary dust tail by evaluating the influences of gravity and solar radiation pressure on dust grains and adding up the scattered light to compare the brightness with observations. Farnham's modifications, in addition to orbital mechanics improvements, and the use of multiple images spaced in time, include the use of realistic scattering functions of the dust. The goal is to be able to make inferences about comet dust grain structure, something previously possible only with in situ spacecraft observations.

Meech and Hainaut began a program of distant comet recovery using the new UH 8K CCD mosaic camera (see ß 4.6). They plan to recover periodic comets much earlier than is typical (usually after they are active, near 23 AU) to better understand the onset of activity in comets. This should address a major observational selection effect in the study of comet activity as a function of distance from the Sun. This will be done primarily in the ecliptic, and the images will go deep, so it is likely that many new Kuiper Belt members will also be found. They have now had two successful observing runs, one during July 1995 on the UH 2.2 m telescope and one during September 1995 on the CFHT. They are employing neural networking algorithms to search the data for faint moving objects.

During 1994–95, Owen, in collaboration with A. Bar-Nun (Tel Aviv), continued his studies of the role of icy planetesimals in bringing volatiles to the planets. These studies, based on laboratory experiments by Bar-Nun and his colleagues, attempt to duplicate the formation of comets in the presence of the gases in the original solar nebula. These experiments have demonstrated that the incorporation of gases in amorphous ice formed at temperatures in the range 15–100 K is a strongly temperature-dependent process. Thus the fractionation of noble gases that occurs in ice forming at about 50 K provides a good match to the abundances of noble gases found in the atmospheres of Mars and the Earth, whereas the noble gases on Venus while silica match an ice-formation temperature of $\leqslant$30 K. Laboratory work carried out in the last year showed that the fractionation of N_2 and CO in ice at 50 K provides a good explanation of the deficiency of nitrogen found in comet P/Halley, and leads to a rather good match to the values of N/C found in the atmospheres of Mars, Venus, and Earth.

These results, published in *Icarus* and *Volatiles of the Earth and Solar System* (edited by K. Farley), have been incorporated in a model for predicting volatile abundances in planetary atmospheres. The model includes a number of testable consequences, starting with the existence of argon but not neon in the ices of comets formed in the Uranus-Neptune region of the solar nebula. It may be possible to carry out this test with orbital ultraviolet observations of comet Hale-Bopp during the next two years. Neon should have been brought to the inner planets by a different process; perhaps it was trapped in the rocks that make up the bulk of these planets. This difference would explain the observation that the isotopes of neon in the Earth's atmosphere are highly fractionated, while those of nitrogen are not. The model also suggests that neon will not be enriched on Jupiter to the extent that carbon is, again because it was not trapped in the ices that originally contributed to the planet. This prediction, and the associated deficiency of nitrogen that is also expected on the giant planet, will be tested by the *Galileo* probe when it enters Jupiter's atmosphere in December.

In a related study, Owen has been investigating the moons of Saturn in collaboration with T. Geballe (JAC), D. Cruikshank (NASA/Ames), A. Coradini (Rome), and C. de Bergh (Observatoire de Paris). The issue here is the remarkable brightness of the inner satellites of Saturn. It appears that this can be explained if these satellites are coated with highly reflective ice, which requires that the ice be unusually pure. The requisite purity can be obtained if the carbon in the Saturn subnebula formed CO and CH_4 that were not incorporated in the ice because the latter condensed at temperatures above 100 K. Siliceous material (dirt) is lacking from this ice as well. Perhaps Enceladus, which is the source of the particulate coating, was itself formed from mantle material of a differentiated icy satellite. This mantle material would be depleted in rock dust, just as our Moon is depleted in iron. These ideas are being tested by means of new spectra of the Saturn satellites in the near-infrared, which have already led to the detection of water ice on Phoebe.

9. SOLAR PHYSICS

Hudson has been working with the *Yohkoh* solar X-ray observations. A new finding concerns "coronal mass ejections," which represent a form of solar mass loss outside the normal Parker-type solar wind. The X-ray data view the entire front-side corona, unlike a coronagraph view, and these data have been used to find clear evidence for the depletion of coronal mass during flares and flarelike coronal events. This provides powerful support for theories of flare energy release that involve large-scale mass motions, and hence (by implication) magnetic reconnection. The *Yohkoh* observations of coronal mass ejections (and of the previously unknown X-ray jets and expanding loops) will greatly enrich knowledge of mechanisms of stellar mass loss. It is fortunate that during this period of *Yohkoh* observations, the first direct out-of-the-ecliptic observations have been made by the *Ulysses* spacecraft.

