PALOMAR OBSERVATORY

ANNUAL REPORT

1993

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FOREWORD

The telescopes of the Palomar Observatory, the 200-inch Hale Telescope, the 48-inch Oschin Telescope, the 60-inch reflector and the 18-inch Schmidt telescope, are used by researchers from the California Institute of Technology, Cornell University and the Carnegie Institution of Washington to conduct scientific studies over a broad range of astronomical interest. Each year, the principal investigators, and their collaborators, report on the results achieved using data obtained at Palomar. The articles collected in this booklet are drawn from those reports.

Together, they illustrate the wide scope of research supported by the Palomar instruments and underscore the fact that, as a result of our efforts to incorporate the newest technological techniques into our equipment, the Palomar telescopes remain among the most powerful astronomical instruments in the world.

Gerry Neugebauer
Director

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COSMIC

The Carnegie Observatories Spectrograph and Imaging Camera

Alan Dressler

The Observatories of the Carnegie Institution of Washington

Subject: Instrumentation

In December, 1993, after an intensive year of building and planning, the COSMIC (Carnegie Observatories Spectrograph and Imaging Camera) instrument for the prime focus of the 200-inch Hale Telescope made its first spectroscopic observations.

The instrument mounting base of COSMIC, including filter wheel, shutter, and guide camera, have served as the basis for a wide-field imaging camera since December, 1991, providing a 9.5' x 9.5' field with a scale of 0.28"/pixel, a field of the same size as the 4-Shooter Cassegrain instrument but with greater throughput and higher resolution. In late 1992 optical designs were completed by Harland Epps of U.C. Santa Cruz for a f/3.52 collimator and f/2.35 camera that would reimage a factor of 1.4 and, with its 3.50-inch beam, allow low-to-moderate spectroscopy with a grism for multiple objects spread over a 13 arcminute field.
A successful proposal was made to the National Science Foundation to provide matching funds for the construction of the spectrograph.

The collimator and camera were challenging optics (two moderate aspherics in both the collimator and the camera) but of a type that were becoming routinely produced at the Lick Optical Shop; this and the close association of the Lick Shop with Dr. Epps made them the obvious choice to supply the lenses. With the focused attention of the Lick Shop and the support of Epps and U.C. Observatories Director Joe Miller, the optics were completed in mid-November. By June, 1993, Bill Kells had completed the mechanical design, checked by finite element analysis, of the tower structure that would support the optics, an aperture wheel holding six slit assemblies, and a four-position grism wheel. Fabrication of the tower, the aperture and grism wheels and associated robotics, and the complex cells for the optics, took place in the Carnegie Observatories machine shop during the Summer and Fall of 1993, under the direction of Pilar Ramirez. The implementing of these new robotic functions was anticipated in the original electronic, firmware, and software design, and so it proceeded very smoothly, with firmware additions provided by Dave Carr.

We also updated the computer system that operates COSMIC, replacing an outdated SUN 386i with a combination Sparc IPX + 486 pc. This allows the user to deal quickly and easily with the 2048 x 2048 pictures COSMIC delivers, even while the instrument is taking or reading out data, a vast improvement over the previous system. The new software was provided by Anand Sivaramakrisnan with help from David Murphy.

We took this new spectrograph and data system to Palomar on December 14, 1993, and remarkably, had it installed and tolerably well aligned and focused for the first night's observing. We took pictures in the reimaging mode (covering an area of 13 arcminutes diameter at 0.39"/pixel) and achieved, on that first night, images as good as 0.8" FWHM, apparently limited by the seeing. (The theoretical limit on the image size should be about 0.6"; the new collimator and camera were designed to degrade to a negligible degree the optimum performance of the 200-inch plus Wynne corrector.) The optics were run used uncoated and with one asphere that was discovered to need reworking, but ghost images were minimal and any degradation of the imaging quality was not obvious at the telescope. (This asphere has subsequently been refigured and all the lenses have been sent out for anti-reflection coatings, in preparation for our next run in February, 1994.)

In subsequent nights of the December run we took multislit spectra of galaxies in distant clusters that I have studied with HST. Ian Smail and I had prepared photographic multislit masks containing typically 35 objects of magnitude $r = 22$ in clusters at redshift $z = 0.4$. We used the first grism of our set, a 300 l/mm that produces a 3.3 Å/pixel scale. With slits of width ~1.6", we obtained spectral resolutions of about 14 Å; considerably higher resolutions are possible with narrower slits and higher dispersion grisms, but this is well suited for taking spectra of distant galaxies. The 300 line/mm grism provides a full spectral range of 3650-9000 Å for objects spread over a 4' x 13' area.

The December commissioning run uncovered a number of small problems, of course, but we did have a working system and were able to collect useful imaging and spectroscopic data. We expect that routine observations by other observers will follow our next run in February, 1994.

Figure Captions

Fig 1 False color image of NGC 891 from a 200 second exposure in red light (r-band). NGC 891, a spiral galaxy (type Sb) similar to the Milky Way, is a disk system seen on-edge. The dark band is interstellar dust in silhouette against the background of stars in the galaxy. The vertical streaks at the bright stars are artifacts of the CCD detector.

Fig 2 Spectra of 32 individual galaxies (magnitude range 20.0 to 21.5) in the cluster 0939+47 at a redshift of 0.40 from a 5000 second exposure. Each vertical strip is the spectrum from 4000Å (top) to 9500Å (bottom) of a small region of the sky containing a galaxy in the cluster. The brighter vertical line is the galaxy spectrum, the rest is the sky spectrum which will be subtracted from the data. The individual bright points are due to cosmic rays striking the CCD detector during the exposure.

