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This report covers the period 1 July 1995 through 30 June 1997.

1. PERSONNEL

Astronomy faculty in the Department of Physics and Astronomy were William G. Bagnuolo, Jr., Douglas R. Gies, William I. Hartkopf, Harold A. McAlister (CHARA Director), H. Richard Miller, Mark A. Shure, Paul J. Wiita (Director of Graduate Studies in Astronomy), and David W. Wingert. Stephen Ridgway continued a half-time appointment as a CHARA visiting scientist and Technical Manager of the CHARA Array project along with his primary appointment as Astronomer at NOAO. Staff scientists and post-doctoral fellows within CHARA were Theo ten Brummelaar, Brian D. Mason, and Laszlo Sturmann. Post-doctoral fellows in extragalactic astronomy were Gang Bao, Damo Nair, and John C. Noble. John W. Wilson was the Coordinator of Laboratories, and Alexandra Land was the CHARA business manager.

Shure joined the Department as an Associate Professor from the University of Hawaii in September 1995; with graduate student Thaller he participated in the NSF Symposium on Graduate Education in Astronomy in Washington, DC (November 1996). Bagnuolo and Hartkopf were promoted to Associate Professor rank in September 1996. ten Brummelaar was promoted to Research Scientist in May 1996. Robert Cadman accepted an appointment as Site Manager for the CHARA Array. Gies acted as Technical Editor for the paper and electronic versions of the Be Star Newsletter (URL http://www.chara.gsu.edu/BeNews/intro.html) for issues 30 (September 1995) and 31 (June 1996). Wiita spent one month as a Visiting Professor at the Indian Institute of Astrophysics (IIA) and the National Center for Radio Astrophysics (NCRA) in India. Mason accepted a position as Astronomer in the astrometry program at the US Naval Observatory.

Our continuing graduate students during this period were Donald J. Barry, Kenneth Guyton, Michael E. Hahula, Jagbir S. Hooda, Minhwan Jang, Liu Ning, John C. Noble, Laura R. Penny, Reed Riddle, Lewis Roberts, Jon Sowers, Michelle L. Thaller, Nils H. Turner, and Xiong Ying. The following students joined the graduate program in this period: Yoon-Jeong Choi, Saswato R. Das, Elizabeth Ferrara, Curtis Goings, Thomas Fallon, James A. Harvin, Amy E. Johnson and Anthony B. Kaye.

Barry was awarded his Ph.D. in December 1995 and joined the University of Texas as the Harlan J. Smith Fellow. Jang joined the faculty of Kyung Hee University in Korea after the award of his Ph.D. in December 1995. Noble remained as a post-doctoral fellow after receiving his Ph.D. in December 1995, then accepted a post-doctoral/lecturer position at Western Kentucky University. Liu received an M.S. in March 1996 and joined the Computer Information Systems department at Georgia State. Penny was awarded her Ph.D. in June 1996, and she then joined the astrophysics group of the University of Montreal as a post-doctoral fellow; she has recently accepted an Assistant Professorship at the College of Charleston.

Long-term visitors included Eiji Kambe (National Defense Acad., Yokosuka, Japan; April 1996 – September 1997) and Rosina Iping (University of Guam; August 1996 – June 1997). Other visitors included Gopal-Krishna (NCRA), Elliot Horch (Yale), Otto Franz (Lowell Obs.), Joel Eaton (Tennessee State), Elizabeth Griffin (Oxford), Marc Buie (Lowell Obs.), Derek Buzasi (Valdosta State), Dany Vanbeveren (Vrije Universiteit Brussel), S. Jeyakumar (NCRA), and Paul Boichat (Nottingham). The University Center in Georgia Visiting Scholars in 1996 and 1997 were Charles Townes (Berkeley) and Stephen Maran (NASA Goddard Space Flight Center), respectively.

2. HARD LABOR CREEK OBSERVATORY

Hard Labor Creek Observatory is operated by Georgia State University and houses the Multi−Telescope Telescope (MTT) built at Georgia State by Bagnuolo, Barry, Gies, and the late Ingemar Furenlid, and the 16′′ ex-KPNO telescope, which was awarded to Georgia State University by the National Science Foundation through a grant to CHARA. The observatory hosted 16 public nights during 1995−97 as part of an agreement with the Georgia Department of Natural Resources which allowed GSU to locate the observatory on the grounds of Hard Labor Creek State Park. Well over 1500 visitors attended these public nights.

The Multi−Telescope Telescope, a 1-m class instrument for high dispersion spectroscopy, has proved to be an effective tool for spectroscopic studies of bright objects. One of the major goals of the instrument was to help separate the composite spectra of binary stars using a tomography algorithm, and major studies have now been completed by Bagnuolo, Gies, Barry and collaborators on the massive binaries Plaskett's star (HD 47129), ι Ori, and 55 UMa (the latter represents the first application of the tomography algorithm to a triple system). The MTT was also used in an international campaign on the Be star λ Eri (organized by R. Hirata and Kambe) and in a UV/optical campaign on the line profile variable B-star, ϵ Per. Kaye, Bagnuolo, D. Hall (Dyer Obs./ Vanderbilt Univ.), and G. Henry (Tennessee St. Univ.) have embarked on a combined spectroscopic (using the MTT) and photometric investigation of the new γ Doradus variable stars. Multiple periodicities were found and are attributed to high-order, low-degree, non-radial, gravity-mode oscillations. Ferrara and Boichat used the MTT to search for molecular bands in Comet Hale-Bopp.

