ANNUAL REPORT
University of Hawai'i
Institute for Astronomy

The Institute for Astronomy (IfA) is the astronomical research organization of the University of Hawai'i (UH). Its headquarters is located in Honolulu on the island of Oahu near the University of Hawai'i at Mānoa, 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 Hawai'i.

This report covers the period from 1 July 1992 through 30 September 1993.

I. 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, Kenneth Chambers, Antoinette Songaila Cowie, Lennox L. Cowie, J.-F. de La Beaujardière, Constantine Deliyannis (Parrent Fellow), Edward DeLuca, George H. Fisher, Isabella M. Gioia, Daniel G/'omez, 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 (JCMT Fellow), Edward Lu (Solar Postdoctoral Fellow), Gerard Luppino, Alexander N. McClymont, Robert McLaren, Karen J. Meech, Thomas Metcalf, Donald L. Mickey, Malcolm Northcott, Frank Q. Orrall, Tobias Owen, Andrew J. Pickles, 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, Takehito Satoh (visitor), Alan N. Stockton, Tjet Sun, David J. Tholen, Alan T. Tokunaga, R. Brent Tully, Sylvain Veilleux, Richard J. Wainscoat, Jean-Pierre Wülser, and Gareth Wynn-Williams.

II. 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 Science and Engineering 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; and the 10.4 m Caltech Submillimeter Observatory (CSO), operated by the California Institute of Technology for the National Science Foundation. The Very Long Baseline Array (VLBA) antenna, officially dedicated in August 1993, was fully operational by the end of the report period.

During the report period, the 10 m Keck I telescope at the W. M. Keck Observatory (WMKO) was completed, and engineering of the first complement of instruments was underway. The construction of the 10 m Keck II telescope began in July 1992. The WMKO 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 of the 8.2 m Japan National Large Telescope (known as "Subaru") also began in July 1992.

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

a. 2.2 Meter Telescope

During the report period, wide-field imaging at $f/10$ remained the most common use of the 2.2 m telescope, with the 2048×2048 CCD in use for imaging 36% of the time and the 256×256 near-infrared camera in use for imaging 23% of the time. Low- and medium-resolution optical spectroscopy accounted for 19% of the telescope time, coudé spectroscopy was performed 8% of the time, and near-infrared spectroscopy was performed 6% of the time. High-resolution imaging using the $f/31$ secondary accounted for only 4% of the telescope time; this low usage level was due to the major engineering work being performed on the $f/31$ secondary.

Work to improve image quality continued. This work is primarily related to the new $f/31$ secondary mirror, which is designed to match the primary mirror. Together they give 80% of the light within $0.2''$. The secondary mirror will be driven at a rate of up to 300 Hz using a piezo-electrically driven tip-tilt platform. The entire $f/31$ top-end ring was shipped to Mānoa in November 1992 for a period of four months. Engineering tests were performed to analyze the ring and spider characteristics with the tip-tilt platform attached. The results were very positive—resonances in the ring and spider are controllable with the use of damping material. A new support structure that uses a hexapod mount was designed. This structure allows the mirror to be remotely tilted in x and y directions, translated in x and y directions, and focused. The new hub will be connected to the ring by new spiders, which contain damping material. Construction of the mechanical and electronic components for the secondary support structure commenced near the end of this report period.

A new near-infrared spectrograph (KSPEC; see § IVc) was first used on the telescope in late 1992. Released for general use in April 1993, it rapidly became a popular instrument. This spectrograph uses a cross-disperser to allow the range 1.15–2.42 μm to be observed simultaneously with a resolution $\lambda/\Delta\lambda$ up to 900.

An infrared spectrograph that suppresses OH airglow was tested on the telescope in November 1992 and March 1993. This large (300 kg) spectrograph, which mounts at the $f/31$ Cassegrain focus, was designed by T. Maihara and coworkers from Kyoto University and is a prototype instrument for the Subaru telescope. It works in the J and H windows, where OH airglow contributes most of the background. The instrument forms a high-dispersion spectrum of the sky on a mirror that is masked off at about 50 discrete wavelengths where the OH lines are measured to fall. The light is then recombined and can be passed either to a lower-dispersion spectrograph or directly to the near-infrared camera, where an image of the slit (minus the OH background) is formed. In March 1993, a reduction in the OH background by a factor of about 25 with a throughput of approximately 10% was achieved.

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

b. Site Characteristics

The wavefront sensor built by the Adaptive Optics group produces quantitative data on the seeing conditions at Mauna Kea. Such data are now collected for statistical analysis during each adaptive optics observing run. A particular effort has been made to estimate the effective turbulence speed, which is a weighted average of the wind speed in the turbulent layers. The turbulence speed determines the bandwidth required for adaptive optics and sets the limiting magnitude for the guide star. The effective wind speed was found to vary by an order of magnitude over six different observing runs, which means that the limiting magnitude for a guide star can vary by 2.5 mag from one observing run to another.

As part of its site characterization program for the proposed Smithsonian Submillimeter Array, the Smithsonian Astrophysical Observatory, in collaboration with the JCMT, has been measuring "radio seeing" from Mauna Kea. The test instrument is an interferometer with a 100 m baseline that receives a 11.7 GHz signal from a geostationary satellite. The results from the first 21 months of observations imply a median resolution at 345 GHz of $1.2''$, corresponding to a maximum usable baseline of 108 m. Twenty-five percent of the time, resolution of $0.5''$ or better should be attainable at 345 GHz, provided correspondingly longer baselines are used. The results also confirm that the dependence of resolution on observing frequency is small, and is in the sense that lower frequencies yield higher resolution, provided a sufficiently long baseline is available. There are significant diurnal and seasonal variations, with better resolution available, on average, at night and during the first half of the year.

c. Mauna Kea Infrastructure

All the currently operating telescope facilities at the Mauna Kea summit, except for the two UH 0.6-m telescopes, are now connected through routers to the fiber distributed data interface (FDDI) token ring, as is the Mid-Level Facility at Hale Pohaku. The bandwidth of this local-area communications network is 100 Mbits s^{-1}. The VLBA connects at the UH 2.2-m telescope via a leased copper circuit. Four T1 (1.544 Mbits s^{-1}) circuits leased from GTE Hawaiian Telephone link telescopes at the summit to base facilities on the Big Island. CFHT and the JAC each have one of these, and Keck has two. From Hale Pohaku, there is a leased T1 to the UH Manoa Computer Center that carries the off-island Internet traffic for all observatories.

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. A major expansion of the camp was completed in March, with the addition of 4 eight-person cabins to house the workers for the Subaru project. Subaru construction started in July 1992, and while the new cabins were under construction, the Subaru workers shared space in the existing 29-bed camp with workers on the Keck II project. Keck II also got underway in July 1992. Additional parking and improved drainage were also provided as part of the construction camp expansion.

III. HALEAKALA OBSERVATORIES

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

a. 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. Rockwell Power Systems has contracted with the IfA to carry out a Haleakala Site Survey. The site survey includes meteorological and geotechnical measurement work in the immediate vicinity of the currently proposed site of the new U.S. Air Force 3.7 m telescope facility.

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

b. LURE Observatory

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.

Satellite ranging at LURE continued to produce data of the greatest accuracy of any station in the network. Improvements in telescope pointing and telescope mount modeling, along with continued software enhancements, have made LURE a most important member of the satellite laser-ranging network.