FIG 1 DRESSLER

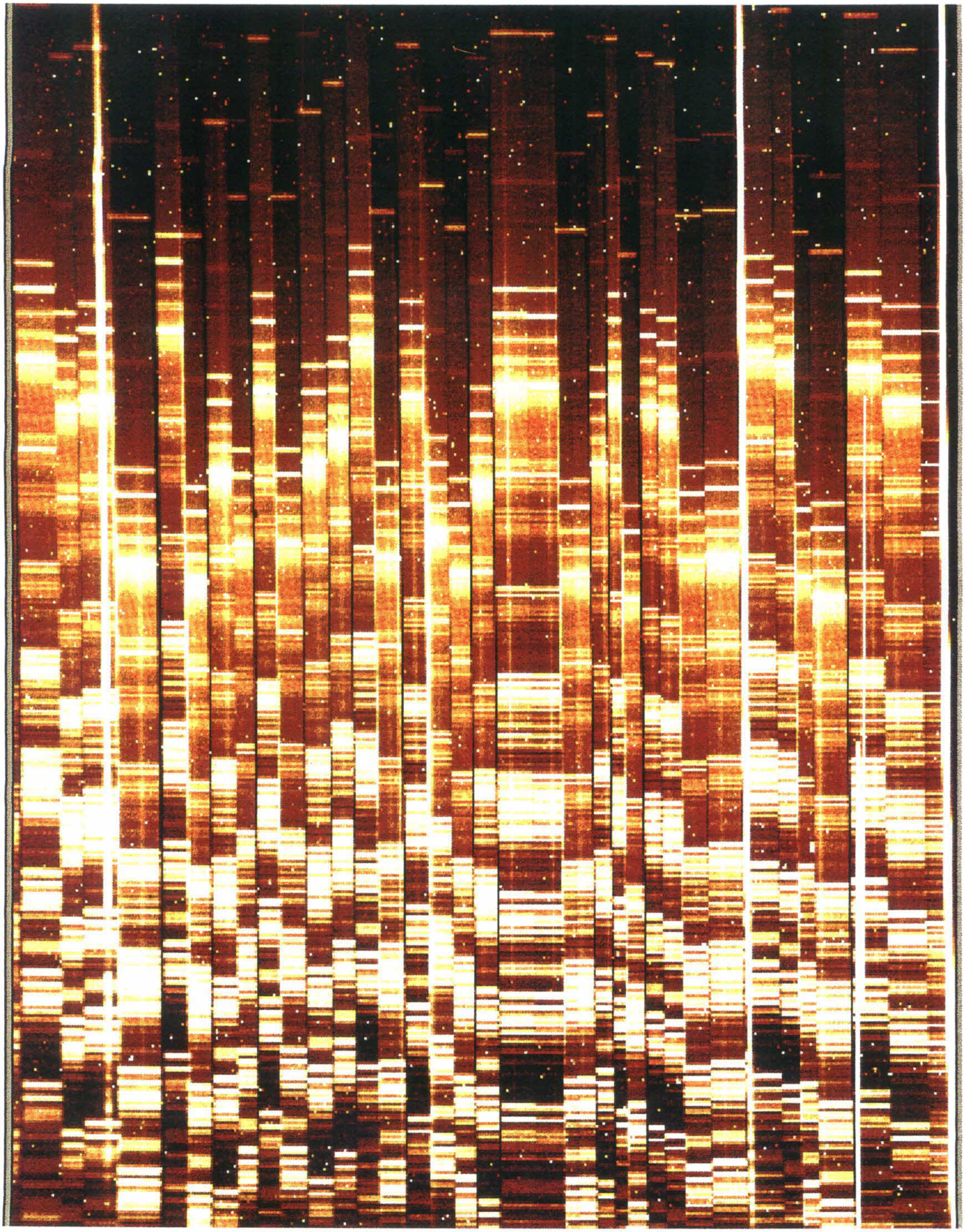

FIG 2 DRESSLER

Recent CCD Developments at Palomar Observatory

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Co-Investigators: William Douglas, Arsham Dingizian,
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Subject Heading: Instrumentation

The past twelve months have witnessed the introduction of three new CCD (Charge Coupled Device: very efficient, low noise, silicon detector arrays for low light level optical imaging applications) chips at Palomar Observatory. These new detectors have dramatically increased the sensitivity of a number of the optical instruments in widespread use at the Observatory. Two more new CCD cameras are about to be introduced into service, and we await the delivery of a third new device. This contribution will describe the performance of the three new CCD chips now in service as well as our immediate plans for the three more soon to follow.

The first upgrade to be performed was to CCD9, part of the dedicated camera for the P60 echelle spectrograph (McCarthy, 1988). The Texas Instruments (T.I.) 800×800 CCD array of 15 μm pixels in this camera was replaced by one of identical size and format, but to which an anti-reflection (AR) coating of Hafnium Oxide (HfO_2) had been applied. By reducing the percentage of incident light lost to reflection (silicon has a high index of refraction in the visible region of the spectrum), the AR-coating increased the Q.E. (quantum efficiency, i.e., the fraction of the incident photons which are detected by the CCD) of CCD9 from 55% to 85% peak, an increase of $1.55\times$ in the net sensitivity of the P60 echelle spectrograph (from 11% to 17% peak). The improvement was better still in the blue part of the spectrum, where the former CCD9 chip had poor sensitivity.

Subsequently, the T.I. 800×800 CCD retired from the P60 echelle spectrograph camera was AR-coated with a red-optimized layer of HfO_2, and re-installed in CCD2, the f/1.0 Schmidt camera on the red side of the P200 Cassegrain Double Spectrograph (Oke and Gunn, 1982). Besides increasing the sensitivity of this camera, the new CCD chip was much better cosmetically, and along with the CCD chip upgrade the associated CCD2 electronics package was overhauled (vastly improving the low signal level performance by reducing the vertical smearing of charge experienced with the earlier generation of electronics). A new problem has arisen, however, since the new CCD is not nearly as flat as the ealier chip and serious focus variations now exist in the fast f/1.0 camera focal plane. We are still in the process of exploring possible remedies to this.

The third new CCD made available to the users of Palomar Observatory has been a thinned and AR-coated Tektronix (TEK) 2048 × 2048 CCD array of 24 μm pixels (a pair of thin TEK1024 chips, CCD15 and CCD16, were introduced the year before). The new TEK2048 chip, actually an "electrical sample" grade device having a small number of column defects and an on-chip amplifier readout noise too high to meet Tektronix's "science grade" or "engineering grade" specification, is housed currently in camera number CCD13. Note that poor noise performance is a disadvantage for spectroscopy and very narrow band imaging, but it is not generally a limitation in practice for broad-band imaging applications, while the large field of view recorded by the big CCD chip is a very definite advantage.

We currently await delivery of a "science grade 1" TEK2048 chip, which will replace the existing electrical grade device in CCD13 when it is received. Meanwhile we are constructing a new Dewar, CCD18, to house the electrical sample which we expect to still be in demand for broad-band imaging work, especially at the 60-inch telescope. The low noise, "science grade" array CCD13 will be devoted primarily to the Norris, East Arm Echelle, and Coudé spectrographs on the 200-inch telescope.

Soon to be introduced into service on the blue side of the P200 Double Spectrograph will be an "engineering grade" TEK1024 CCD in camera CCD14, noteworthy for its high quantum efficiency at 4000 Å (40%) compared to the other TEK1024 CCDs we have tested. Installation of this chip into CCD14 has until recently been on hold pending delivery of custom fused silica optics for the Dewar window (a negative meniscus) and a biconvex field flattener lens, both designed to minimize optical aberrations over the relatively large (24 mm square) detector array. The fully assembled system is now undergoing lab tests, and should go into service soon.

Finally, we shall soon begin testing of CCD17, which contains a Loral CRAF-Cassini 1024 × 1024 CCD array of 12 μm pixels for dedicated use on the Shack-Hartmann interferometer at the prime focus of the 200-inch, to be used for test and adjustment of the primary mirror supports. The Shack-Hartmann interferometer, developed by Gary Chanan at U.C. Irvine, is along with CCD17 part of a concerted effort by Palomar Observatory to restore the mirror supports' performance (and thereby the telescope's optical performance) to the original design specificiations, and likely even surpass them. CCD17 will be unique also in that it will use thermo-electric coolers (TECs) to regulate the CCD temperature at a setpoint at or below $-40°$ C, rather than use liquid nitrogen (LN_2) to cool to between $-90°$ C and $-130°$C. A CCD design and clocking scheme known as MPP (multi-pinned phase) drastically reduces the CCD's inherent (thermally-generated) dark current and so allows the chip to operate satisfactorily at temperatures as warm as $-40°$ C.

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The Second Palomar Sky Survey

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Subject Heading : Instrumentation

The second Palomar Sky Survey (POSS II) is a photographic survey of the entire northern celestial hemisphere. Like the original sky survey (POSS I), carried out between 1949 and 1957, the plates are being taken on the 48-inch Oschin telescope. Since the original survey, there have been many improvements in the quality and sensitivity of photographic emulsions, and the new survey extends 2.5 magnitudes (or nearly 10 times) fainter in the blue than the old POSS I plates. Besides the blue survey (covering a wavelength range of $\lambda\lambda 3800 - 5500 \mathring{A}$), we are also taking plates in the red ($\lambda\lambda 6100 - 6900 \mathring{A}$) and near-infrared ($\lambda\lambda 7700 - 9000 \mathring{A}$). Combined with the southern surveys by the UK Schmidt telescope in New South Wales, Australia, these provide a deep reference catalogue covering the entire sky.

Each individual Schmidt plate covers an area of 6.5 × 6.5 degrees on the sky, although the unvignetted field (i.e. the region where the full 48-inch aperture in visible) is only 3^o in radius. To allow for sufficient overlap between adjacent fields, the POSS II plates are being taken on a grid of points with 5^o spacings. This divides the northern hemisphere into 894 fields - hence the full survey will comprise 2682 plates. During the past year (Oct 1, 1992 to Sep 30, 1993) we obtained 350 plates, of which 294 (or 84 %) are of sufficient quality to be included in the final survey. In total, we now have accepted plates for 626 fields in the blue (70 %), 689 in the red (77 %) and 279 (31 %) in the near-infrared. Based on the current progress, we expect to finish (at the 99 % level) the red and blue surveys by late 1996, while the entire project should be completed by the end of 1997.