Riddle and Bagnuolo have developed a simpler user interface for the MTT control program, as well as numerous other improvements to facilitate ease of use. Kambe worked

with Bagnuolo on developing plans for another MTT-type telescope and spectrograph to be constructed at the National Defense Academy in Japan. We anticipate new joint spectroscopic programs on short period variables and binary stars where the extended longitudinal coverage will greatly reduce diurnal gaps in observations.

Miller, Nair, Wilson and Ferrara are maintaining a program for monitoring the optical variability of active galactic nuclei (AGN) utilizing the Photometrics CCD camera at the 16″ telescope. The primary focus of the program is to provide extended studies of the microvariability of bright blazars. During the summer of 1997, a highly concentrated effort was made to monitor the major optical outburst of BL Lac. Variations of more than 1.0 mag./day were observed on several occasions. Of particular interest were coordinated optical/EGRET observations of BL Lac which detected a simultaneous flare of BL Lac at both gamma ray and optical wavelengths.

3. CENTER FOR HIGH ANGULAR RESOLUTION ASTRONOMY

3.1 Binary Star Speckle Interferometry

The CHARA speckle program continued its affiliation with Mt. Wilson Observatory; over 6,500 observations were obtained during 11 observing runs on the Hooker 100-in telescope. In addition, a run at CTIO in March 1996 enabled us to complete a duplicity survey of bright O stars (described below) and, in collaboration with T. Henry (CfA) to observe large samples of both chromospherically active and inactive G dwarfs. Chromospheric activity in these stars is a good measure of age: inactive stars (emission levels similar to that of the sun) have ages of a few billion years or more, while the active stars comprise a younger population with ages of a billion years or less. There has been significant debate in recent years about the evolution of multiplicity with age, from nearly 100% of T Tauri stars to only 60% of solar-type stars in the solar neighborhood. Analysis of the survey results for these two identically-chosen samples will allow us to discover if there is any evolution in multiplicity between ages of less than one and a few billion years.

Work on our ongoing series of speckle measurements of binary stars resulted in 7 measurements papers being published in this period. Work also continued on the determination of accurate orbital elements of close visual binaries; elements were published for a total of 57 binary or multiple systems during this period. The primary participants in this effort were Hartkopf, Mason, McAlister, and ten Brummelaar.

Mason published results of a speckle survey of 334 occultation binaries, including 30 systems resolved by speckle for the first time, as well as orbital elements for 12 occultation systems subsequently resolved by speckle through at least a major portion of their orbits.

Collaborations between the CHARA speckle team and several spectroscopists have resulted in combined spectroscopic/astrometric analyses of a number of systems. These coordinated efforts are especially important as they are the primary source of accurate stellar masses, as well as an important method for determining distances to these objects.

Mason, McAlister, and Hartkopf collaborated with E. Griffin (Oxford) and R. Griffin (Cambridge) in combined analyses of three bright binaries, all of which have giant components and all of which were first resolved interferometrically by CHARA about 15 years ago.

A similar collaboration with F. Fekel (Tennessee St. Univ.), C. Scarfe and D. Barlow (Univ. of Victoria, BC), the late A. Duquennoy (Obs. de Genève, Switzerland), and A. Tokovinin (Sternberg Astronomical Inst., Moscow) on the spectroscopic/visual triple HD 202908 allowed us to determine accurate masses and absolute magnitudes for all three solar-type stars in this system. Chromospheric emission, lithium abundance, and projected rotational velocity indicate that this system is quite young, probably about the age of the Hyades cluster.

A combined spectroscopic/astrometric/photometric analysis of the nearby metal-rich solar-type star HR 6697 = McA 50 was carried out by McAlister *et al.*, together with Fekel, P. Ianna (Univ. Virginia), Tokovinin, R. Griffin, and R. Culver (Colorado St. Univ.)

Using speckle data plus spectroscopic measurements in the literature, Mason *et al.* derived an accurate distance, plus component masses and luminosities for another nearby solar-type star, HR 3650 = Fin 347.

Liu *et al.* combined speckle data with tomographically-separated spectra from the MTT in a study of 55 UMa, a system composed of three early-A dwarfs, two of which are probably moderate Am stars. Spectroscopic and astrometric observations of this system are continuing, with the goal of obtaining precise masses and absolute magnitudes for all components.