IV. INSTRUMENTATION

a. NASA IRTF Infrared Array Camera

By the end of the report period, construction of a 1–5.5 μm infrared array camera based upon the Santa Barbara Research Center 256×256 InSb array was completed. The primary features of this powerful new instrument are three user-selected platescales, a variety of fixed bandpass filters (broad-band and 1%), 1–2% spectral resolution circular variable filters (CVFs), coronagraph masks, a polarization imaging capability from 1 to 2.5 μm, an optical guider/imager, and a grism.

The three platescales of 0.30, 0.15, and 0.06 arcsec pixel^{-1} provide a range of spatial resolutions that can be used to match a wide range of seeing conditions and scientific programs. The smallest platescale was specifically chosen to take advantage of image improvements expected from the tip-tilt secondary image stabilization system. Simultaneous optical and infrared imaging of the same field will be possible through the use of a cold dichroic that reflects wavelengths <1 μm. This capability will be used for both guiding and scientific imaging.

The array clocking and data acquisition will be controlled by multiple Motorola 96002 digital signal processors (DSPs). The instrument will be operated by observers through a sophisticated X-Windows-based user interface running on a Sun workstation. There will be several unique operating modes, including "shift-and-add mode" (real-time shifting and addition of images using point sources to register images and partially correct for image motion), "IR guiding mode" (telescope guiding on infrared objects in the array field), and "movie mode" (fast subarray acquisition for short-term time dependent events, such as planetary satellite and lunar occultations).

Tests of the camera with an engineering-grade array began at the IRTF in April 1993. The first run with a science-grade array was in early September. Later during that run, the camera was commissioned as a "shared-risk" instrument. Through the end of 1993, the camera was available for use at the three pixel scales with the broad-band and 1% bandpass filters only. The CVFs, polarization imaging, and the grism will become available in spring 1994.

b. Adaptive Optics

An experimental adaptive optics (AO) system is currently being developed at the Institute. The system is based on the concept of wavefront curvature sensing and compensation. The sensor measures the intensity difference between oppositely defocused images, and the deformable mirror is a piezo-electric bimorph. Compared with other AO systems developed for astronomy, the UH system is expected to be more cost effective and to work with fainter guide sources. Early tests made in July 1992 at the coudé focus of the CFHT produced CCD long-exposure stellar images with a full width at half-maximum (FWHM) of $0.08''$.

After this successful run, most of the effort was put into developing a very high sensitivity detector array for the wavefront sensor. A choice was made to purchase prepackaged avalanche photodiodes with a two-stage thermoelectric cooler and photon-counting electronics. The quantum efficiency of these devices peaks around 42% at 600 nm, and the average dark current is below 5 counts s^{-1}. The maximum count range is of the order of 1.6×10^6 counts s^{-1}.

Coupling the light to the detectors presented somewhat of a challenge. Each detector is 100 μm in diameter, and light is coupled to it by means of a graded index lens and fiber. A decision was made to build a custom lenslet array that focuses a star image onto the end of each fiber. The entrance aperture of each lenslet has a shape that closely matches that of the associated electrode in the bimorph mirror. Two key features of the optical design by Guy Monnet (CFHT) are the choice of the achromatic glass combination PSK3/LaSFN3 and the extension of the rear element all the way to the focal plane. In this way the fiber can be located very accurately in the focal plane and optically coupled with oil to minimize losses. The overall transmission of the lenslet-fiber combination was measured to be 90%.

The new wavefront sensor was tested at the CFHT coudé focus in March and April 1993. A reduction by a factor of 3 was observed in the FWHM of long-exposure stellar images, recorded at 1.2 μm, while using a guide star with a photon-counting rate equivalent to visual magnitude 15, a performance never reached before. Efforts include building a new control system with real-time diagnostic capabilities, which will allow the control parameters to be continuously optimized according to photon-counting rates and seeing conditions, and improving the optical quality of the bimorph mirrors.

In parallel with this development effort, the out-of-focus image technique has been widely used to measure the optical quality of telescopes on Mauna Kea and to predict the image improvement one can expect from adaptive optics. Wavefront data from the wavefront sensor have been accumulated and used to improve the knowledge of the seeing characteristics on Mauna Kea.

c. KSPEC

KSPEC, the cross-dispersed medium-resolution infrared (K-band) spectrograph, was first used at the telescope in October 1992 and was commissioned as a common-user instrument in April 1993. KSPEC has two infrared detector arrays of the NICMOS-3 type: An engineering-grade array for slit viewing in the K band and a science-grade array for recording spectra. The spectrograph uses a fused silica prism as a cross-disperser to separate the K band (3rd order), H band (4th order), and J band (5th order). Higher orders are also recorded, but they overlap significantly and are therefore difficult to use. The slit length is only $6''$, but this is sufficient for sky subtraction around point sources. For extended objects, separate sky frames must be taken. A number of different slit widths can be installed in KSPEC to adapt it to different observing programs. A long-slit, single-order mode of KSPEC in which a different spectrograph camera is used and the prism is replaced by an order sorting filter was also tested. In this mode, the maximum slit length is $25''$.

KSPEC has been successfully used for a variety of projects, ranging from spectroscopy of planetary satellites to the search for high-redshift galaxies associated with ultra-steep-spectrum radio sources.

d. Large-Format Infrared Detector Arrays

During the report period, negotiations were initiated with the Rockwell International Science Center to develop an infrared array of 1024×1024 format using HgCdTe material with a cut-off wavelength of 2.5 μm. These arrays will based on the technology developed for the NICMOS devices. The goal is to address some of the shortcomings of the NICMOS devices in the design process. The arrays will be optimized for low-noise, low-dark-current operation under low-background conditions in high-resolution spectrographs, but will also be usable for broad-band imaging.

V. GALACTIC AND EXTRAGALACTIC STUDIES

Gioia and Henry continued the optical identification study of the NEP (North Ecliptic Pole) region of the *ROSAT X-Ray Astronomy Satellite* 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. Such evolution was first detected in the *Einstein Observatory* Extended Medium Sensitivity Survey (EMSS). By the end of the report period, about 150 sources had been observed. Preliminary data reduction has revealed ∼40 clusters, a similar number of active galactic nuclei, 4 BL Lac objects, and about 50 stars. Determination of luminosities for the evolution studies must await complete identification of the sample and spectroscopic confirmation of the clusters. Redshifts are now available for about one-third of the sources. As often happens in surveys, this one has serendipitously revealed a few objects of special interest. These include the most distant X-ray-selected QSO ($z = 4.32$, the eighth largest known) and a cluster at $z = 0.32$ showing an arc in a 10 min I exposure. The latter is bright enough to be observed spectroscopically with some hope of success. The *ROSAT* survey is the first for which it will be possible to directly measure the mass function of X-ray groups and clusters, since their temperatures are too low to have been detected by previous X-ray all-sky surveys.

Gioia, Luppino, and graduate student J. Annis continued their observational program to 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 both the UH 2.2 m telescope and CFHT. The selection of the sample is based on X-ray luminosity, since it is assumed that the X-ray gas is in hydrostatic equilibrium with the gravitational potential and thus serves as a tracer of the total potential caused by both the luminous and dark matter. Large X-ray luminosities would then imply deep potential wells and so identify true clusters. Deep potential wells are more likely to make arcs. At $z = 0.426$ and $z = 0.583$, the first two arc clusters discovered are the highest-redshift clusters in which arcs have been observed. About 15 new arc clusters have been identified. The high lensing frequency contrasts with the much lower frequency (a few percent) seen in optically selected clusters; this confirms that the search strategy is effective. The next step will be spectroscopic confirmation that these arcs are images of distant galaxies gravitationally distorted by the massive foreground clusters. Also, the redshifts of the arcs will be determined using the CFHT and the Keck telescope.