POSS I was copied to paper and glass by the Caltech Graphic Arts facility, and has proved an invaluable tool for many astronomical projects worldwide. In an effort to make POSS II available on a similarly wide scale, Caltech has entered into an agreement with the European Southern Observatory whereby ESO Photolabs are copying the new survey onto both film and glass. So far more than 500 plates have been sent to ESO for copying, and some 300 film and 180 glass copies have been issued. In addition, an agreement has been reached with the Space Telescope Science Institute concerning the digitisation of the survey plates using the PDS machines at that institution. The initial plate scans have been made and the Caltech side of the operations is being co-ordinated by Djorgovski. Finally, a team of astronomers (headed by D. Monet) at the U.S. Naval Observatory is also developing a plate-scanning machine which will be optimised for accurate astrometric measurements. This group will also scan the survey plates and, in addition, a series of short-exposure (3 minute) unhypered IIIaJ plates which will tie together the faint, radio-star astrometric reference frame and the brighter fundamental reference stars.

[1] The Sky Survey team includes : C. Brewer, R.J. Brucato, D. Mendenhall, J.R. Mould, J. Mueller, G. Neugebauer, J. Phinney, W.L.W. Sargent and R. Thicksten

A Flexible Speckle Reimaging System for the Hale Telescope

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Subject Heading: Instrumentation

Speckle interferometry is a means of achieving the ultimate angular resolution possible of a large ground based telescope. When doing direct imaging, atmospheric turbulence limits the detail we can observe on astronomical objects. However, by taking very short exposures at high magnifications, and applying extensive computer processing, we can extract from our images detail up to the theoretical limit of the 200 inch telescope. Typically, this is a factor of ten improvement over what we can resolve using direct imaging. To do this high resolution imaging it is necessary to set the angular distance on the sky seen by each pixel on our detector, or pixel scale, to a small value. In the past, we accomplished this with a special f/415 infrared secondary. Over the last year, we have designed, constructed, and installed a "speckle reimager," also called the "scale changer," for the Hale telescope. The reimager takes the the beam from the standard f/70 infrared secondary and converts it to the appropriate scale. This new set of optics allows some exciting new advances in doing high resolution imaging at Palomar.

The reimager consists of four mirrors: two flat mirrors for maintaining the position of the focus at the focal plane of the current infrared camera, and a concave spherical mirror and a convex spherical mirror for changing the magnification of the beam. The convex mirror is removable, and the scale changer design allows for easy installation of three different focal length mirrors appropriate for achieving the optimal pixel scales for observations at wavelengths of 2.2, 1.6 and 1.2 microns. The observed pixel scale with the reimager is 0.038 milli-arcseconds per pixel with the 2.2 micron mirror. This scale was determined by observing binary stars with known separations.

The reimager is small enough to fit in front of the existing Cassegrain infrared camera and its supports. To change between standard imaging and speckle imaging, we move the existing tertiary mirror on its track until it looks up through the reimager, a process which takes only 10 seconds. Hence it is now possible to switch between direct and speckle imaging at any time and thus to use telescope time more efficiently.

In addition to being able to provide correct pixel scales for multi-wavelength imaging, the reimager has the advantage of use in conjunction with the features of the standard f/70 infrared secondary. Objects for which there is a calibrator within the chopping distance of the secondary, approximately 5 arcminutes, can be observed by rapidly switching between them. This reduces artifacts in the data produced when the atmosphere changes significantly between observations. Since atmospheric effects may now be measured on a calibration star, it is possible to select the object images with the best seeing. Furthermore, we are now able to use the offset guider. The field of view in speckle mode is only a few arcseconds on a side. In the old data, small amounts of image wander made the speckles fall outside this tiny field and off the detector. Use of the guider helps to correct this problem by keeping the object well centered in the field and hence provides greater signal to noise per pixel. We should also be able to image fainter sources through use of tip-tilt correction with the secondary since this will concentrate the speckles in a smaller area of the detector and hence improve signal to noise.

All of these improvements in high resolution imaging will allow us to look at faint stars and galaxies in finer detail than has ever before been possible in the near infrared.

SOLAR SYSTEM

PHOTOMETRY OF THE COMET 2060 CHIRON IN 1993

Principal Investigator: Bonnie J. Buratti
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Subject Heading: Solar System

As primitive bodies believed to be remnants of the protosolar nebula, comets provide direct clues to the composition and physical state of regions from which solar systems form. They are believed to have provided the prebiotic material - molecules containing C,H,O, and N - from which life arose on Earth. Paradoxically, cometary impacts with the Earth have been held responsible for the mass extinctions which periodically occur, including the demise of the dinosaurs (and most other species) at the Cretaceous-Tertiary boundary. Finally, comets have provided significant amounts of volatiles to create the oceans and atmospheres of the terrestrial planets. The study of comets is thus an important endeavor providing answers to some of the fundamental questions in both astrophysics and planetary sciences.

Comets remain in their pristine state in the Oort Cloud until they are perturbed by a nearby star. During their inward journey towards the sun, they successively shed volatiles, including ionized gasses, and dust. In their interactions with the solar wind these ionized gasses (along with electrostatically charged dust) provide an astrophysical laboratory to study the behavior of particles entrained in the magnetic field of the solar wind.

The purpose of our work on the 60-inch telescope on Palomar Mountain is to provide the first accurate photometric measurements of the comet 2060 Chiron which is in a critical state of its evolution, viz., the transition from an inert primordial body to an active comet. By studying both secular and short term brightness variations of the comet in its journey towards perihelion (which occurs in about 3 years), we are providing an observational basis to obtain an understanding of the stages of evolution of a comet, its dynamics, and the degree of mass loss.

Since it was discovered (at Palomar) in 1977 orbiting between Saturn and Uranus, 2060 Chiron has proven to be an one of the most interesting objects in the Solar System. Originally classified as the most distant asteroid, it began to exhibit cometary behavior in 1988, including a steady full magnitude increase in brightness between mid-1987 and late 1988, and the development of a coma. Archived observational evidence also exists for an earlier outburst which peaked in 1971 (Bus et al., 1991a). Chiron is about 200 km in diameter with a geometric albedo of ~0.1 and a spectrum similar to primitive C-type (carbonaceous chondritic) asteroids. It has a well-defined rotational lightcurve of about 6 hours. Its large size is puzzling in light of its cometary behavior; diameters of comets are more typically 10-50 km. In early 1989, Chiron began to exhibit a **decrease** in brightness; between that time and early 1992, it dimmed by approximately 0.5 magnitudes in the R filter. The reduction of our one night of observations in 1993 show that its brightness has remained about the same as the last two years (see Figure). This observation was somewhat unexpected because Chiron will not reach perihelion until 1996.

In January 1990 Luu and Jewitt (1990) and Buratti and Dunbar (1991) both observed short term variations of ~10% in the brightness of Chiron's coma. These observations demonstrate that Chiron exhibits impulsive variations in its brightness on time scales of a day, in addition to secular changes on time scales of months or years. The mechanisms responsible for the secular changes in Chiron's brightness are undoubtedly distinct from those causing the shortterm, impulsive outbursts and decays. The impulsive outbursts have been associated with the detection of CN on Chiron (Bus et al., 1991b). In our past three years of observations on the 60-inch, we have paid particular attention to characterizing these short term variations. A full description of its changes in brightness - particularly on the time scale of hours - will provide an empirical foundation for understanding the physical mechanisms (including outgassing, sublimation of volatiles, and even significant mass ejections) driving the evolution of comets. In 1991 and 1993, Chiron was quiet; it exhibited a rotational lightcurve of its solid nucleus. In 1992, Chiron underwent bursty behavior, and for the first time both the rise and decay of an impulsive burst was observed, to enable the determination of a timescale of these events (~1-2 days). In all of our

Buratti

observations, the color of the outbursts remains constant; the material ejected form the comet is therefore dust-laden (Buratti and Dunbar, 1991; Marcialis and Buratti, 1993)

With the recent discovery of four primitive objects similar in size and color to Chiron (1992 AD, 1993 RO, 1993 RP, and the transplutonian object 1992 QB1), 2060 Chiron may represent the first of a class of new objects dwelling in the outer reaches of the Solar System (Chiron is the only body which is active however). Specifically, they may be very large comets originating in the Kuiper belt, a putative reservoir for comets which is much closer to the sun than the Oort Cloud. These bodies are occasionally perturbed inward, outgas, and possibly evolve into planetary satellites such as the Saturnian satellites Phoebe and Hyperion, or large asteroids.