Mason, Gies, Hartkopf, Bagnuolo, ten Brummelaar, and McAlister completed a speckle interferometric survey of all Galactic O-type stars with $V<8$. The speckle camera can detect binaries in the angular separation range $0\farcs035<\rho<1\farcs5$ with $\Delta m<3$, and they have discovered 15 new binaries among 227 O systems. They have combined the results on visual binaries with a literature survey of the spectroscopic binaries among the sample to investigate the overall binary frequency of the sample and the orbital characteristics of the known binaries. Binaries are common among O stars in clusters and associations ($>59\%$ have a visual or spectroscopic companion) but less so among field, and especially runaway, stars. There are many triple systems among the speckle systems, and they may play a significant role in the ejection of stars from clusters. One such system, HD 193322, was found by McKibben (Oxford College/Emory Univ.), Gies, Fullerton (Univ. Munich), and Bolton (Univ. Toronto) to contain a central 311 d binary in a wide 31 y orbit with a distant star. The binaries in the sample have been investigated to determine the distributions of binary period, mass ratio, eccentricity, and longitude of periastron. Mason, Gies, and Hartkopf have also completed surveys of groups of related stars including southern Be stars, Wolf-Rayet stars, and B-type supergiants.

A major program of speckle observations was carried out in collaboration with O. Franz (Lowell Obs.) at the Lowell

1.8-m from 1982 through 1988, as part of a search for low-mass companions to known binaries. Fu (National Taiwan Normal Univ.), Franz, and CHARA colleagues published the second paper containing results of this effort, including data analyzed by Fu as part of his doctoral research, as well as a similar quantity of data reduced by Mason and Hartkopf. Rereduction of some of the older data, as well as analysis of the entire sample for possible submotions, is ongoing.

McAlister *et al.* published a brief survey for duplicity among white dwarf stars, in which it was determined that the stars comprising GD 319 form an optical pair (and show purely linear relative motion), while HZ 43 is a true binary (composed probably of a WD and a dM star) with a period of order 2100 years.

Roberts *et al.* analyzed 179 observations of 57 asteroids in a search for duplicity; no companions were detected, yielding an upper limit to the size of any possible unseen components within the separation range visible to our equipment.

A quick survey was made of a sample of 116 stars suspected of duplicity in observations with the Hipparcos astrometry satellite. While all previously known binaries falling within our Δm and separation limits were resolved by speckle, we were unable to confirm any of the suspected Hipparcos binaries. Following the recent release of the Hipparcos Catalogue, we are embarking on a major campaign to observe as many of the closer Hipparcos binaries as possible using speckle, with the goals of confirming the Hipparcos discoveries and providing continuing coverage of more rapidly moving systems which may be amenable to later orbital analysis.

Hartkopf continues to maintain the *Double Star Library* on the WWW, containing IAU Commission 26 (Binary and Multiple Stars) circulars, as well as address lists, catalogues, bibliographic data, meeting information, and related web links of interest to the double star community.

3.2 Adaptive Optics Imaging of Binaries

The CHARA adaptive optics (AO) program began in 1995 when, after being awarded a grant by the NSF, ten Brummelaar, Mason, Bagnuolo, Hartkopf, McAlister and Turner used the Starfire Optical Range 1.5 m telescope equipped with laser guide star and AO to measure the differential magnitudes of 10 binary systems in the I and R filters. A total of 8 nights observing time was allocated to the group for these preliminary observations. This group, now including Roberts, continued the program in 1996 and 1997 using the Mount Wilson Institute's (MWI) AO system installed on the Hooker 100 inch telescope. The MWI-AO system uses an unfiltered Shack-Hartmann wavefront sensor, and has only ten reflections in the optical path. These factors allow the system to operate on objects as faint as 12th magnitude. This ties in very well with the CHARA speckle program, which has a similar magnitude limit. So far over 30 binary systems have been observed in the U, B, V, I and R wavebands with some preliminary results having been presented by Roberts *et al.*

Another program the above group currently has underway on the MWI-AO systems is a search for faint companions to local stars. In order to see as faint a companion as possible, many frames of each star are taken. Exposure times were selected to get as many photons as possible without saturating the CCD, and ranged from 0.25 to 5 seconds, depending on the magnitude of the star. These frames were then combined using a shift-and-add routine and the primary image then was removed, allowing faint companion stars to be located in the field. Twenty-seven stars were observed and reduced in this manner. Four stars showed signs of companions, two of which, GJ 738 and GJ 678, were previously known to be binary. This search for faint companions continues and confirmation of those objects already found is planned.

The third program on the MWI-AO system is to use the telescope and AO system as an imaging interferometer. This project was the centerpiece of a successful proposal to MWI and 20 nights observing time have been allocated in 1997. By placing a non-redundant mask in the aperture plane within the AO system the telescope can be used in an interferometric mode. This technique was first used by Michelson on this very telescope, and the combination of AO with aperture masking is hoped to yield much higher resolution data than can obtained with the AO or speckle systems alone. We expect that the AO system will allow much longer integration times than are normally possible with an aperture masking system, with the magnitude limit being determined by the AO detector, and not the size of the sub-aperture used.