McClymont continued to work with I. Craig (Waikato) on magnetic reconnection. They found that gas trapped in a collapsing current sheet, whose pressure halts the collapse thus preventing the reconnection from attaining the "fast" rate, can be expelled along the separatrices, enabling a second collapse that reaches a higher rate of reconnection. It has not yet been determined whether the "fast" rate is reached on the second collapse.

Graduate student K. D. Leka (now at National Center for Atmospheric Research), in collaboration with L. van Driel-Gesztelyi (Observatoire de Paris-Meudon), Canfield, and McClymont, finished her thesis on evidence for current-carrying emerging flux in AR 7260. Using Mees and *Yohkoh* data, she showed that (1) the Hα and X-ray structures associated with these bipoles do not agree with potential-field extrapolations of magnetograms; (2) proper motions imply that the flux bundles that make up these new bipoles were twisted before they emerged; (3) these new bipoles were cospatial with significant vertical electric currents; (4) the morphology, proper motion, and measured currents of these bipoles all imply the same sense of twist; (5) this sense of twist was the same as the large-scale twist of the preexisting large spot; (6) the increase of these currents, as new flux emerged, was not consistent with their generation by photospheric motions. She concluded that the new magnetic flux that emerged in this active region carried current generated in subphotospheric layers—the current was not generated by photospheric shear motions.

Graduate student L. Jiao worked with the *Yohkoh* solar soft X-ray observations and Mees solar magnetic field observations. He has been developing computer tools to formalize and automate the procedures in related data and image processing. He has successfully worked with Z. Mikic (Science Applications International Corp.) and McClymont in using the most advanced nonlinear force-free solar magnetic field model and Mees observational data to reconstruct the three-dimensional solar coronal magnetic field. The result is well verified by *Yohkoh* solar soft X-ray observations. Such work will improve both the theoretical model and the knowledge of the role and behavior of solar magnetic field to overall solar activities.

T. Metcalf developed a new technique for synthesizing hard X-ray images from *Yohkoh* Hard X-ray Telescope data. The technique uses pixons to minimize the number of degrees of freedom used in the reconstruction. Comparisons to maximum entropy reconstructions indicate that the new algorithm is superior and gives better photometry and noise suppression. Metcalf also worked with G. Fisher (California, Berkeley) to verify a theoretical relationship between flare loop length and flare X-ray rise and decay times and flare apex temperature. The relationship will be useful for studying stellar flares and solar flare data with little or no spatial resolution.

Pevtsov, Canfield, and Metcalf have been studying the helicity of solar magnetic fields using both the Haleakala Stokes Polarimeter and *Yohkoh* Soft X-ray Telescope (SXT). Generally speaking, the helicity of photospheric magnetic fields is determined by subphotospheric convection, which lets them use it as a new tool to study deep unobservable layers of the solar convection zone. They have found that the magnetic fields of active regions show two spatial scales of helicity, i.e., local (several seconds of arc) and global (whole active region). Local patterns of helicity exist for time intervals of several days and probably reflect an interaction of rising magnetic flux tubes with motions in the convective zone. Global scale helicity is presumably connected with the bottom of the convective zone. The latitudinal variation of the global helicity agrees, roughly speaking, with current dynamo theories. However, the hemispheric correlation of the helicity is very weak. They are finding that, instead of the strong hemispheric rule predicted by classical dynamo theory, long-lived areas of both signs of the helicity exist in both hemispheres.

Research Associate K. Reardon has been active in coordinating ground-based and space-based observations. The space-based observations come from the *Yohkoh* SXT. For example, simultaneous observations of a coronal mass ejection or filament eruption from a quiet region of the solar surface with SXT, spectra in the Hα line from Mees Solar Observatory, and magnetic field observations from the Mees Imaging Vector Magnetograph could provide crucial information about what is occurring in the middle levels of the visible solar atmosphere (e.g., chromosphere) coincidently with the changes observed in the soft X-ray corona. He has also compared observations made in quiet regions of the corona with SXT and in the same region with another chromospheric line, Ca II K to see how far the patterns in the magnetic field from these lower levels of the atmosphere pervade the corona. Finally, he has been working on a new technique to measure temperatures from the observations taken by the SXT by looking at the variance of a series of images in order to determine, for a coronal source, the mean wavelength of the photons passing through a filter's passband.