Henry continued his work on clusters of galaxies using the *ROSAT*. With U. Briel (Max-Planck-Institut für Extraterrestrische Physik) and P. Nulsen (Univ. of Wollongong), he presented the first spatially resolved X-ray spectroscopy of a rich cluster of galaxies (A2256) performed with a true imaging telescope. Within 0.75 Mpc of the center, the X-ray gas is isothermal. The mass of the cluster could therefore be determined free of the usual assumptions inherent in a virial analysis using optical data. With Briel and S. White (Univ. of Cambridge), Henry studied the X-ray emission of the Coma cluster. This object was observed for four days during the reduced pointing phase of the mission; the resulting map contains well over a factor of 10 more photons than were contained in the best previous map. These data show that the Coma cluster, long regarded as the prototypical smooth relaxed cluster, has significant substructure on a variety of spatial scales. Most of the substructures are the remnants of smaller groups of galaxies falling into the cluster at various times in the past. This activity was continuing.

With Briel, Henry observed a complete sample of 145 Abell clusters. Approximately 90% of all Abell clusters are X-ray sources above a flux level of 1×10^{-13} ergs cm^{-2} s^{-1}. Further, there is a clear correlation between X-ray luminosity and Abell richness class: richer clusters are more X-ray luminous. Thus the Abell catalog is not strongly contaminated by projection effects.

Hu and R. McMahon (Univ. of Cambridge) studied the fields of quasars known to lie at high redshifts ($z > 4$), corresponding to times when the universe was only 1–2 Gyr old. Follow-up spectroscopy of emission-line candidates identified from deep narrow-band imaging at wavelengths coincident with the quasar's redshifted Lyman-α yielded a number of objects with single emission lines (near the quasar's redshifted Lyα) and faint to undetectable continuua.

Hu and graduate student S. Ridgway discovered two extremely red objects ($(I - K) \sim 6.5$) in the field of the redshift 3.8 quasar PC 1643+4631A. On the basis of the spectral energy distribution and angular extents of these objects, they suggest that these are most likely to be elliptical galaxies at $z \sim 2.4$. The existence of such evolved objects at this redshift would imply a current age of the universe substantially in excess of 1.0×10^{10} years ($q_0 = 0.02$).

Hu, graduate student J. Huang, and L. Cowie used the Hawaii Deep Survey (I- and K-band) data to set limits on the density of low-mass stars and their contribution to the dynamical mass of the disk and halo. With a sample area >100 arcsec^2 and $K < 19$, they find that the luminosity function drop seen between $M_{\rm bol} = 10 \rightarrow 13.8$ continues to $M_{\rm bol} = 15.5$, and that the number density limits exclude the possibility that stars at or near the hydrogen-burning limit contribute any substantial fraction of the dynamical mass of the disk or halo.

J. Kormendy reviewed his search for supermassive black holes (BHs) at the Heidelberg Workshop on Elliptical Galaxies. He also began to extend the BH search to higher spatial resolution using the new Subarcsecond Imaging Spectrograph (SIS) on the CFHT. SIS solves the main problem with his previous spectroscopy: the spatial resolution of the Herzberg Spectrograph was limited by the camera optics to FWHM $\gtrsim 0.9''$. Now the resolution is limited by the seeing and by telescope optics. Early trials of SIS on NGC 3115 improved the spatial resolution by 20%; results are consistent with the BH detection reported last year by Kormendy and D. Richstone (Univ. of Michigan).

Kormendy continued work on *Hubble Space Telescope (HST)* photometry of the cores of early-type galaxies, as part of a team including Y. Byun, A. Dressler (Carnegie Observatories), S. M. Faber and C. Grillmair (Univ. of California, Santa Cruz), T. R. Lauer (National Optical Astronomy Observatories [NOAO]), Richstone, and S. Tremaine (Canadian Institute for Theoretical Astrophysics). They obtained V-band photometry of ~ 30 galaxies using the *HST* Planetary Camera. Most giant ellipticals have resolved, non-isothermal cores: at the "break radius" r_b (formerly called the core radius r_c), the steep outer surface brightness profile turns down into a shallow inner power law $I(r) \propto r^{-\gamma}$, $\gamma \simeq 0.1 \pm 0.1$. Low-luminosity ellipticals are unresolved to the smallest measurable radii ($\gamma \simeq 0.8 \pm 0.2$). There are signs of a dichotomy between resolved and unresolved objects. Galaxies with resolved cores continue to satisfy fundamental plane parameter correlations like those found from ground-based photometry. Finally, dust disks and nuclear disks of stars are seen in many bulges and elliptical galaxies.

Kormendy continued his CFHT surface photometry of low-luminosity elliptical galaxies. The purpose is to see whether they lie in the extrapolation of the fundamental plane correlations for bright galaxies and hence to explore the transition or discontinuity in properties between small ellipticals and dwarf spheroidal galaxies. The sample of Virgo ellipticals is essentially complete; it includes several objects that are as low in luminosity as M32.

Kormendy lectured on elliptical galaxies at a Nordic Summer School on "Galaxies: Structure, Formation, and Evolution" (Gräftåvallen, Sweden). He also gave a review paper on the dynamics of galaxy bulges at IAU Symposium 153, "Galactic Bulges." This summarized observational and theoretical evidence that some "bulges" are built secularly out of disk material. Many bulges show photometric and kinematic evidence for disklike dynamics. This includes (1) velocity dispersions σ much smaller than those predicted by the Faber-Jackson $\sigma - M_B$ correlation, (2) rapid rotation $V(r)$ that implies V/σ values well above the "oblate line" describing rotationally flattened, isotropic spheroids in the V/σ – ellipticity diagram, and (3) spiral structure dominating the $r^{1/4}$ part of the galaxy. In these galaxies, the steep, $\mathrm{r}^{1/4}$-law central brightness profiles belong not to bulges but to disks. That is, some galaxy disks have central brightness profiles that are much steeper than the inward extrapolation of an exponential fitted to the outer parts. These observations and n-body simulations of gas flow in nonaxisymmetric galaxies imply that high-central-concentration, flat components can be formed out of disk gas that is transported toward the center by bars and oval distortions. These effects are signs that important secular evolution processes are at work in galaxy disks.

Stockton, Ridgway, and S. Lilly (Univ. of Toronto) continued their detailed investigation of the Cyg A radio galaxy. They confirm that the featureless blue component that dilutes the late-type stellar absorption lines in the spectrum of the central region of Cygnus A comes from the prominent double morphology seen in optical images. From regions that appear to be least affected by obscuration, they find that $f_\nu \sim \nu^{-0.1}$ for this component. This result could be consistent with a population of young stars or with a quasar continuum scattered by electrons. It is probably not consistent with a quasar continuum scattered by dust; this would make a bluer spectral energy distribution. They also find an upper limit on the equivalent width of broad Hβ; this is well below that seen in typical quasars. Therefore this flat-spectrum component (FSC) is not scattered quasar radiation at all. At high angular resolution, the apparent morphology of the FSC is spiral-like. Although this impression may be partly due to obscuration, the distribution of the dust actually reinforces the spiral morphology. The FSC is most likely to be radiation from a starburst at the center of Cyg A.