3.3 Spectroscopy with the Multi-Telescope Telescope

The operation of the MTT continues to produce significant results. Both hardware and software upgrades have been a major focus of Riddle, Bagnuolo, Kaye, Ferrara, and Kambe. Hardware improvements have included a new thinned CCD chip, a new grating, and a new 15 ft. dome for better wind, light, and vermin shielding. It is planned to upgrade the spectrograph with new filters, optical bench, and temperature control. Software improvements have included a new user interface and recentering algorithms. Current performance is a SNR of 100 per pixel for a 3.0 magnitude star at 600 nm with the 600 g/mm grating ($R \approx 13{,}000$) in 1 second.

Observations have continued in a number of areas. Hot binaries have been observed by Bagnuolo, Barry, Riddle, Gies, and Harvin in a program aimed at reconstructing the individual spectra by a tomography algorithm. Observations have been made in the campaign on the Be star λ Eri and in a UV/optical campaign on the variable B-star ϵ Per, headed by Gies.

Kaye and Bagnuolo, in conjunction with Hall (Dyer Obs. and Vanderbilt Univ.), Henry (Tennessee St. Univ.), and Mantegazza and Zerbi (Osservatorio Astronomico di Brera, Italy) engaged in an in-depth investigation of the newly-discovered γ Doradus variable stars. Both multi-color photometry and high-resolution spectroscopy revealed the presence of no less than three individual periodicities. The length of the periods, in addition to the analysis of the line profile variations reveal the source of the variation to be high-order, low-degree, non-radial, gravity-mode oscillations. These stars are of paramount importance to the field of asteroseis-

mology as they have revealed the first evidence of oscillation in gravitational modes in the lower part of the instability strip. The extraction of asteroseismological information, and therefore an improved understanding of the critical stellar parameters and basic stellar physics, requires a reliable mode identification which is only possible through observations such as these. Additional studies of these variables, including major, international, multi-longitude campaigns are underway.

3.4 The CHARA Array

Ground was broken on 13 July 1996 on Mt. Wilson for construction of the CHARA Array, Georgia State University's five-telescope optical/IR interferometer for submilliarcsecond imaging. Mt. Wilson was selected as the site for the Array on the basis of its documented excellent intrinsic seeing characteristics, its infrastructure, and its relative ease of access from Atlanta. Furthermore, the high spatial resolution programs being carried out on Mt. Wilson by the University of Illinois, the University of California at Berkeley, and the Mount Wilson Institute offer the attractive possibilities of scientific and technical collaborations. These programs, along with the CHARA Array, give Mt. Wilson a special distinction as *the* U.S. site for the development of techniques for high spatial resolution imaging.

Because of the funding schedule, the construction of the Array is necessarily a phased effort. The first phase of construction consisted of the central ''Beam Synthesis Facility,'' a 12,000 ft^2 building comprised of a football field length section to house the variable and fixed components of the optical delay lines and a Beam Combination Laboratory to house the variety of electro-optical subsystems for beam control and combination. The architectural and engineering design of this facility was initiated in the fall of 1995 by R.T. Santos, AIA, Architects, of Pasadena, CA. Sea West Enterprises of San Dimas, CA, was competitively selected as the contractor. This first phase of construction was completed during the summer of 1997.

Terrain and existing structures on Mt. Wilson have challenged us to lay out an array and its required buildings, utilities, and access trails that provide the degree of (U,V)-plane coverage required by our science goals. We believe this has been accomplished with the present design, and we have identified two additional sites for telescopes beyond the five-telescope array presently funded. Georgia State contracted with Sea West for the installation of access trails and underground conduits for utilities and communication lines to the three arms of the Y-shaped array. We anticipate the completion of that work as well as the installation of concrete footings, foundations, and telescope piers for all five telescope enclosures and their associated electronics bunkers by the end of 1997.

Fabrication of the mounts and optics for the five 1-m aperture alt-az collecting telescopes is well underway. The primary (Sitall) and secondary (Zerodur) mirrors, which together comprise a system of confocal paraboloids, are being fabricated at the Leningrad Optical Mechanical Works (LOMO) in St. Petersburg, Russia, under a purchase agreement with Telescope Engineering Company of Lakewood, CO. The first matched primary/secondary set, which has been fabricated and tested in parallel, has been delivered to Atlanta. LOMO has met or exceeded all manufacturing specifications. The telescope mounts are being fabricated in Tucson by M3 Engineering and Technology Corporation following the detailed design developed for CHARA by Larry Barr, also of Tucson. We anticipate that the first telescope will be available for delivery to the site upon completion of its telescope enclosure by mid-1998.

The optical delay lines are being built in collaboration with the interferometry group at JPL. Detailed design of the mechanical parts was provided to CHARA by JPL, and those parts are being fabricated in the Physics and Astronomy shops at Georgia State, predominantly by Charles Hopper, using a Bridgeport NC machine purchased by CHARA. JPL will integrate and align those parts and is developing the control hardware and software. On-site installation and alignment of the rail system will begin in the fall of 1997.