Our observational strategy over the next two years will be to obtain CCD images with temporal resolution of 5-10 minutes in the V and R filters. Our specific measurement goals and scientific objectives are to 1) derive an absolute magnitude to measure the secular (~months or years) changes in Chiron's brightness; 2) detect and characterize short term (~hours) outbursts or decreases in brightness and understand their cause(s); and 3) measure the lightcurve of the nucleus to monitor the growth and decay of the comet's coma and to understand the dynamical properties of the nucleus (e.g., whether it's precessing, and whether it's prograde or retrograde.) Detailed study of the color variations (if any) of the lightcurve will result in a rough map of volatiles on the surface. Similarly, the regular appearance of high frequency components in the lightcurve can be related to the existence of facets (mountains, craters, and chasms) on the surface. Fourier analysis of our observations from 1990-1993 show at least 8 facets which regularly appear.

Because other comets, including Halley and Schwassmann-Wachmann I, have exhibited anomalous outbursts and declines in brightness (although none of the events have been observed with the photometric accuracy or temporal resolution as the Palomar work), this study is important for understanding the present nature and evolution of comets as a class.

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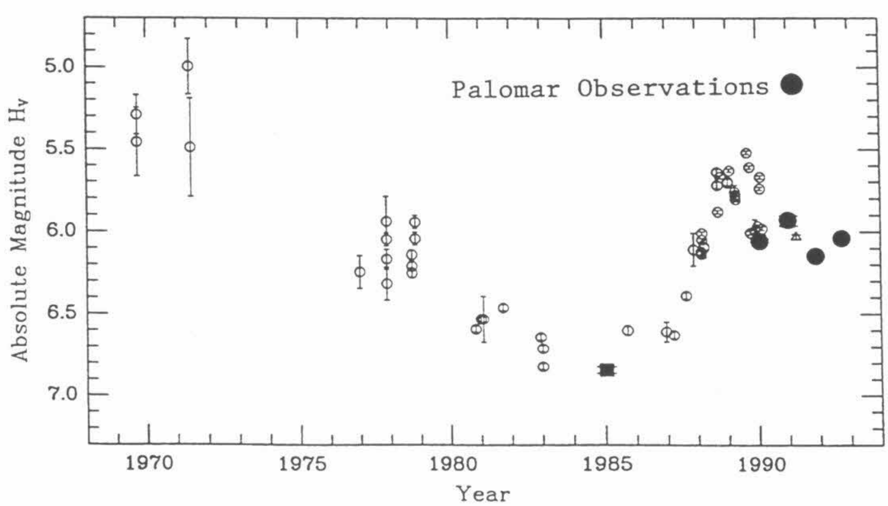

Figure. The brightness of Chiron over the last two decades (observations before discovery are archival). Our observations from the last 3 years show the decline in brightness has persisted, even though Chiron has not yet reached perihelion. (For sources of earlier observations, see Marcialis and Buratti, 1993).

ASTEROID SURVEY

ASSOCIATED COMETARY RESEARCH

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Coinvestigators: Raymond Bambery
The Jet Propulsion Laboratory

Donald Hamilton
California Institute of Technology

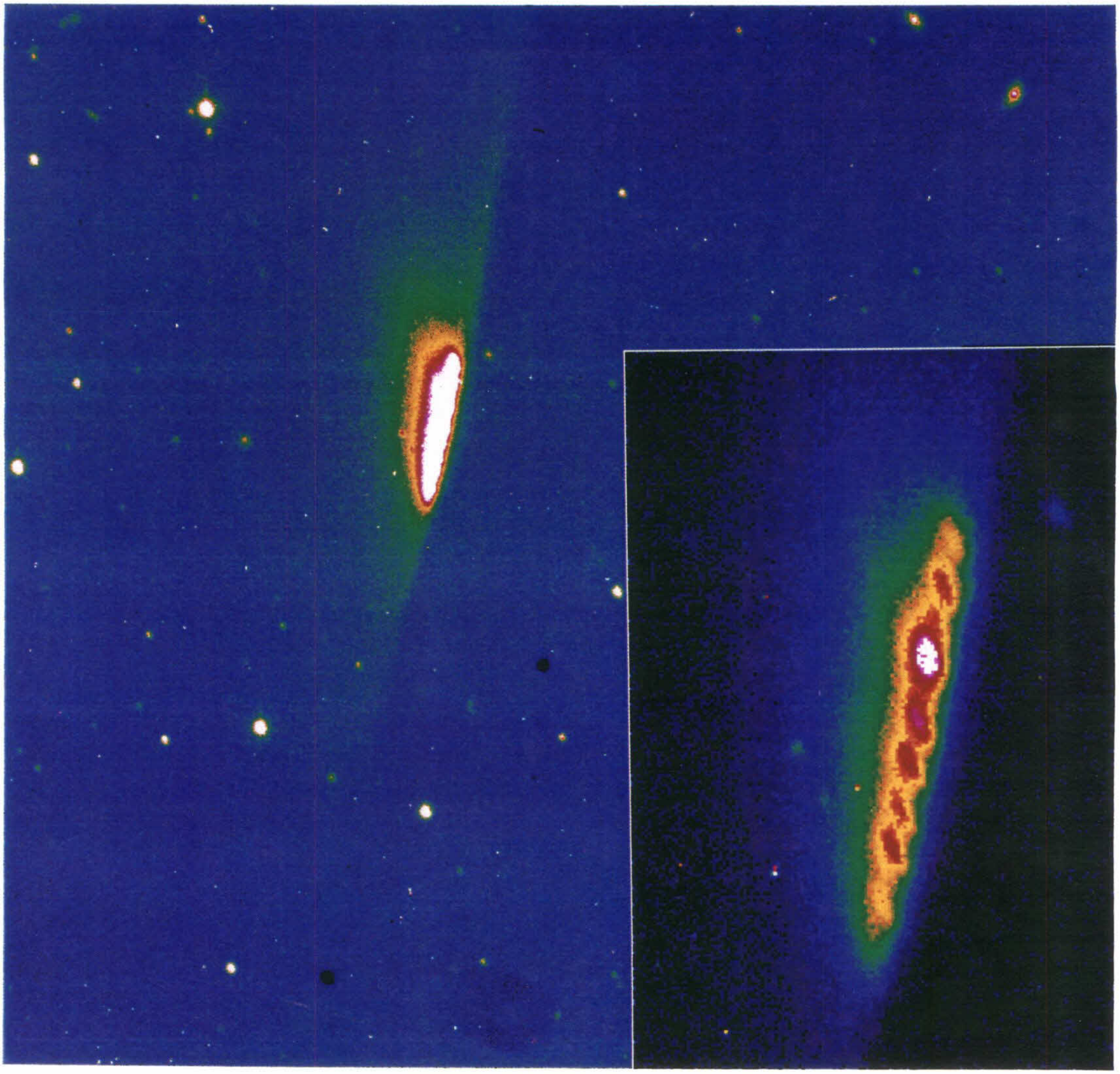
Subject Heading: Solar System

The newly discovered Comet P/Shoemaker Levy 9 (1993e) was imaged by Eleanor Helin, Raymond Bambery and Donald Hamilton using an electronic camera on Palomar's 60-inch Telescope, March 31. The color image shown here was acquired in a 300 second exposure and computer enhanced. This comet, disrupted into mutiple pieces as a result of a close pass by Jupiter, appears as a long pod shaped shell as it heads towards a collision with Jupiter in July, 1994. This awesome comet was first photographed and noted by Helin and her associate the night of March 18/19 on Palomar's 18-inch Telescope.