Systematic differences are present in the distribution of [O III] and that of [N II] and other low-ionization species. After a large common component to the distribution is removed, the remaining [O III] excess is aligned with the radio axis, while the [N II] excess is distributed in what appears to be a planar structure perpendicular to the radio axis. The association of dust with this latter component indicates that it is a distinct morphological structure and not simply the result of shadowing effects.

The redshift of Cyg A, $z = 0.05562 \pm 0.00015$, was measured using a strongly diluted Mg I*b* feature seen in high-S/N spectra of the central region. The velocity field of the ionized gas is complex, showing at least two components along some lines of sight. In general, discrete clouds show velocity curves consistent with rotation rather than with outflow, but high-velocity gas probably associated with the radio jets is seen on both sides of the nucleus. The ionized gas centered on the nucleus is counter-rotating relative to the bright cloud to the NW and to most of the fainter material in the same area. This counter-rotating gas in the nuclear region, a secondary IR peak $1''$ N of the nucleus, and the extensive ragged swath of low-ionization gas and dust stretching to the N and S all suggest that Cyg A recently underwent a merger.

Graduate student D. Maraziti and Stockton completed a simulation of the recovery of QSO host galaxies at a redshift of 0.3 based on various nearby galaxies as models. By using a simple monotonicity criterion to constrain the removal of the QSO nucleus, they were able to reliably recover about 90% of the host-galaxy flux. The dispersion in this value was small and did not seem to vary greatly with galaxy type.

Stockton and Ridgway continued a program to obtain deep images of a sample of low-redshift ($0.15 < z < 0.45$) QSOs in two line-free optical bands as well as at K' in order to study host-galaxy morphology. They found that a significant fraction of their sample shows evidence of very close companions or other strongly asymmetric structure within a few arcseconds of the QSO nucleus.

Ridgway worked on an optical and IR imaging study of a complete sample of 3CR quasars and galaxies at $z \sim 1$. By comparing deep images of the radio galaxies and quasar hosts, she will obtain constraints on the relationships (e. g., the unified model) between quasars and FR II radio galaxies. By comparing this sample of quasars with the quasars in the low-redshift sample mentioned previously and a third sample having the redshift distribution of the $z \sim 1$ 3CR sample and the mean radio power of the low-redshift sample, she will also be able to distinguish correlations between host-galaxy properties and epoch from those between galaxy properties and radio power.

Continued use has been made of the Hawaii Imaging Fabry-Perot Interferometer (HIFI) for studies of extended regions of anomalous emission around active nuclei in galaxies. Of particular note during the report period was a study by S. Veilleux (now at NOAO), Tully, and J. Bland-Hawthorn (Rice Univ.) of NGC 3516, a lenticular galaxy with a Seyfert nucleus. High-excitation, moderately high-velocity gas lies in two symmetrically opposed curved jetlike features; *on one side of the nucleus only* this gas is coincident with a one-sided, nonthermal radio jet. The curvature in the jet can be explained as due to precession of the jet source or to ram-pressure bending through interaction with a rotating ambient medium.

Tully and M. J. Pierce (NOAO) continued work on the extragalactic distance scale and on the measurement of galaxy peculiar velocities. The emphasis in the past year has been on the accumulation of a large body of CCD photometry and on the development of a database of H I profiles and photometry. Tully and Pierce reported at several conferences that the current calibration of the luminosity-linewidth relation suggests that the Hubble constant is 90 ± 10 km s^{-1} Mpc^{-1}.

Graduate student C. Dudley and Wynn-Williams completed a study of Arp 299C, a 5×10^{10}-$L_\odot$ infrared source in the merging galaxy Arp 299. This is the most luminous object known that is not obviously associated with a galaxy nucleus. Their data show that the 8–13 μm spectrum of Arp 299C has a strong [Ne II] emission line and emission features like those of polycyclic aromatic hydrocarbon (PAH) molecules. These emission features are characteristic of H II regions associated with a burst of star formation. They did not detect high-excitation ion lines characteristic of an active galactic nucleus, nor a deep silicate absorption feature that might indicate a hidden compact nucleus. They deduce that Arp 299C is powered by an intense burst of star formation.

For theoretical studies, see § Xa.

VI. INTERSTELLAR MATTER

Graduate student J. Deane, Ladd, and Sanders compared the far-infrared (7–135 μm, from the *IRAS Infrared Sky Survey Atlas*) emission from the W3 Giant Molecular Cloud with their ^{13}CO map of the same region taken in 1992. Local values of the star formation activity were determined from the ratio of the far-infrared luminosity to the molecular gas mass from the CO line measurements. Measured on arcminute-size scales, the bulk of the cloud mass is relatively inactive ($L/M \sim 2$), while 3% of the total mass, confined in the most massive cores, has $L/M \sim 70$, and contributes nearly a quarter of the total luminosity of the region. Such a wide range of L/M ratios implies that the spatially averaged values previously determined by studies of ensembles of molecular clouds reveal little about the character of individual star-forming cores.

Greene and Rayner used CSHELL, the high spectral resolution infrared spectrograph, on the IRTF to obtain high-resolution near-infrared spectra of the S106 and GL 2591 outflow sources. The H I Brackett-γ spectrum of S106 shows both the luminous young stellar object (YSO) and its outflow to be spectrally resolved. The Brγ linewidth in the outflow ($\sim$80 km s^{-1} FWZI [full width at zero intensity]) is comparable to that of the Hα widths in the region, suggesting that they are both formed in an expanding H II region that is photo-ionized by the central source. Little Brγ emission in the outflow can be scattered from the central source. Their spectra of the GL 2591 outflow show little Brγ emission in the region, and this emission is too narrow ($\sim$30 km s^{-1} FWZI) to arise in a YSO wind. It is also too narrow for the emission to arise from ionization by J-shocks where the YSO wind impacts ambient molecular material, contrary to the prediction of Tamura and Yamashita. H_2 S(1) 1–0 emission is seen throughout the region with linewidths from <14 km s^{-1} to 70 km s^{-1}, and this emission is likely caused by C-shocks induced by the YSO wind.

Herbig completed a major review paper on the diffuse interstellar bands, in the course of which a number of relevant issues had to be investigated. Among these were (1) C_{60} has often been suggested as a DIB carrier. The strong electronic transitions of C_{60} lie below the atmospheric cutoff, but a weaker laboratory band at 3240 Å is accessible. That region was observed at 2 Å resolution (with the CFHT) in a number of reddened OB stars, but no interstellar feature could be found. An upper limit of $N(C_{60}) < 2 \times 10^{13}$ can be set for two lines of sight in the Cyg OB2 association. (2) Another suggested DIB carrier is free polyatomic chains of the type C_n, with $n = 3$ to 8. Again, the strongest transitions are in the terrestrially inaccessible ultraviolet, but weaker bands near 3040 and 3450 Å cannot be found in the CFHT spectra. Since the f-values are not known, all that can be said is that neither feature is present in strength comparable to the well-known DIB at 4428 Å. (3) A puzzling feature of DIB systematics is that the stronger features appear to saturate in stars of very large reddening. Herbig has shown by numerical experiments that this may be the consequence of a concentration of DIB carriers in the outer layers of diffuse clouds, as was suggested 20 years ago by Snow and Cohen. Such a reduction of DIB carrier density in cloud interiors could be due either to the influence of the external radiation field or, more likely, to a formation mechanism that is less effective at the lower H I densities in the interiors.