We anticipate that all required subsystems will be on Mt. Wilson to enable ''first fringe'' to occur by the end of 1998. Extensive details of these and other subsystems for the CHARA Array, including all related technical documents, are found on the CHARA Web site (http://www.chara.gsu.edu/chara.html). Technical reports written during the time frame covered by the observatory report are included in the Publications section below. The CHARA Array is funded jointly by Georgia State University and the National Science Foundation. The primary faculty, staff, and student participants in this project are Bagnuolo, ten Brummelaar, Hartkopf, Harvin, Hopper, Land, McAlister, Ridgway, Roberts, Shure, Sturmann, and Turner.

4. STELLAR ASTRONOMY

Penny completed her dissertation on the reconstruction of the individual spectra of the components of massive binary systems using the tomography algorithm. She applied the method to IUE high-dispersion spectra of 6 O-type binary systems in open clusters, and analysis of the reconstructed spectra provides the parameters to place the individual components in the H-R diagram. Four of the systems have already or are currently undergoing Case A Roche lobe overflow, and several appear overluminous for their mass. Two stars which have ceased Roche lobe overflow now appear to lie on evolutionary tracks corresponding to their new mass. Penny, Gies, and Bagnuolo plan to extend the tomographic analysis to some three dozen massive binaries with IUE coverage with the eventual aim of creating an IUE atlas of reconstructed spectra. Penny and Gies are also investigating the Hipparcos light curves of several O-type binaries, including HD 152248.

Bagnuolo, Barry, Riddle, Harvin, Kaye, and Gies (with G. Koenigsberger, UNAM) are searching for hot binaries similar to Plaskett's star (HD 47129) with evidence of mass exchange and chemical composition differences.

Riddle is performing much of his doctoral research on solar seismology at the National Solar Obs., Tucson. He is investigating the use of algorithms originally developed for geology in tracking earthquake propagation in the study of the solar interior and atmosphere.

Thaller and Gies are studying the Hα spectra of massive binaries to explore the orbital phase-related variations and to search for evidence of colliding winds. Thaller has obtained a large number of spectra from Kitt Peak National Observatory and Mount Stromlo Observatory (Canberra, Australia), and additional targets have been observed in collaboration with Kaper, Fullerton, and Baade (ESO). The work has demonstrated that Hα emission is more commonly found in close binaries than single stars (especially among those binaries containing giants and supergiants, i.e., stars with vigorous stellar winds). Detailed studies of individual systems, such as HD 149404 and HD 163181, are now underway.

Gies, Hahula, Kaye, and collaborators are studying the rapid profile variations found in O- and B-type stars. The periodic component of variability is probably the result of photospheric nonradial pulsations (NRP), and these oscillations may promote episodic mass loss in the rapidly rotating Be stars. Thaller obtained time series of spectra of high quality of the Be star α Eri in September 1995 from Mount Stromlo Observatory, and these spectra are being analyzed by Guyton. Guyton has developed a surface integration code for rapidly rotating stars, and will use this to search for latitude-dependent line formation and to help determine how close stars can be to the critical rotation rate. Gies, Kambe, and Guyton will use the NRP code by Townsend (Univ. College London) to help identify modes in α Eri, λ Eri, and other Be stars.

Shure has begun an imaging survey of young star regions which are associated with CO outflows identified in a single-beam radio survey of low temperature far-infrared point sources. He has been using the near-IR camera ''NSFCAM'' at the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii. The goal of this survey is to study the formation of stars resulting from the collapse of molecular clouds induced by shocks from adjacent regions of ionized gas, which in turn were created by the recent formation of massive stars. Lynds Dark Nebula 1206 is an example of just such a source, embedded within a dense gas ''globule'' which is immersed in the ionized gas of an adjacent optical H II region Sharpless 145.

Though still in its early stages, the survey has already resulted in the discovery of a near-IR (optically invisible) nebula embedded in a dark cloud at the edge of the H II region Sharpless 302. The dark cloud is likely the remnant of a dense core in the same molecular cloud which gave birth to the massive O and B stars which ionize the H II region. Flux at far-infrared wavelengths (> 60 μm) dominates the output of the nearby point source IRAS 07299-1651, which was discovered by IRAS. Its flux implies a total luminosity roughly 10,000 times that of our own Sun. This source probably represents the early stages in the formation of a massive B-type star. Images at 4.8 μm show a point source near the center, in the reddest part of the nebula, suggesting a central source hidden by a nearly edge-on disk. Images in the hydrogen Brackett-γ recombination line (at 2.17 μm) show no signs of local ionized gas. Perhaps this star has been caught at a very early stage, before it has generated a sizable amount of ionizing radiation. The brightnesses at 1.3 and 3.6 cm measured recently by E. Churchwell (Univ. Wisconsin) with the VLA agree with this interpretation. These fluxes are close to those predicted by thermal radiation from cool dust at a temperature of 60 K with little emission from ionized gas. The nebula is surrounded by a cluster of much less luminous point sources, probably lower mass stars, as well as slightly extended clumps, which may be shocked Herbig-Haro objects.