This false color image was produced from the March 31 Palomar data by the Image Processing Laboratory. The colors in the comet image represent relative brightness variations of the structures within the cloud of gases surrounding the nuclei segments. The brightest regions are white, while regions of decreasing brightness are graded from red through yellows and greens. The sky background is blue.

Helin
Cometary
Research

60-Inch Telescope Image of P/Shoemaker-Levy 9, 1993e



North

STARS AND THE INTERSTELLAR MEDIUM

Reddening and Metallicity Variations within Galactic Globular Clusters

Principal Investigator: Judith Cohen
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Co-investigator – Celeste Sleeper
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Subject Heading: the Milky Way Galaxy

There is a group of poorly studied globular clusters in the nuclear bulge of our Galaxy. Because they are heavily reddened, rather crowded, and in general 8 kpc away, it is quite difficult to use optical techniques on this sample of objects. Instead we rely on the new generation of infrared arrays to construct new color–magnitude diagrams in $J-K$ and $V-K$ reaching from the tip of the giant branch to the horizontal branch. We selected a sample of 5 globular clusters. The three highly reddened ones are NGC 5927, NGC 6528, and NGC 6624. To these we added NGC 6171 and NGC 7099, more metal poor objects with relatively small interstellar absorption.

These objects were originally observed in June 1992 using the Nicmos 3 array on the Swope telescope of the Las Campanas Observatory. But for two clusters, we did not have any infrared array images taken under photometric conditions from Chile. We were very fortunate to have two clear nights with good seeing, even relatively far south, on the 200–inch Hale telescope in July 1993 using the InSb infrared array to provide a photometric calibration for some of the Las Campanas data. Keith Matthews was invaluable in obtaining these data and we are very greatful to him.

The most interesting results obtained so far is that we see definite evidence for wide giant branches in the highly reddened clusters, much wider in $V-K$ at a fixed K magnitude than in $J-K$. Such spreads are not seen in the low reddening, metal poor clusters. These spreads are caused either by the presence of differential reddening (variable interstellar absorption along the line of sight to different stars in the cluster) or by the possibility of varying metal abundances among the globular cluster stars.

We believe we are seeing the effects of patchy interstellar absorption. By comparing the spread of the upper giant branch as a function of wavelength, we can derive strong limits on the presence of metallicity variations within a cluster. It appears that patchy interstellar absorption is capable of explaining everything, and strong upper limits on any internal range in metallicity can be obtained.

We also observed several RR Lyrae variables which were included by chance in the area covered by our frames. We can use those to derive distances to the clusters using the infrared period – luminosity relationship for RR Lyrae variables. In all cases the distances thus derived are within 10% of that determined optically. The number of RR Lyraes observed is too low to proceed further along these lines, and a separate project may be undertaken to pursue this in the future.

Studies of Magnetic White Dwarfs

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Coinvestigators: Angela Putney, James McCarthy
California Institute of Technology

Subject Heading: Stars

White dwarf stars are one of the possible end stages of stellar evolution; they are electron degenerate objects which no longer burn hydrogen, nor anything else, but derive their luminosity from thermal cooling. A small fraction of them contain strong magnetic fields, and in a few cases the fields are enormously strong, up to a billion Gauss. The origin and maintainence of such strong fields is in some dispute, and their influence on the late stages of stellar evolution is unknown. The progenitors of these magnetic white dwarfs (MWD) are probably the magnetic Ap stars, but the statistical association is not well-defined.

Our goals in studying the MWD are twofold. The first is to study the statistics of their occurence, to find their space density and test the hypothesis that they are the descendents of the magnetic Ap stars. Ms. Angela Putney is working on this as one aspect of her thesis project. She wants to find the fraction of DC white dwarfs (those with a nearly continuous spectrum) which contain a magnetic field of 100,000 Gauss or more. She is doing this by measuring the degree of circular polarization in the spectrum, since the most dramatic change introduced by the magnetic field is polarization in the star's optical radiation. For this work Ms. Putney is using the 5-meter Hale telescope with the double spectrograph and the polarimetry optics, which have been adapted to measure circular polaraization. She plans to observe 54 DC stars. To date she has observed 12, of which one has a detectable field. The remaining 42 will be observed in 1994.

The second objective of this work is to model the magnetic field in the strong-field stars, by studying their polarization spectra. This will form the second part of Ms. Putney's thesis. In this work she is collaborating with Dr. Stefan Jordan at the University of Kiel, who has written a computer code for the radiation from the atmosphere of a magnetized white dwarf star. A few of the equations in the code, especially those describing the continuum opacity in a magnetic field, are at best semi-empirical rather than being well-grounded in physical theory. This study, then, also will help test the theory of radiation in a highly-magnetized plasma.

We have so far observed 7 of these strong-field MWD, and three of them are being fit to atmospheric models, using Jordan's code. It has become clear that a flux spectrum can be fit by several different models, but generally the ambiguities can be eliminated when constraints due to circular polarization are added.

SpectroCam-10 Observations of Protoplanetary Globules in Orion

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Cornell University

Coinvestigators: James R. Houck and John W. Miles
Cornell University

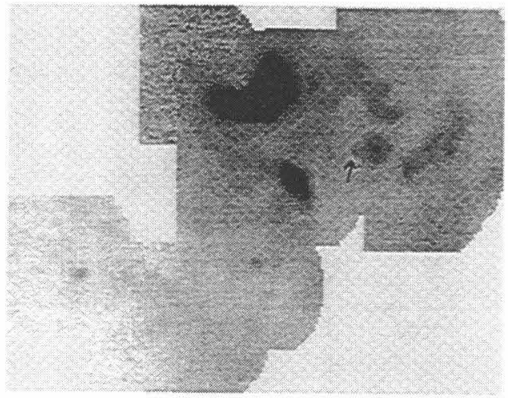
Subject Heading: Interstellar Medium

From July 1992 through June 1993, SpectroCam-10, the new infrared camera-spectrograph for the Hale telescope, was used on four observing runs. Built at Cornell University under a collaborative agreement between Cornell and the California Institute of Technology, SpectroCam is optimized for imaging and spectroscopic observations in the 8 to 14 micron wavelength range. The instrument's array detector is the largest and most sensitive available for these wavelengths, and when combined with the great light-gathering power of the Hale telescope it is one of the most powerful instruments of its kind in the world.

One of our continuing projects with SpectroCam is the study of regions of star formation in our galaxy. Beginning as clouds of dust and gas, these nebulae collapse under their own gravitational attraction and after tens or hundreds of millions of years become the birthplaces of new stars. We have surveyed a number of such regions to determine the distribution of infrared-emitting warm dust at a spatial resolution comparable to optical and radio studies.

A primary target for us is the Orion nebula, one of the closest and best studied sites of star formation. Located here are numerous objects associated with star formation processes, from dense clumps of gas which may be in very early stages of collapse to young but fully formed stars. One class of Orion objects that has recently been the subject of intense study is solar system-size globules of gas. The globules are visible at optical and radio wavelengths because their outer surfaces are ionized by the ultraviolet radiation from θ^1 Orionis C, the hot, massive star primarily responsible for ionizing the entire Orion nebula. Recently, high resolution ***Hubble Space Telescope*** images showed that many globules have cometary-like gaseous tails that are being blown away from θ^1C by the star's intense radiation pressure and stellar wind. It is thought that these globules, some of which have stars at their centers, are the material left over from the star formation process that under normal circumstances might condense into a planetary system. In the harsh environment of the Orion nebula, however, their fate is unclear.