Herbig, in collaboration with P. J. Sarre (Univ. of Nottingham) also obtained spectrograms (at the 2.2 m coudé) of many reddened OB stars in the 3700–4800 Å region to determine if any DIBs can be found shortward of 4428 Å, where the DIB spectrum appears to come to a halt. A very broad, very shallow feature does seem to be present near 4180 Å, as suggested by others, and possibly another near 4066 Å, but the problem is difficult even on this high-S/N material because of confusion with stellar lines.

Hodapp used KSPEC for spectroscopic observations of a K-band magnitude-limited sample in a subregion of the Orion Trapezium cluster. The goal of this project is to spectrally classify all stars in this cluster for which absorption line spectra were obtained, and to get constraints on the accretion activity for the other stars that only show continuum or emission-line spectra.

Hodapp continued the analysis of the K-band imaging data of all sources of molecular outflow from Fukui's list. For most outflows, some features in the K band were detected: the star seen directly, scattered light of cometary or bipolar morphology, or shock fronts. Approximately one-third of outflow sources are associated with clusters of stars, and most of the nearby clusters show a peak in the K-band magnitude histogram, indicating the evolutionary effects of deuterium burning.

In some of the first observations using the newly commissioned KSPEC on the UH 2.2 m telescope, Hora obtained the 1–2.5 μm spectra of several planetary nebulae (PN), including IC 418, AFGL 618, M 2-56, and NGC 7026. The $1'' \times 8''$ slit of KSPEC was used to obtain the spectrum of the PN at several positions, including the central star, the brightest part of the nebular ring or lobes, and the halo region. In the PN NGC 7026 and IC 418, the nebular emission was found to be dominated by the hydrogen Paschen, Brackett, and Pfund series recombination lines, with contributions from several He I lines. The H line ratios observed are close to those predicted by recombination theory. Also found in the NGC 7026 spectrum are the H_2 line at 2.122 μm and an unidentified line at 2.287 μm that had previously been detected by others in several other moderate- to high-excitation PN. No H_2 was detected in the spectra of IC 418, but a strong continuum component, presumably due to hot dust emission, was seen in the 2–2.5 μm region. Observations of the bipolar PN M 2-56 showed it to have an almost featureless continuum from 1.15 to 2.5

μm. The spectrum of the protoplanetary nebula AFGL 618 is dominated by H_2 lines, with Paβ and Brγ H recombination lines also detected.

Ladd, Sanders, Wynn-Williams, and Deane began a submillimeter continuum survey of high-mass star-forming regions. They have found several bright submillimeter continuum sources that apparently have no associated radio continuum emission. The bright submillmeter emission suggests that these sources are luminous, and if powered by main-sequence–type stars, should generate radio continuum emission. That no radio continuum emission is seen suggests that these sources are embedded within very dense cocoons or are not main-sequence–type objects.

Ladd, with collaborators P. Myers (Harvard-Smithsonian Center for Astrophysics [CfA]), G. Fuller (National Radio Astronomy Observatory), R. Padman (Univ. of Cambridge), and F. Adams (Univ. of Michigan), studied the environs of one nearby embedded young star L1551-IRS 5 in the submillimeter continuum and in rare isotopes of CO. They have found that the distribution of material around this source is nonaxisymmetric and shows some evidence for being shaped by the bipolar outflow emanating from this source. They also find that at least some of the material within 10,000 AU (in projection) of IRS 5 must be very cold, with dust temperatures $\sim$6 K.

Ladd, in collaboration with Myers and E. Lada (Univ. of Maryland), presented a near-infrared survey of embedded *IRAS* sources in the Perseus Molecular Cloud Complex. They found that in regions outside of the star-forming clusters in Perseus, young stars have low luminosity and form in relative isolation, much as they do in the Taurus Molecular Cloud. However, they find that the isolated sources in Perseus as a group are slightly more luminous and redder than the sources in Taurus.

Also in Perseus, Ladd, with Myers and A. Goodman (CfA) searched for dense gas around 10 *IRAS* sources using the (J,K) = (1,1) inversion transition of NH_3. They found dense gas around eight of ten sources and mapped it around seven. As a group, these Perseus cores have larger temperature, linewidth, and mass than NH_3 cores in the Taurus Cloud, but smaller temperature, linewidth, and mass than NH_3 cores in the Orion Cloud. Both the infrared and spectral line data identify the Perseus Cloud as intermediate between the Taurus Cloud, which produces predominantly low-mass stars, and the producing Orion Cloud, which produces high-mass stars. They conclude that Perseus is a hybrid complex that contains examples of isolated, low-mass star formation, as well as examples more commonly associated with higher-mass, clustered star formation.

Ladd and M. Heyer (Univ. of Massachusetts) began a multitransition CO study of a dense core in the Cepheus Complex. They find that there exists a gradient in excitation temperature along the line of sight, varying from approximately 10–15 K on the outside of the core, to a minimum of $\sim$6 K in the interior, but increasing to $\sim$10 K near the 100 $L_\odot$ embedded source. They also find suggestions of rotation in the velocity structure of the self-absorption seen in the ^{13}CO(2$\rightarrow$1) spectra.

Myers and Ladd developed a formalism for classifying the spectral energy distributions of young stars. Using the first moment of a star's spectral energy distribution, they define the "bolometric temperature" as the temperature of a blackbody function whose spectral energy distribution has the same first moment. This formalism allows for a generalization of the Hertzsprung-Russell diagram to pre–main-sequence objects and provides for a clear distinction between deeply embedded "Class I" sources, classical T Tauri stars, and "naked" (weak-line) T Tauri stars.

Tokunaga and J. Carr (Ohio State Univ.) finished initial observations of young stellar objects (YSOs) using CSHELL at the IRTF. The CO 2–0 overtone bandhead at 2.3 μm was observed in six YSOs, all of which were known to have CO emission. CO was chosen because emission from the overtone bands requires high densities ($n_{\rm H_2} > 10^{10}$ cm^{-3}) and an excitation temperature of >3500 K. Thus the emission must arise from a region very close to the surface of the YSO. They found strong evidence for a rapidly rotating disk around WL 16, with an inner rotational velocity of about 240 km s^{-1}. The profile of the 2–0 bandhead was consistent with a rotating disk line profile. The mass of the central object is found to be <2.5 $M_\odot$, and the CO emission arises from a region that is within $<8R_\odot$ of the central object. Other objects that show some evidence for a disk line profile include AS353A and 1548CL27. Interestingly, the outflow source SVS-13 had relatively narrow CO emission lines (≈40 km s^{-1}) and no evidence for a disk signature.

T. Brooke (Jet Propulsion Laboratory [JPL]), Tokunaga, and S. Strom (Univ. of Massachusetts) finished a 3 μm spectral survey of T Tauri stars and Herbig Ae/Be stars that was started to search for the 3.29 μm aromatic hydrocarbon emission feature and other carbonaceous features like those seen in comets. About 20% of 24 Herbig Ae/Be stars showed this emission feature. The observations indicate that the 3.29 μm feature is more extended around Herbig Ae/Be stars of earlier spectral type and that the total number of aromatics is also greater for earlier-type objects. Interestingly, none of 45 T Tauri stars (observed by Brooke et al. and others) showed any carbonaceous features. Whether this is a result of a low abundance of carbonaceous material or insufficient excitation has not been determined.

Graduate student H. Chen (now at CfA) and Tokunaga finished a far-infrared and near-infrared survey of *IRAS* sources in L1641. The most important results were that (1) most *IRAS* sources could be identified with a 1.6–4.8 μm counterpart; (2) 14 *IRAS* sources were found to be associated with small (but statistically significant) groupings of stellar objects that were named stellar density enhancements (SDEs); and (3) these SDEs may represent an important mode of star formation in L1641 that is intermediate between the large clusters (such as the Trapezium infrared cluster) and single stars.