In collaboration with T. Greene (Univ. Hawaii) and C. Lada (CfA), Shure undertook sub-millimeter observations with the James Clerk Maxwell 15-m telescope. The purpose of this work was to map the molecular outflow of IRAS 07299-1651, to determine whether it is aligned with the observed near-IR bipolar axis. If so, this would have important implications for the timing between the appearance of bipolar outflows and the development of ionizing radiation by the star. The results clearly show red- and blue-shifted lobes of molecular CO emission. The directions of this outflow match quite well with the predictions of an edge-on disk; the less-reddened lobe of the near-IR nebula coincides with the blue-shifted CO flow, just as expected for an outflow lobe tilted toward the observer. High-resolution imaging of similar protostars will be undertaken with the CHARA Array at 2 μm, to provide a direct test for the existence of nearly edge-on disks which would be unresolved by traditional imaging.

Shure is also collaborating with M. Ressler (JPL), who has built a 10-20 μm 128×128 array camera. They used NSFCAM at the NASA IRTF to survey a sample of the coldest known young stars in search of signs of outflow. The purpose of this work is to determine how soon after formation the youngest (i.e., coldest) protostars experience outflows. In several of these sources, they have already discovered extended emission which may indicate outflows. One of them, IRAS 19262+1924, shows extended structure at 3.8 μm which is not visible at 2.2 μm, implying a source deeply embedded in an obscuring dust cloud. Later they used the JPL mid-infrared camera at the IRTF to find the central sources in survey sources which are so extincted that the illumination source is not visible even in the near-IR (1-5 μm). These may represent some of the youngest stellar objects ever seen.

Shure has proposed building a ''Near-Infrared Camera for High-Resolution Studies of Star Formation.'' This camera would be used for lunar occultations, speckle imaging, and Array fringe detection at the HLCO 16-in, the Mt. Wilson 2.5-m, and the CHARA Array to resolve circumstellar structures and nearby companions to newly-formed stars.

Miller, Nair, Wilson and Ferrara have obtained high-time resolution photometry of the cataclysmic variable star, PG 2337+12 utilizing the Photometrics CCD camera on the 16-in telescope. Although variations have been detected on timescales ranging from minutes to days, no periodic modulation of these variations has been found.

Recent analyses of Ginga observations have shown that temporal variability is strongly coherent between different X-ray energies (channels) in some black hole sources, e.g., the galactic black hole candidates, GX 339−4 and Cygnus X-1. Most of the current theoretical models for the X-ray variability are incapable of producing such coherence. Bao and Wiita, along with M. Abramowicz (Chalmers Inst. Tech.

and Göteborg Univ.) and S. Larsson (Stockholm Obs.) have shown that the bright spot irregularities on accretion disks can naturally account for the observed coherence.

5. EXTRAGALACTIC ASTRONOMY

Miller and co-workers continue their program investigating the very rapid low amplitude variations in the optical and ultraviolet portions of the electromagnetic emission from active galactic nuclei (AGN). This group was the first to show that microvariability was both real and common, at least for the blazar class of AGN (BL Lacertae objects and Optically Violently Variable Quasars). Miller, M. Carini (Western Kentucky U.) and Noble continue their detailed program of studying the variability for individual blazars on timescales of minutes to decades. The most recent study published was for OI 090.4, with similar studies of 3C 371 and 3C 66A currently in preparation.

Miller and Noble have investigated samples of X-ray selected versus radio selected blazars and have found that there are an anomalous number of large amplitude microvariations found for the radio selected blazars that are not present in the observed variations for the X-ray selected blazars. This strongly supports the hypothesis that the radio selected blazars are more highly beamed and have higher Lorentz factors than do the X-ray selected blazars.

Miller and co-workers have also embarked upon a program to study the character of the microvariability for a large sample of EGRET blazars. Preliminary results suggest that large amplitude variations are present, independent of whether the blazar is in a flaring state or in a quiescent state. Miller and co-workers are also studying a set of high-luminosity blazars and contrasting the findings for these objects with a sample of low-luminosity blazars. In addition, a major effort is currently underway to intensively study the TeV detected blazars, and to see if additional evidence can be found that would link these objects to the X-ray selected blazars rather than the radio-selected blazars.

Miller and co-workers have participated in a number of multifrequency monitoring programs to study blazars from gamma-rays to radio wavelengths. The objects studied have included PKS 2155−304, 3C454.3, 3C 279, PKS 1622 −297, PKS 0528+13, ON 231, 2A 1219+305, Mkn 421, Mkn 501, and PKS 1510−089. The microvariability for the Seyfert galaxy, Akn 120, is also being studied. Observations have been proposed for RXTE coordinated with groundbased optical observations to examine the variability of this AGN on timescales ranging from seconds to months utilizing telescopes around the earth to obtain 24-hour coverage.

Accretion disks around massive black holes in AGN are presumably clumpy in their inner regions because of various instabilities; Bao, Wiita, and Xiong are studying several effects related to accretion disk variability.