We imaged these globules with SpectroCam on two runs this observing season. Instead of observing the gaseous component, SpectroCam is sensitive to infrared emission from warm dust which should make up about 1% of a globule's mass. At the center of the Orion nebula, where the globules are found, dust grains are distributed in a diffuse nebula and are heated to about 300 Kelvin by the same ultraviolet radiation from θ^1C that ionizes the gas. *Dust concentrated*



in the globules should be heated by the same mechanism. For a successful detection, however, we had to resolve the globules from the strong infrared emission of the diffuse dust, a feat which previous infrared observations had failed to accomplish.

The accompanying image, at a wavelength of 11.7 microns, was made under excellent observing conditions in March 1993. Most of the labeled sources correspond to optical and radio globules. The spatial resolution, about 0.5 arcseconds, corresponds to a distance of < 3 times the diameter of Pluto's orbit at the distance of Orion. Many sources are unresolved and thus closely correspond to the size of their optical and radio counterparts (about half our resolution limit). Photometry and spectra of a few condensations show their dust temperature to be about 300 Kelvin, as expected. However, some of the objects are unusual. Two compact sources are spatially resolved, the dust being much more extended than the ionized gas, and a third has a spectrum characteristic of unusually cool dust.

Also visible in our image are diffuse arcs which lie between θ^1 C (arrowed) and several globules. With no known counterparts at other wavelengths, the arcs seem to be concentrations of warm dust which are piled up against the outer borders of the globules, possibly swept there by the strong radiation from θ^1 C.

The high spatial resolution and sensitivity of this image is a direct result of the Hale telescope's large aperture and high optical quality, and the often excellent seeing conditions on Palomar mountain. In the future, we plan to continue such observations to improve our understanding of not only the Orion sources, but of similar small-scale structure in other regions of star formation.

We thank G. Gull, J. Schoenwald, and T. Herter at Cornell for their support of SpectroCam-10, and the staff of Palomar observatory for assistance with the observations. SpectroCam-10 is supported by grants from NASA and the Department of Astronomy at Cornell University.

An Eclipsing Binary Pulsar

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Stars

A decade ago, the relationship between the x-ray binaries and the radio pulsars in binary systems seemed clear. In particular, the handful of known low-mass radio pulsar binaries fit comfortably into their roles as the old, cold remnants of once active low-mass x-ray systems: recycled pulsars and white dwarfs with life expectancies exceeding the Hubble age.

In recent years, the discovery of a number of unusual pulsar binaries has challenged this simple picture. In several cases, such as PSR 1257+12, with two planetary mass companions, it is not clear where—if anywhere—on the standard evolutionary track the systems belong. At the same time, it seems increasingly likely that processing (or "recycling") in binary systems is intricately tied to the reduction of pulsar magnetic field strengths, and therefore that properly understanding binary evolution may prove critical to understanding the general pulsar population.

One of the most peculiar pulsar binaries discovered recently is PSR 1718−19. This pulsar is projected against the globular cluster NGC 6342, which is at a distance of about 11.4 kpc, but the pulsar's dispersion measure suggests that it may be much closer than the cluster, about 2.6 kpc. PSR 1718−19 is in a 6.2 hr eclipsing system, and is only visible for 25-50% of each period at low radio frequency, though it is hardly modulated at frequencies about 21 cm. These absorptive eclipses suggest the presence of a strong wind from the companion, arguing that it is not likely to be a white dwarf. Furthermore, the pulsar itself is quite slow (1 s period), and shows no signs of recycling during an earlier LMXB epoch. By modeling the eclipses as free-free absorption in an r^{-2} wind, we have estimated the orbital inclination angle and found that the most likely companion mass is about 0.2 solar.

In an attempt to pin down the nature of the companion, and hopefully the evolutionary status of the binary, we have made observations with the 200-inch at Palomar. Within about an arcsec of the nominal pulsar position, we find a very red star with $m_R \sim 19.3$. This is much too bright for the candidate star to be the pulsar's companion if system is in NGC 6342, or for the companion to be a white dwarf or main sequence star at 2.6 kpc. It is, of course, possible that we have simply observed an obscuring object in this crowded field. A more exciting possibility is that the companion has actually expanded to fill its Roche surface, in which case the observed star could be the companion at the nearer distance. These possibilities can be distinguished with better radio astrometry of the pulsar and optical spectroscopy of the candidate.

If our identification holds up, then the companion may actually be a stripped main sequence turn-off star, as recently proposed by T. Zwitter. Such a model can naturally account for the active wind we observe. If so, the PSR 1718−19 may actually prove to be a precursor, rather than a descendent, of an LMXB.

The Oldest White Dwarfs?

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Subject Heading: Stars

Millisecond pulsars, pulsars rotating with millisecond periods, are probably one of the most fascinating stars. They appear to have incredible temporal precision, better than man made clocks. This aspect is being exploited in the search for a cosmic gravitational wave background, frame tie (precision astrometry), probing the interstellar medium etc. A not so well recognized aspect is that "millisecond pulsars shine forever". This follows because the vast amount of rotational energy store allows them to shine for a timescale longer than the age of the Universe.

Millisecond pulsars are usually found with a white dwarf companion. In the standard evolutionary picture, the neutron star is spun up by mass transfer from the companion which subsequently evolves to a hot white dwarf. The only store of energy of a white dwarf is its internal store of heat energy. Once formed, a white dwarf cools, getting dimmer as it ages. Models of white dwarf cooling have been developed to infer the age of white dwarfs from their inferred surface temperature. The absence of very cool white dwarfs is usually attributed to the finite age of the disk, about 10 Gyr (10 billion years).

A millisecond pulsar system has two clocks: the white dwarf clock which can be linked to white dwarf cooling and the millisecond pulsar clock. The millisecond pulsar age, t_p, is based on the observed rate slowing down of the pulsar and the assumption that the pulsar was born with a period much smaller than the current period. The fortunate juxtaposition of these two clocks allow us to place new constraints on the age of our Galaxy. To this end we have begun a program of detecting white dwarfs in millisecond pulsar systems. The detection is not so trivial because the typical distance to these systems is about 1 kpc.

This year we have detected two white dwarfs (J1713+0747, $t_p = 14$ Gyr; J2145−0750, $t_p > 13$ Gyr) and placed stringent upper limits in four other systems (1855+09, $t_p = 5$ Gyr; J2019+2425, $t_p = 27$ Gyr; J2317+1439, $t_p = 15$ Gyr; PSR J0034−0534, $t_p = 4.4$ Gyr). Typical upper limits are 26 mag in the R band and a bit worse in the i band. The white dwarf in the J1713+0747 system ($m_i \sim 24.5$, $m_R \sim 25.4$) is consistent with being as old as indicated by the pulsar clock. The white dwarf in the J2145−0750 is about as faint as in the J1713+0747 system. In other systems, the lack of detection of a white dwarf companion allow us to conclude that these systems must be about as old as J1713+0747.

These white dwarfs are amongst the oldest white dwarfs and should be of considerable interest to theorists working on modelling the cooling of white dwarfs. Indeed, at the moment, the observations are quite ahead of theory. Reliable models of white dwarf cooling model, especially low mass He white dwarfs, are urgently needed. Once these become available, new constraints on the age of the disk of the disk of Galaxy can be obtained. A subsidiary conclusion of our studies is that these millisecond pulsars are born with periods considerably less than the current periods. This conclusion has very important ramifications for the birth and birthrate of millisecond pulsars.