Canfield, Reardon, and Leka, with K. Shibata and T. Yokoyama (National Astronomical Observatory of Japan) and M. Shimojo (Tokai), studied jets in X-rays (*Yohkoh*) and surges in Hα (Mees). Two new phenomena have been discovered, both of which strongly support a magnetic reconnection interpretation. They developed a model that explains the temporal and spatial relationship of the observed jets and surges, satellite sunspots and their motion, flaring X-ray loops and their converging Hα footpoints, the newly discovered moving-blueshift phenomenon, the spin of the surges, and the temporal development of the Hα redshifts and blueshifts in surges and at their bases.

Metcalf, Canfield, Wülser, and T. Kosugi (National Astronomical Observatory of Japan) have collaborated with J. Li to study the spatial relationship between hard X-ray emission sites in solar flares and the distribution of the density of vertical electrical currents. For this study, Li has been using images from the Hard X-Ray Telescope aboard *Yohkoh* and photospheric electric current maps derived from the Stokes Polarimeter at Mees Solar Observatory. She analyzed hard X-ray sources and vertical currents in six large flares with M/X X-ray class during the period from November 1991 to December 1994. She obtained the surprising result that electron precipitation sites do not coincide with sites of strong vertical current at photospheric levels in these large flares, which rules out some of the most common models of particle acceleration in flares.

10. THEORETICAL STUDIES

10.1 Cosmological Theory

Kofman, A. Klypin (New Mexico State), D. Pogosyan (CITA), and Henry discussed the structure of clusters in a class of flat cosmological models with the fraction of mass $\Omega_{CDM} \simeq 0.8$ in cold dark matter, and the rest in hot dark matter in the form of massive neutrinos. Cold + Hot Dark Matter (CHDM) models with one, two, or three massive neutrinos, with total mass $\simeq 4.6$ eV, were considered. Neutrinos of that mass range are too hot and cannot constitute the halos of galaxies and groups, only those of clusters of galaxies. The limit on the density of neutrinos in the central parts of galaxy clusters was estimated from the phase space density constraints. The ratio of the density of neutrinos to that of cold dark matter through the cluster was found analytically. It appears that the density of the neutrinos is suppressed within the Abell radius. However, neutrinos contribute $\sim 20\%$ of the mass density to the cluster halo. The numerical simulations match these analytical results fairly closely. The simulations indicate that the cluster halo dark matter density profile has the power-law slope $\alpha \simeq 2.5$, which is close to that in the model with the cosmological constant. In the CHDM models the velocity dispersion is almost constant across the cluster. This is quite different from the model with the cosmological constant or from the open model where the velocity dispersion in the cluster outskirts declines. Observational tests that can probe cold, neutrino, and baryonic components unequally distributed in clusters include X-ray emission and weak gravitational lensing. The spherically symmetric fit to the CHDM mass density profile and the X-ray surface brightness for the cluster A2256 was input into a simple model of the hydrostatic equilibrium of the hot gas.

The derived theoretical temperature around the center departs from both the observational data and actual prediction of the cosmological model, which give almost constant temperature. The problem of high baryonic fraction in clusters is not resolved in the CHDM models.

J. R. Bond (CITA), Kofman, and Pogosyan studied the physics behind the formation of a network of filaments in hierarchical clustering models of structure formation. At a given snapshot in time, as the density threshold drops from high values, the regions that first emerge are clusters, then arms stretching from the clusters, which ultimately join to form the predominantly filamentary network: the first pattern to percolate is filamentary, and it is that which the eye picks out. The same sequence follows from nonlinear dynamics, even from the simplified Zel'dovich approximation, with the filaments arising from ''correlation bridges'' between neighboring cluster-scale peak-patches that exist in the initial conditions—provided the clusters are not too far apart ($\lesssim 30h^{-1}$ Mpc for Abell clusters) and their shear tensors are not too misaligned. Walls are identified with the expanding boundaries of rare minima and their connecting ''correlation trenches''; voids are identified with the interiors.