Tokunaga, and A. Sakata and S. Wada (Univ. of Electro-communications, Tokyo), continued their studies of quenched carbonaceous composite (QCC) as a laboratory analog to the material that gives rise to the 3.3, 6.2, 7.7, 8.6, and 11.3 μm emission features in the interstellar medium (ISM). New ultraviolet spectroscopy of derivative materials shows a good correspondence to the 2175 Å interstellar absorption. This supports previous work that suggests QCC (an amorphous carbonaceous material containing both saturated and unsaturated hydrocarbon molecules) is a plausible laboratory analog.

VII. STELLAR ASTRONOMY

Heasley continued his work on the photometry of stars in globular clusters. He began a major new program of photometry of the evolved stars in nearby globulars in collaboration with K. Janes and K. Montgomery (Boston Univ.). The initial observations for this program were obtained with a Tektronix 2048×2048 CCD on the Kitt Peak 0.9 m telescope. Further, from a preliminary study using images of M92 obtained by Luppino during the testing of the Tektronix 2048 × 2048 CCD, new V vs. $B - V$ and V vs. $V - I$ color-magnitude diagrams for the cluster with over 14,000 stars was derived. The combined Mauna Kea and Kitt Peak data for M92 produced a significant improvement in the photometry available for this cluster. Additional clusters were observed at the UH 2.2 m telescope in June 1993.

In an analysis of HRCamera observations obtained at CFHT to support an *HST* program to observe globular clusters near the Galactic center, Heasley, Janes, C. Christian (Univ.

of California, Berkeley), and Montgomery obtained a new V vs. $V-I$ color-magnitude diagram for the metal-poor globular cluster NGC 6293 that reaches approximately 2 mag fainter than the cluster turnoff. Comparing this new result with photometry of the evolved stars in M92 (see above) and HRCamera data for the main-sequence stars in that cluster suggests that NGC 6293 is the same age as M92. However, the uncertainties in the current data do not preclude the former cluster's being older than the outer halo clusters, as has been suggested by recent analyses of the bulge stars by Y.-W. Lee.

Christian and Heasley have used HRCamera observations of NGC 6864 to derive a new color-magnitude diagram for that cluster. The diagram exhibits well-defined sequences for the evolved stars that typify clusters of intermediate metallicity, e.g., [Fe/H] ~ -1.3. The data extend to the main-sequence turnoff at $\sim$20.5 mag.

Graduate student B. Han and Heasley began analyzing photometry of globular clusters in the Fornax dwarf spheroidal galaxy. They used observations of clusters #2 and #4 obtained at the UH 2.2 m telescope to construct V vs. $V-I$ color-magnitude diagrams to address the sensitivity of horizontal-branch stars with metallicity. These two clusters provide almost a full dex of metallicity baseline to examine this problem. Calibrating data for the Mauna Kea observations were provided by R. Zinn (Yale Univ.).

Herbig investigated the cluster IC 348, imbedded in the front surface of the molecular clouds from which the expanding Perseus OB2 association was formed. However, the photometric age of IC 348 (5 to 20 $\times$ 10^6 yr) is much older than the expansion age of Per OB2 (1–2 $\times 10^6$ yr). Partly to clarify this discrepancy, the *BVRI* color-magnitude diagram of IC 348 was redetermined to about $V = 19$. Herbig also discovered about 70 faint-emission Hα stars in the region, but they are distributed over a much larger area than are the bright members of IC 348. Using *ROSAT*, H. Zinnecker (Würzburg) has discovered many X-ray sources in the region, some of which can be identified with cluster members, both emission and nonemission. Spectroscopy was being carried out on as many of the X-ray sources as possible.

VIII. SOLAR SYSTEM STUDIES

a. Planets and Rings

In collaboration with R. G. French (Wellesley College), Meech obtained observations of the Uranus MKU102 occultation on 7 July 1992. The goal in this continuing observational program is to refine the orbital characteristics of the Uranian rings. Past observations have been used to determine the Keplerian orbital elements to high precision. By studying the small deviations from Keplerian motion it has been possible to investigate weak dynamical effects on the rings. The ring event times are being included in a new solution for Uranus ring orbits that incorporates all available Earth-based and spacecraft observations of the rings since their discovery. An additional occultation of Uranus was successfully observed on 16–17 August 1993. Accurate IR photometry has also been obtained for most stars predicted to be occulted by Neptune, Uranus, and Saturn from 1994 through 1999. This will allow the selection of the highest S/N occultations for the remainder of the century.

With J. Elliot and L. Young (Massachusetts Institute of Technology [MIT]), T. Roush, D. P. Cruikshank, and M. J. Bartholemew (NASA Ames), B. Schmitt (Univ. of Grenoble, France), C. de Bergh (Observatoire de Paris at Meudon, France), T. Geballe (JAC), and R. Brown and K. Tryka (JPL), Owen published a report on observations of the surface and atmospheric composition of Pluto. The chief results were the discovery of N_2 and CO ices on Pluto's surface, with the consequence that N_2 must be the dominant constituent of the atmosphere. The methane ice absorptions that had been discovered by previous workers were studied in detail, with one new feature added to the list. This weak absorption, together with the measured strengths and wavelength shifts of the other CH_4 features demonstrates that solid CH_4 comprises only about 1.5% of the ice covering Pluto's surface and that CH_4 is dissolved in the nitrogen, which is the main constituent. Solid CO has an abundance of 0.5%. Cosmic abundances dictate that neon should be present with the same atom abundance as nitrogen, suggesting that $Ne/N_2 = 2$ in the atmosphere, since Ne doesn't condense at Pluto's surface temperature (35–50 K). The absence of neon from the atmosphere—to a level of a few percent—therefore indicates that Pluto was not formed from unmodified, low-temperature interstellar grains. On the other hand, the presence of abundant N_2 on Pluto's surface lends support for the conventional explanation of the "missing" nitrogen in the ISM, namely, that it is in the form of N_2.

Additional support for this conclusion comes from a complementary study of Triton by the same team of scientists (without Elliot and Young). Here the proportion of N_2 to CH_4 and CO is even higher, and CO_2 ice is also present. On both of these icy worlds, the high ratio of N_2/CO is a problem. In the ISM, CO $\sim N_2$. Evidently processes acting during or subsequent to the formation of these objects have converted the CO to other compounds (CO_2? CH_4?) or allowed massive loss of original N_2 and CO with subsequent replacement of N_2 from frozen nitrogen compounds.

Owen pursued the question of the state of nitrogen in the early solar system by considering sources that could have delivered this gas to the inner planets. The studies of Pluto and Triton have emphasized that there were two principal reservoirs for nitrogen in the solar system—N_2 and condensed compounds. Owen pointed out that the apparent deficiency of nitrogen in comet Halley could easily be the result of the degassing of N_2 from the active region of the comet's nucleus, which would leave only the nitrogen compounds to carry this element. (The proportion of C/N in Halley is about the same as that observed in the ISM.) Thus comets would deliver a value of C/N to the inner planets that is very close to that observed in the volatile reservoirs of Venus, Earth, and Mars.