A Search for Acoustic Oscillations in Solar-Like Stars
With the Palomar East Arm Echelle Spectrograph

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Coinvestigator: M.L. Peri

Subject Heading: Asteroseismology

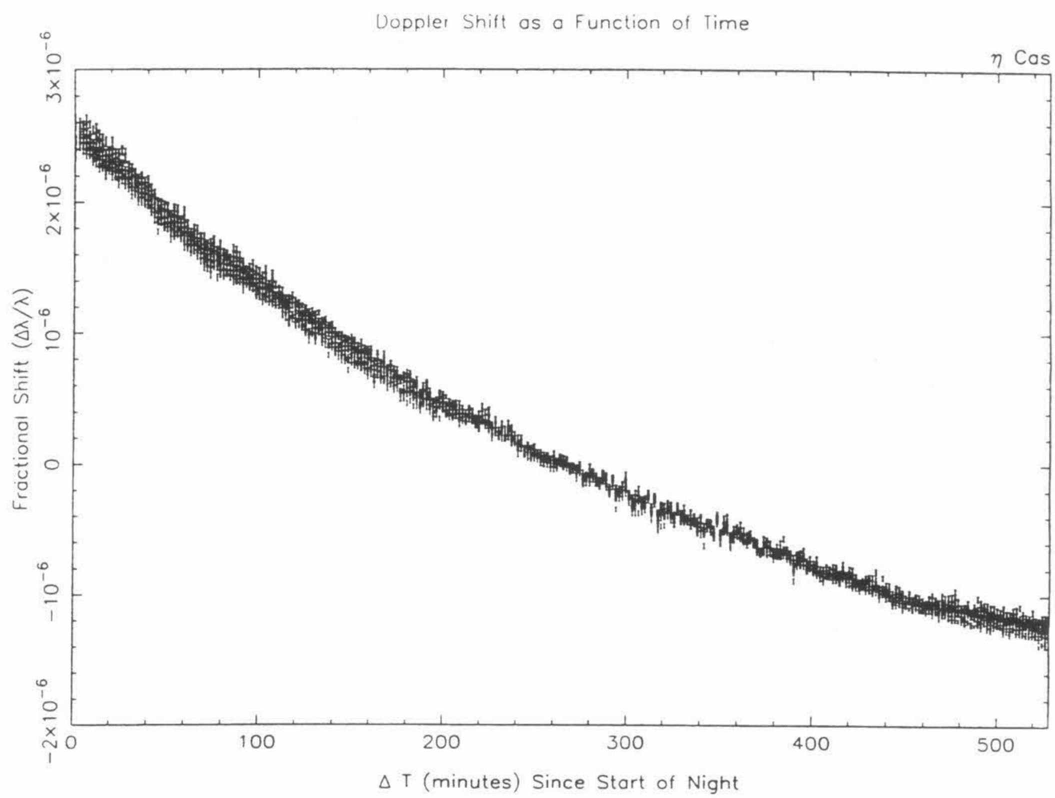
Asteroseismology is the study of acoustic oscillations – sound waves – in stars. Such oscillations probe stellar interiors, and thus carry information on the physical conditions in regions of the star that are not accessible through ordinary observational techniques. These acoustic oscillations can be seen in the Sun, but to date no-one as observed them in any other solar-type star. We hope to make such observations by measuring minute Doppler shifts in the stellar absorption lines caused by gas motions associated with the oscillations. The radial velocities to be detected are very small; in the Sun they are about 10 cm/sec per mode of oscillation.

Photon noise is a fundamental limitation to measuring Doppler shifts with such high precision. This limitation can be alleviated by looking at bright stars with large telescopes, and by observing a large number of spectral lines simultaneously. The new East Arm Echelle Spectrograph on the Hale 5-meter telescope is especially suited to make such observations. The instrument includes a double-scrambling fiber optic feed for enhanced spectral stability, and an I_2 absorption cell for instantaneous calibration. Used in high-resolution mode the spectrograph yields an effective resolution of $R \equiv \lambda/\Delta\lambda \simeq 40000$ over a spectral range exceeding 4000 – 7000Å.

Development of the Palomar East Arm Echelle Spectrograph was completed this year. The overall instrument plus telescope efficiency was measured to be 1-5% , depending on atmospheric seeing and on the spectrograph input mode used: low- ($R \simeq 12000$) and high-resolution modes are available. A timeseries of data on the rapidly oscillating Ap star HD134214 taken last year was used to assess the performance of the instrument when used in conjunction with the iodine calibration cell. Additional test data was acquired in July 1994 by running a fiber optic cable out the catwalk door to collect sunlight. Since the Sun is bright and the characteristics of the solar oscillations are known *a priori*, these data allow us to analyze our experimental methodology independent of photon noise limitations and the constraints of atmospheric seeing.

Instrumental preparations completed, we commenced the scientific portion of our asteroseismology program in fall 1993. Drs. Peter Goldreich and Norm Murray have recently made considerable headway on understanding the interaction of acoustic modes with convective energy in the stellar atmosphere. These theoretical advances allowed them to predict that the oscillations will be stronger in main-sequence stars that are slightly more massive than the Sun. Verification of this prediction being a primary goal of our observation program, we selected η *Cas* (G0V, V = 3.4) as our first target star. This bright main-sequence star is slightly more massive than the Sun and has extremely sharp photospheric absorption lines, which is desirable for high sensitivity to small Doppler shifts. The star's northerly coordinates keep it at a favorable viewing position all night, enabling the collection of a long timeseries of observations. Moreover, η *Cas* is in a well-studied binary system so good estimates of its mass are available.

We collected a timeseries of over 1600 frames on η *Cas* on a six-night run in fall 1993. In the figure below, radial velocity measurements derived from a single night of this run easily show the slow variation caused by rotation of the Earth during the course of the night. Preliminary analysis of these data yield a root-mean-square velocity noise of 3.6 m/s per 60 sec exposure. By combining data from all 1600 frames, we anticipate being able to detect radial velocities down to a threshold of 10 cm/sec. According to theory, dozens of oscillation modes should lie above this level. Thus these data provide a good chance of achieving the first detection of acoustic oscillations in a solar-type star other than the Sun. With luck, our run on η *Cas* will be the first step of a campaign to form a database of oscillation mode characteristics on a range of solar-type stars, so that we can begin an observational study of the physics of stellar interiors.



A timeseries of doppler shift measurements on the star η *Cas* taken with the East Arm Echelle Spectrograph on Aug 31, 1993. The different points for a given time are from the different echelle orders, and the slow variation is caused by the rotation of the Earth during the course of the night. We hope to find stellar oscillations by studying small periodic variations in these observations.

A Coronagraphic Search for Brown Dwarfs

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Samuel T. Durrance and David A. Golimowski, Johns Hopkins University

Subject Heading: Stars

Stellar coronagraphy is a technique to occult a bright star by a small mask at the focal plane of the telescope with a special care to reduce scattered light by the telescope optics, and to image the vicinity of the star with high dynamic range. For successful coronagraphic imaging, it is essential to center the star on the mask of a few arcseconds in diameter. A basic adaptive optics is an image stabilizer that senses the image motion of a star caused by atmospheric fluctuations in every ten milliseconds and corrects the motion by an actively controlled tilt mirror. The John Hopkins University Adaptive Optics Coronagraph (AOC) is an innovative instrument that improves the performance of a coronagraph by the help of an adaptive optics.

Using AOC, we have begun a search for brown dwarfs around nearby stars. A brown dwarf is a star that is not massive enough to ignite the hydrogen fusion reaction at its core due to insufficient gravity. However it is still self-luminous mostly in the near infrared, since the contraction of the star releases its gravitational energy. Only a limited number of brown dwarf candidates are known because they are faint and/or because they are rare. To identify a brown dwarf, its absolute luminosity must be known. The distances to nearby stars have been measured from their parallaxes. If a faint star is orbiting a nearby star, its absolute luminosity will be known immediately. It is expected that a brown dwarf is fainter than a typical nearby star by four orders of magnitude at 0.8 μm, the wavelength of our search, while AOC is capable of finding a companion more than five orders of magnitude fainter than the main star at an angular distance of 4 arcseconds.