Kofman, A. Linde (Stanford), and A. Starobinsky (Moscow) studied the theory of reheating of the universe after inflation. They found that typically at the first stage of reheating the classical inflaton 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.

L. Kofman, Linde, and Starobinsky extended a new theory of reheating after inflation. According to this theory, parametric resonance, which may occur at the first stage of reheating, very rapidly transfers most of the energy of the oscillating inflaton field ϕ to the energy of bose fields interacting with the field ϕ. The subsequent decay of these fields is described by a more conventional theory of reheating. Quantum fluctuations of bose fields produced at the first stage of reheating are much greater than they would be in a state of thermal equilibrium. This may lead to cosmological phase transitions of a new type that happen soon after the first stage of reheating. These phase transitions are so strong that they may result in an additional short stage of reheating after inflation and in a copious production of topological defects even in the theories where the reheating temperature is very small.

10.2 Extragalactic Theory

Barnes continued development of a new hierarchical N-body code that accomplishes a complete force calculation with a single recursive tree-scan. Compared with earlier ''tree-codes,'' the new code is more robust and accurate thanks to a more conservative approximation strategy. Moreover, a substantial portion of the square-root calculations previously required can be replaced by in-line applications of Newton's method, yielding a further speed-up while maintaining high accuracy. A production version of this code was used for several projects described in this section.

Barnes began a study of encounters and mergers between unequal-mass disk galaxies that focuses on close parabolic passages of galaxies with mass ratios of 1:3. Initial conditions for individual bulge/disk/halo galaxy models were realized using a modified Jeans-equation approach that closely approximates true dynamical equilibria. The galaxies were scaled to obey the Tully-Fisher relation. Eight encounters, with parameters chosen to complement existing studies of equal-mass encounters, were run in parallel on the Maui High-Performance Computing Center IBM SP-2. The results show that disk galaxies are not as fragile as expected; disk-like kinematics persist in roughly half of the merger remnants produced. In particular, retrograde encounters do significantly less damage because disk stars respond only weakly to retrograde perturbations, while the response of the halo material is insensitive to orbital inclination.

Barnes studied the effects of initial galaxy structure on ''look-alike'' models for the interacting system Arp 252. This work used the Jeans-equation approach to build a variety of initial galaxy models with accurately prescribed mass distributions. The pattern speed of the tidally induced bar in the southern member of this system is sensitive to the initial mass profile of the galaxy; only models with rather diffuse bulges reproduce the observed morphology.

Barnes and Hibbard began working on a model for ''The Mice,'' NGC 4676. As a first step, a reasonable ''look-alike'' was obtained using an elliptical orbit. Neutral-hydrogen velocity fields will be used to constrain the models and search for parabolic initial orbits.

Barnes and Hernquist (Lick Observatory) finished a study of gas dynamics in self-consistent simulations of mergers between equal-mass disk galaxies. The large-scale dynamics of bridge- and tail-making, orbit decay, and merging are not much altered by the inclusion of a gaseous component. However, tidal forces during encounters cause otherwise stable disks to develop bars, and the gas in such barred disks, subjected to strong gravitational torques, flows toward the central regions where it may fuel the kpc-scale starbursts seen in some interacting disk systems. Similar torques on the gas during the final stages of a collision yield massive gas concentrations in the cores of merger remnants, which may be plausibly identified with the molecular complexes seen in objects such as NGC 520 and Arp 220. This result appears insensitive to the detailed microphysics of the gas, provided that radiative cooling is permitted. The inflowing gas can dramatically alter the *stellar* morphology of a merger remnant, apparently by deepening the potential well and thereby changing the boundaries between the major orbital families.

Barnes presented invited reviews on galaxy mergers at the March 1995 Royal Astronomical Society Discussion Meeting in London, England, and at IAU Symposium 171 in Heidelberg, Germany. These talks summarized the ''solid results,'' ''good bets,'' and ''hopeful guesses'' that have emerged from numerical simulations. Barnes also composed an extensive set of World Wide Web pages covering a graduate-level lecture course in galactic dynamics.

10.3 Solar Theory

Solar theory is included in § 9.

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