With A. Bar-Nun (Tel Aviv Univ.), Owen worked on a model for cometary delivery of volatiles to the inner planets that relies on Bar-Nun's laboratory experiments on the trapping of noble gases in ice. The experiments demonstrate that trapping in ice will reproduce the fractionation effects observed in the planetary atmospheres, if the ices are formed at temperatures near 50 K. At such temperatures, molecular nitrogen is also trapped by the ice, whereas at temperatures near 100 K, very little gas trapping occurs. A feature of this model is therefore the requirement that volatiles were brought to the Earth by comets formed in the Jupiter region of the solar nebula as well as comets formed in the Uranus-Neptune region.

Tholen continued the analysis of the six-night sequence of Pluto-Charon observations for purposes of detecting the barycentric wobble of the system. This effort also involved J. Elliot, L. Young, and C. Olkin (MIT), and M. W. Buie (Lowell Observatory). The results show a Pluto-Charon mass ratio close to 7, which implies nearly equal densities, a result in conflict with that of a similar experiment performed using the *HST* by G. Null (JPL), who found a mass ratio of around 12. Although the *HST* observations benefit from better and more consistent seeing, they suffer from severe field distortion, only a half orbit of coverage, and a single reference star. The Mauna Kea observations provide coverage of nearly a full Charon orbit, involve multiple reference stars, and have much less field distortion.

Tholen continued as a member of NASA's Outer Planets Science Working Group, which is currently developing plans for a potential spacecraft mission to Pluto later this decade.

b. Asteroids

Tholen initiated a series of astrometric observations of (243) Ida using the IRTF encoders and a CCD frame taken at the 2.2 m telescope, for purposes of assisting with the navigation of the Galileo spacecraft to its second asteroid flyby target. Twenty-two observations were made during 1993, most by the IRTF telescope operators W. Golisch, D. Griep, and C. Kaminski. All residuals, as determined from the final orbit delivered to the Galileo project, were $<1''$, and the rms residual was slightly$<0.4''$, which represents superb astrometric performance.

Tholen and J. R. Spencer (Lowell Observatory) completed their analysis of the infrared observations of Ida taken in early 1992. The bolometric observations, combined with the standard thermal model and a spin axis orientation and shape determination by P. Magnusson (Uppsala Astrophysical Observatory) yielded estimated dimensions of $42.3 \times 23.5 \times 21.4$ km and a visual geometric albedo of 0.24. The infrared reflectance spectrum between 0.8 and 2.5 μm revealed the expected pyroxene absorption features, but the olivine component was clearly much weaker than for (951) Gaspra, the first of the Galileo asteroid flyby targets, revealing Ida to be much more similar to the typical S-type asteroid.

(4660) Nereus is one of the most accessible objects in the solar system, given its low ΔV requirements, which helped make it a leading candidate for the proposed *Near Earth Asteroid Rendezvous (NEAR)* mission. During late 1992 and early 1993, Nereus made its most favorable apparition for the rest of the decade. Tholen secured colorimetry of this object in October, February, and May, with the best data coming from the last of these efforts. Unlike the other spacecraft flyby targets, Nereus has a more neutral spectrum, though the lower-quality data from the earlier runs will need to be incorporated before it will be possible to distinguish between the C and X (that is, E, M, or P) spectral types.

An intensive observational effort was directed toward the Apollo-type asteroid (4179) Toutatis during its close approach (0.024 AU) to Earth on 8 December 1992. Tholen spent seventeen nights on one of the 0.61-m telescopes and two nights on the IRTF (with Spencer) to obtain lightcurve, colorimetric, and bolometric observations of this asteroid. Two additional nights of data were acquired on the 2.2 m telescope during the more distant opposition in July 1992. Although weather losses were uncharacteristically high, a good dataset was acquired at evenly spaced phase angles from near 0° up to a record 121°. Analysis of the lightcurve data has not yet yielded a unique rotation period, which supports the hypothesis by A. W. Harris (JPL) that Toutatis may be tumbling. The colorimetric observations revealed a typical S-type reflectance spectrum. Phase reddening effects have yet to be studied.

Following the discovery of another transsaturnian object, 1993 HA2, by the Spacewatch Camera project, Tholen obtained colorimetric observations of this faint ($V = 20.5$) asteroid in May 1993. Comparison with the colors of (2060) Chiron and (5145) Pholus showed that 1993 HA2 shares the extremely red colors of the latter object, providing yet more evidence that organic-rich bodies may be common in the outer solar system.

Tholen continued a project to obtain colorimetry of a significant sample of planet-crossing asteroids, with emphasis directed to those objects of the Earth-approaching variety. Nearly 20 additional objects were observed during the report period, including the objects mentioned above.

In his capacity as the manager of the asteroid subnode of the Small Bodies Node of the Planetary Data System, Tholen continued efforts to assemble, document, and archive datasets on the asteroids.

c. Comets

Jewitt and J. Luu (Stanford Univ.) continued their long-term collaboration to search for transneptunian objects. In 1992, this search yielded the first such object, now known as 1992 QB1. Initial observations from the UH 2.2 m telescope placed the object about 42 AU from the Sun. The apparent red magnitude of 23 suggests a diameter of about 200 km. Subsequent astrometric measurements have shown that the orbit of QB1 is nearly circular (eccentricity = 0.09) and has a perihelion at 40 AU. The radius of the orbit of Neptune is 30 AU. Therefore, it appears that 1992 QB1 is a member of the long-sought Kuiper Belt, a reservoir of ice-rich relics from the formation of the solar system. The continued study of objects in this belt is expected to provide much new information about the accumulation of solid bodies in the preplanetary solar nebula, and about the origin of comets.

Graduate student J. Chen and Jewitt used CCD images of comets to assess the rate of splitting of cometary nuclei. They find that cometary nuclei split, on average, about once per century. In the 10^4–10^5 yr dynamical lifetime of a typical short-period comet, the nucleus would split 100 to 1000 times. This high rate suggests that the secondary fragments of split comets are very small compared to the original nucleus, probably containing much $\ll$1% of the original mass. Cometary splitting is evidently a common process, and it may contribute to the excess population of near-Earth "asteroids" in the 10–100 m diameter range, as recorded by observers in Arizona.

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 that had been ongoing for several years 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. Observational highlights during this report period include the following:

1. Observing cometary comae of dynamically new comets at large heliocentric distances is now routine, and these observations clearly indicate that there is a strong difference in the brightness curves of the Oort comets compared to the periodic comets. During the upcoming year, observations are being deemphasized, and work will concentrate on data analysis and model development. Further image processing will remove contaminating field stars in order to discern the full extent of the coma of the distant comets, and noise reduction algorithms will be used to enhance the low contrast features in the comae to search for structure. The main effort, however, will be in the area of modeling and interpretation.

One spectacular result of the distant comet program is the detection of Comet Cernis (1983XII) at 23 AU. This was done in collaboration with R. West and O. Hainaut (European Southern Observatory [ESO]) on the New Technology Telescope (NTT) at La Silla. Unless the coma is populated by extremely large grains, the existence of coma combined with dust models of the coma at this distance implies activity as far out as 18 AU. Continued collaboration with the ESO scientists is planned. The NTT and the Soviet 6 m telescope will be used during the upcoming year to observe Cernis (at 25 AU) and several other distant cometary nuclei to place limits on the nucleus sizes.

2. In support of Meech's *HST* observations made of the unusual object Chiron during February and March 1993, M. Buie (Lowell Observatory) and M. Belton (NOAO) have collaborated with Meech in an extensive ground-based campaign using the facilities on Mauna Kea, at Lowell Observatory, and the NOAO facilities outside Tucson. Fifty nights of data have showed some extraordinary behavior for Chiron, including significant irregular activity from night to night, the development of a tail longer than 45″ in January, and changing coma colors indicative of changing grain populations in the unbound coma. The *HST* data were being analyzed to search for the bound coma predicted by Meech and Belton, and will also be used to place constraints on the mass of Chiron.