The bright spots within this clumpy matter should have some intrinsic polarization, produced either by electron scattering or synchrotron emission. Rapid variability in both the percentage of the polarization and the angle of the polarization plane is caused largely by the strong gravitational field of the black hole, i.e., the gravitational bending effect, and to some extent, by relativistic aberration, as shown by Bao, Wiita and P. Hadrava (Astronomical Inst., Czech Academy of Sciences). The most remarkable feature of the variability is that it is frequency-dependent, in the sense that the polarization variability amplitude is larger at higher energies. Its observance in future X-ray satellite missions could serve as a signature of black holes. Bao, Hadrava, Wiita, and Xiong have considered more detailed radiation transfer formalism, synchrotron flares, and different angular distributions for the emissivity. This type of variability is only important in the harder X-ray bands for Seyfert galaxies, although it may be detectable on longer timescales at lower energies for quasars and may also be relevant in stellar X-ray binaries.

The idea that accretion disks may be in state of Self-Organized Criticality (SOC), where a physical system lacks characteristic length- and time-scales, was proposed a few years ago. Xiong and Wiita have recently examined a wide range of variants on this SOC picture, by changing the: inner and outer radii of the disk; initial deviations from critical density; accretion rate; amount of mass dumped when a zone went over the limit; amount of differential rotation; and sideways and outward (as well as inward) diffusion. Their key conclusion is that substantial variations in the predicted slopes of power spectra densities occur, mainly depending on the ratio of the inner to outer radii of the unstable region. With Bao and Abramowicz, Xiong and Wiita are extending these calculations to incorporate relativistic effects.

Bao, Wiita, and Hadrava have improved upon the standard reflection models for the EUV and X-ray spectra of AGN by computing the composite spectrum of the original disk, plus a primary X-ray power-law as well as the reflected emission from the disk. All special and general relativistic effects are considered in a Schwarzschild geometry. The strength, shape and broadening of the reflected spectrum are diagnostics of the geometry of the X-ray source and the viewing angle. Thus the spectral shape may allow the locating of the primary X-ray source in either the base of a jet or in a disk corona. They are currently investigating spectral variability produced by changes in the location of the source of the power-law X-ray component.

Jang and Miller have studied a sample of 30 quasars selected from the PG-quasar survey. This set contains both radio-quiet as well as radio-loud quasars. A total of 11 of the objects studied were radio-loud, and the remaining 19 were radio-quiet. For the 11 radio-loud objects, 9 exhibited clear evidence of microvariations, which is similar to the results of other studies. In contrast with these results, only 2 out of 19 objects in the radio-quiet sample exhibited microvariability, in agreement with the work discussed in the next paragraph. These results strongly suggest that most microvariability is associated with radio-loud AGN. This association is consistent with the models based on jets being primarily responsible for observed variations. However, it is believed that most AGN have accretion disks around their central regions. Thus if the AGN are viewed close to face-on, as unified schemes indicate should be the case for both the radio-quiet QSOs and radio-loud QSOs, the intrinsic variations in the disk are expected to be visible to the observer. Our results show a clear contrast between these two classes. It could imply that the strengths of disturbances, if they are present

on the accretion disks, are so low as not to be detected in most cases, and the weak disk disturbances would be swamped by jet-based disturbances for radio-loud AGN.

Wiita collaborates with R. Sagar (Uttar Pradesh State Obs., India) and Gopal-Krishna (NCRA) on observations of rapid variability in radio quiet quasars. They have observed 15 such objects over the course of 6 observing seasons. The most recent reduced data shows moderately strong evidence for microvariability in the radio-quiet QSOs 0946+301 and 1444+408; weaker evidence is found for 0117+213. Additional observations of these and other QSOs could provide a powerful means of discriminating among various theoretical mechanisms proposed for the energy source and, in particular, the origin of optical microvariability in active galactic nuclei. Finally, by comparing the latest observations with those made $\sim$1 year earlier, long-term variability (5 to 15%) is detected for 4 of the QSOs.

Three-dimensional numerical simulations of light supersonic hydrodynamic jets have been performed by Hooda and Wiita. Extragalactic jets emerge through power-law atmospheres (ISM) of their host galaxies and then cross into hotter, but less dense, intracluster media (ICM). They have computed 7 low-resolution and 8 medium-resolution simulations, with different jet velocities, jet densities, extensions of the ISM (along the jet's axis), and inclination angles of the ISM/ICM interface. The shear layer between the jet and the shock-processed gas is affected by non-linear hydrodynamical instabilities. Complex patterns of asymmetric vortex rings and superimposed streamwise vortex tubes arise in the cocoon, while internal shocks form in the jet. The low Mach number jets have higher growth rates of instabilities in comparison with higher Mach number jets and the Mach disks or ''working surfaces'' at the heads of the slower jets break down. Greater tilts of the interface induce more wiggling and ribboning of the jets but none of these simulations evince substantial jet bending. Hooda has performed analytical studies of the growth of various perturbations in slab and cylindrical jets. He has improved upon earlier calculations by including additional modes and carefully considering their interactions at the jet/cocoon interface.