3. Observations of comet P/Machholz obtained during August 1992 show that it has an unusually rapid rotation period. Analysis of the data was underway to interpret the rotational lightcurve in terms of the observed activity on this unusual comet and in terms of its bulk density.

4. Graduate student G. Knopp, with Meech and D. Green (CfA), began to analyze data taken on the split comet Wilson from 1986 to 1989. The analysis shows that the nucleus probably split during November 1987, much later than previously suggested. The splitting was accompanied by a large surge in brightness, and a large fraction of a year after the split, the two pieces appeared to be accelerating apart. An orbital analysis was ongoing to detect any nongravitational effects between the fragments.

In collaboration with Meech, graduate student T. Farnham began thesis work 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 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. Observations of comet P/Arend-Rigaux at heliocentric distances of 1.8, 2.2, and 2.8 AU were successfully modeled. Additional observations of several bright comets were obtained during August 1992. The model is being used to invert the lightcurves to obtain the velocity distributions and scattering properties of the grains, as well as the onset and cessation of activity. A focus of the current work is comet Torres, an Oort comet that has an observational database from 1987 to 1992.

IX. SOLAR PHYSICS

T. Metcalf studied solar active region development utilizing data from the Mees Solar Observatory and the *Yohkoh* satellite. Results indicate that there is no direct relationship between active region electric current systems and soft x-rays observed with *Yohkoh*. Metcalf also began 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. Relations between the linear Hα polarization and hard and soft X-rays observed with *Yohkoh* are being explored.

Wülser studied the relationship between energy transport, chromospheric heating, and chromospheric evaporation in several large solar flares. Hard X-ray images and spectra from the *Yohkoh* spacecraft provided the diagnostics of energy transport and heating by nonthermal particles; soft X-ray images and line spectra from *Yohkoh* provided the thermodynamical parameters of the corona and the diagnostics of conductive heating; and $H\alpha$ imaging spectroscopy observations from Mees Solar Observatory provided the diagnostics of the chromospheric plasma. Wülser found that the observations can discriminate between nonthermal electron heating and conductive heating, especially early in the flare. The results also showed that both heating processes are present in the early impulsive phase, and that both lead to chromospheric evaporation. Furthermore, the relative importance of nonthermal and thermal heating varies strongly with space and time, and from one flare to another.

The *Yohkoh* data include images from a white-light camera (the aspect system of the soft X-ray telescope). This has made possible several studies of "white-light" flares, some in conjunction with direct observations from Mees. At the time of writing of this report, nine white-light flares had been identified, with more very likely. This is probably the most extensive homogeneous set of white-light flare data yet obtained. Hudson, Canfield, Wülser, and Lidia van Driel-Gesztelyi are the principals working on these studies.

In addition to these flare data, the white-light images of the whole Sun have considerable significance. Again the homogeneity of the database makes it rather unique, since never before has a CCD camera been used for long-term studies of the Sun from space. The determinations of the solar diameter, for example, are considerably better than the best ground-based observations. Initial results in this area were presented by Hudson at IAU Colloquium 143. Results in the area of precise relative photometry should be available in the future. These will be used to follow up on the precise ACRIM observations of the variability of the solar "constant," but now with full spatial resolution (of the two-inch lens of the *Yohkoh* camera).

Yohkoh studies of the outer corona have begun to reveal new properties of the "true" corona, that is the direct X-ray emission. Studies reveal a radial extension of this emission out beyond one solar radius. In the observed range, there are structures matching meter-wave radio observations of type III sources, indicating that *Yohkoh* will be able to determine physical parameters for the interesting plasma physics underlying these and other remarkable phenomena.

For theoretical studies, see §Xb.

X. THEORETICAL STUDIES

a. Galactic and Extragalactic Theory

Barnes developed a new suite of large-scale N-body codes based on the hierarchical force calculation algorithm. The new codes were extensively tested and proved to be more robust and reliable than earlier implementations. Interchangeable versions for scalar or vector machines permit calculations to be run on a wide range of architectures, and a modified version tuned for Cray computers runs almost three times faster than previous versions. These codes are available by anonymous ftp, and they will also be distributed with a book of astronomical software to be published by Springer-Verlag.

Barnes began an investigation of dynamical instabilities in galaxy halo models. Several groups have proposed halo models in which the density profile has a local *minimum* at the center; such hollow structures may be used to construct models of dwarf galaxy halos that do not violate cosmological constraints on neutrino phase-space density. However, many of these "hollow-halo" models turn out to be dynamically unstable, a result that may have implications for the nature of dark matter. More recently, Barnes examined the stability of collapsing spherical halos. Such radial collapses are known to exhibit the "radial-orbit" instability, but in addition, these collapsing systems also exhibit a modified form of Hénon's spherically symmetric instability. The latter instability had heretofore only been observed in highly artificial systems.

Barnes and L. Hernquist (Lick Observatory) continued to analyze the stellar and gas dynamics of interacting disk galaxies. A major goal of this analysis is to understand the transfer of angular momentum from the dissipative gas to the collisionless components (stars and dark matter). Rapid central inflows are seen when the gas is either allowed to cool radiatively or artificially maintained at a fixed temperature of 10^4 K; no such inflows occur if the gas is heated by shocks but not allowed to cool radiatively. The rate of inflow depends sensitively on the geometry of the encounter, with the most rapid inflows occurring in close, nearly direct encounters.

Barnes and Hernquist completed a review article for *Physics Today* on numerical simulations of interacting galaxies.

b. Solar Theory

Graduate student Y. Fan, Fisher, DeLuca, and McClymont studied the rise of buoyant magnetic flux tubes from the base of the convection zone to the photosphere. They find that as a loop of flux from an initially toroidal flux ring approaches the photosphere, where it will erupt as a new active region, the magnetic field strength in the leading leg is about twice that of the following leg at the same depth, and that the loop becomes tilted, with the leading leg closer to the equator than the following leg. Both of these asymmetries are produced by the Coriolis force acting on the motions of the flux tube. The difference in field strength offers a natural explanation for the observation that the leading polarity of an active region tends to be in the form of large, well-formed sunspots, whereas the following polarity tends to have a less organized, more fragmented appearance. The computed tilt angles agree well with observations, too.

Gómez, in collaboration with McClymont and De Luca, studied heating of the active region corona by dissipation of currents generated through intertwining of magnetic field lines by turbulence in the photosphere. They analyzed the nonlinear energy transfer between Fourier modes of the magnetic field. A truncated system of three modes shows an abrupt transfer of energy from the externally driven mode to two new modes, in a process that can be regarded as the building block for a much more complex energy cascade. This energy cascade can efficiently enhance the magnetic dissipation that contributes to coronal heating. The development of a numerical code to study the full energy cascade, by integrating the magnetohydrodynamic equations with boundary conditions appropriate to real footpoint motions, was in progress.

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 computed a coronal field from a magnetogram of active region AR 5747, obtained on 20 October 1989 , and used it to show that current-carrying magnetic field lines tend to form coronal loops with much more uniform cross sections than potential field lines. This offers a possible explanation for the observation that many loops seen in soft X-rays appear to be of remarkably uniform thickness. They also computed an approximation to the coronal magnetic field of AR 6919 (15 November 1991), which produced a well-observed X-class flare.

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