Gopal-Krishna, Hooda, and Wiita used published VLA maps of high luminosity, steep-spectrum radio quasars showing prominent kiloparsec-scale one-sided jets, but faint hotspots (i.e., weak-headed quasars) to call into question the common perception that the mechanism leading to such unusual morphologies is the strong dissipation of the jet's power through a vigorous entrainment of thermal gas by the initially relativistic jet. Combining statistical arguments with results from numerical simulations, they suggest that the anomalous weakness of the heads of the jets is probably linked to the weakening of the Mach disk, following the onset of decollimation of the jet's working surface as its forward motion slows down to nearly subsonic speed.

A new explanation was proposed by Gopal-Krishna and Wiita for the striking correlation that in powerful radio galaxies the brighter [O II] λ3727 line emission is nearly always found on the side of the (shorter) radio lobe which is closer to the nucleus. Instead of the conventional interpretation where the above result is understood by postulating a large-scale density asymmetry about the parent elliptical galaxy, they argued that the side of the longer lobe is marked by a greater accumulation of dust, which leads to an increased attenuation of blue/UV photons in that region. This dust enrichment is caused by the motion of the galaxy.

Bao and Wiita found that gravitational bending and lensing plays a vital role in what is observed when the jet direction makes a very small angle with the line of sight. Emission from the receding component can then be greatly magnified with respect to the approaching component. Of course, the approaching component is strengthened, and the receding one weakened, by the well-known special relativistic Doppler effects. The full formula is significantly different from the one considering only Doppler effects when the angle between the line of sight and the jet is small ($i<10°$). Under rare ($i\sim1°$) circumstances the two effects can nearly cancel, thus rendering the receding component (counterjet) visible. This model predicts sub-luminal motion of the jet and relatively more variation in the counterjet, and slightly modifies the limits derived for NGC 1275 jet kinematics.

6. SPACE BASED ASTROPHYSICS

Miller served as the Co-Mission Scientist (with R. Polidan of NASA/GSFC) for the joint NASA/DARA Space Shuttle–based mission, ORFEUS (Orbiting and Retrievable Far and Extreme UV Spectrograph) which flew a second time in November 1996. ORFEUS is a 1-m German–built telescope which is mounted on the free–flying space platform, ASTROSPAS. Far and extreme ultraviolet spectrographs are mounted on the telescope providing a spectral coverage from 400–1200 Å. This mission provides an early, limited look at the 900–1200 Å spectral region which will be investigated by FUSE.

Gies, Bagnuolo, Ferrara, Kaye, Thaller, Penny, and Peters (Univ. Southern California) have obtained HST/ GHRS spectra of the Be binary ϕ Per in several UV regions that show clearly for the first time the spectral signature of the faint remnant companion, the stripped-down remains of the mass loser in this binary. They derive a double-lined solution for the radial velocity curve which yields masses of 9.3 ± 0.3 $M_\odot$ and 1.14 ± 0.04 $M_\odot$ for the Be star and companion, respectively. A Doppler tomographic reconstruction of the secondary spectrum shows a rich spectrum dominated by sharp Fe IV and Fe V lines which indicate it is a hot subdwarf O-star, the brightest such object in the sky (hitherto lost in the glare of the bright Be star). The spectrum of the Be primary appears normal for a very rapidly rotating early B-type star, but the star is probably overluminous for its mass (perhaps due to accretion induced mixing). The observations demonstrate that at least some Be stars are formed by mass transfer in close binaries.

Gies, Kambe, and collaborators obtained continuous UV spectroscopy of the line profile variable B-star, ϵ Per, over a 5 day interval in January 1996 with IUE (selected as a ''key'' project in the final year of IUE operation). Complementary ground-based spectroscopy was obtained at the same time with the GSU MTT. IUE high dispersion spectra were generally regarded as too noisy to be useful for studying the subtle profile variations associated with nonradial

pulsations, but Gies and collaborators have found that the variations can be extracted from cross-correlating the individual spectra with that of a sharp-lined B-star. The long time series obtained by IUE offers an unprecedented opportunity to study the rapid variations without the complications introduced by diurnal gaps in the sampling and to search for pulsation induced mass loss in the stellar wind lines. Howarth (Univ. College London) and collaborators (including Gies) have applied similar cross-correlation techniques to IUE spectra of the B-supergiant, HD 64760, and the runaway O star, HD 93521.

Gies, Mason, Hartkopf and collaborators are continuing a multi-year project with the Fine Guidance Sensors aboard HST to obtain astrometric measurements of the O star binary 15 Monocerotis. This binary is now close to periastron in its 24-yr orbit, and the angular separation is too small for resolution with the CHARA speckle camera. A series of spectra for radial velocity measurements to improve the orbit have been taken by Bagnuolo and collaborators. Continued astrometric and spectroscopic observations of the system will lead to a combined orbital solution and, hence, masses and a distance for this important massive binary.

Miller and collaborators are planning to propose to NASA for an extended duration mission which will provide the capability of obtaining simultaneous optical, FUV, and X-ray monitoring for a number of variable AGN. The goal of this mission would be to obtain continuous observations of a single object for a period of up to 3 months with a time resolution of a few seconds at all three wavelengths. The duration of this mission is expected to be about 3 years.

Additional information on the astronomy research program can be found at URL http://www.chara.gsu.edu

7. SUPPORT

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