So far we have observed the fields around 24 nearby stars and detected 94 stars. Most of the stars in the fields near the Galactic plane appear to be background field stars unassociated with the nearby stars. However, we found several faint and close companion candidates in the fields near the Galactic North Pole where background field stars are very rare. These stars are too faint to be ordinary stars that shine by burning hydrogen, if they are true companions of the nearby stars. Especially one of the companion candidates appears to be red and cool enough to be a good brown dwarf candidate. A coronagraphic image of this star is given in Figure 1. A statistical analysis indicates that some of these stars can be true companions. In order to complete our statistical analysis, we plan to continue the AOC observations and increase the sample to one hundred nearby stars. We also plan to follow up good companion candidates in the infrared wavelengths where brown dwarfs are expected to be bright. Our initial results demonstrate that the AOC search is one of the efficient methods to discover brown dwarfs around nearby stars. A paper based on our initial results has been submitted to Astrophysical Journal.

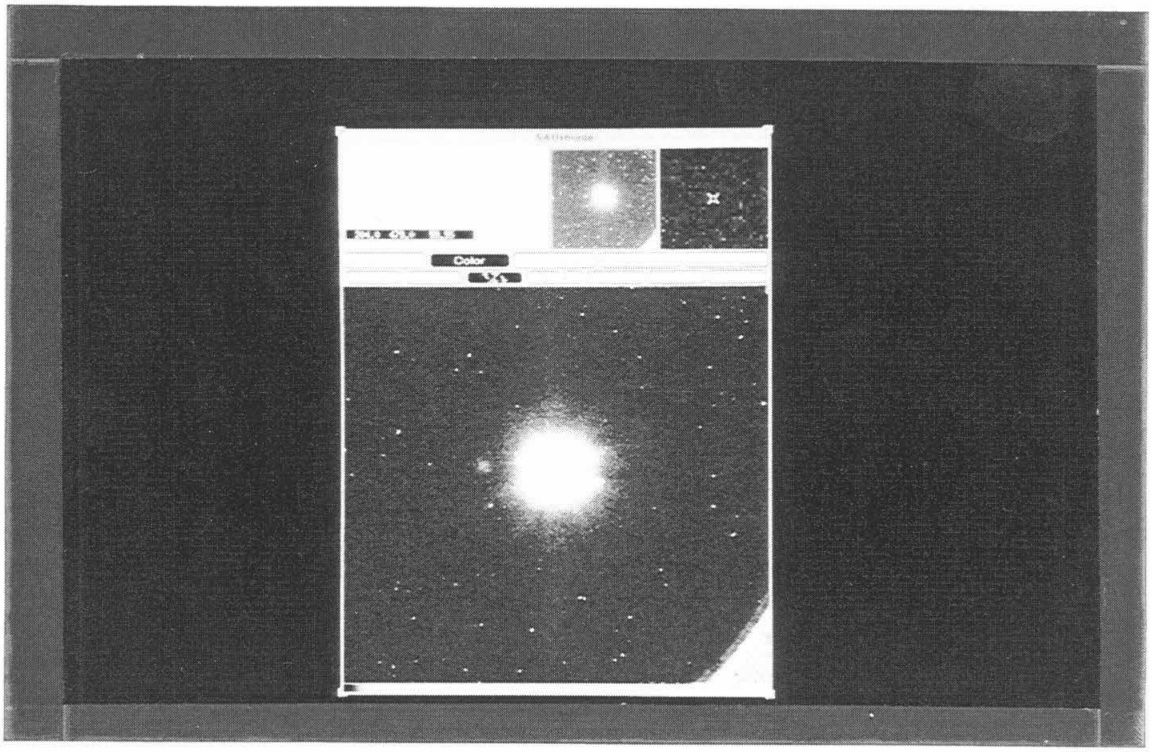

Figure 1. A brown dwarf companion candidate detected around a bright nearby star (to the right of the bright star). It is 10000 times fainter than the bright star. An extended object to the left of the bright star is a distant galaxy in the background.

Low mass stars in Galactic open clusters

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Subject Heading : Stars

Open star clusters are concentrations of 200-500 stars, typically lying close to the Plane of the Galactic disk. The stars in these clusters are physically associated, having formed together within some molecular-cloud complex. Since the typical mass of an open cluster is less than 1000 solar masses, the members are only loosely-bound gravitationally, and the cluster gradually disperses over a number of Galactic orbits, as stars are stripped from the cluster by tidal interactions. The rate of this dispersion depends on the cluster orbit - the less time the cluster spends in the high star-density Galactic Plane, the longer the cluster survives. Current estimates are that 50 % of clusters are destroyed within $\sim 10^8$ years of formation, although a small fraction survive for 5×10^9 years or more. Hence, open clusters are useful not only for studying stellar evolution and star formation theory (since the stars are coeval), but also for investigating Galactic dynamics.

The three nearest substantial open clusters are Praesepe (the 'Beehive' in Cancer), the Pleiades and, less spectacular because of its proximity, the Hyades in Taurus. A vital first step in any analysis that uses these clusters is defining a complete sample of cluster members - not a straightforward process since, although the brightest members standout, the overall star-density is relatively low, and fainter members are usually outnumbered 100-1000 to 1 by background field stars. The most effective way of separating out the members is by using stellar proper motions. Since the cluster stars have essentially identical space motions (the velocity dispersion is less than 200 m/sec), the tangential motions are also closely grouped (but not identical, since nearer stars in the cluster have larger motions than those stars on the farside), and stars in the nearby clusters lie well away from the bulk of the field stars. Even after applying the proper motion criteria, field stars still contaminate the sample, and further observations are required before one has a clean sample of cluster members.

The main observational problem is that each of these three nearby clusters covers a significant solid angle - particularly the Hyades, which has members distributed over an area more than 40 degrees in diameter. Covering such a large area demands high-quality, deep, wide-angle photographic plates spanning a time baseline of several decades. Fortunately, such material exists in the form of plates taken as part of the first Palomar Observatory Sky Survey (POSS I) in the early 1950s, and, indeed, Willem Luyten combined these with plates taken on the Oschin Schmidt in the 1960s and 1970s for just this purpose, although his survey suffers from low-accuracy photometry.

Over the last three years I have been working on a more detailed survey of a part (approximately half) of the Hyades cluster, using, as did Luyten, the POSS I plates as the first-epoch material, but combined with second-epoch plates taken on the UK Schmidt Telescope (in Australia) in 1985/6. These plates, covering four fields, each of 28 square-degrees solid angle, have been scanned on the automated measuring engine COSMOS (at Royal Observatory, Edinburgh), providing accurate positions and photometric measurements for the more than 100,000 stars and galaxies within each field. Based on those positions, I have calculated proper motions for each object, tying these motions into a reference frame defined by the 1400 or so faint galaxies visible on each plate. A mere 411 of the 400,000 stars measured turn out to have proper motions consistent with membership of the Hyades and, from the distribution of their proper motions, we can deduce a distance of 47 parsecs (or 153 l. yrs.) to the cluster centre.

Many of the brighter stars in the COSMOS sample had been identified previously as members of the Hyades cluster, but most of the faint stars (and the survey extends to an apparent visual magnitude of 19.5 - that is, an absolute magnitude $M_v = +16$ or a mass of ~ 0.15 solar units) are observed here for the first time. As mentioned above, merely having a proper motion that coincides with that expected for a Hyades star is necessary, but not sufficient, to confirm membership. However, if the star is a Hyad, then the magnitude (luminosity) and colours (temperature) should match a well-defined relation. I have used a CCD camera on the 60-inch telescope at Palomar to bserve more than 210 of the fainter candidate members in the V (λ5500), R (λ6500) and I (λ8000) passbands (150 stars in the sample already had such observations). Figure A shows the results - the bulk of the stars lie on a relatively tight sequence, with a smattering of stars at bluer colours. The lower-mass Hyades K and M-dwarfs, as we shall discuss later, share a common characteristic - hydrogen emission at $H\alpha$ and $H\beta$. Using both the P200 and (for the brighter stars) the P60, we have obtained spectra of more than 80 % of the stars plotted in figure A. All of the stars lying on the sequence show emission, while the outliers, marked as crosses, have only $H\alpha$ absorption. The conclusion is that the latter are background field stars which happen to match the Hyades proper motion vector.

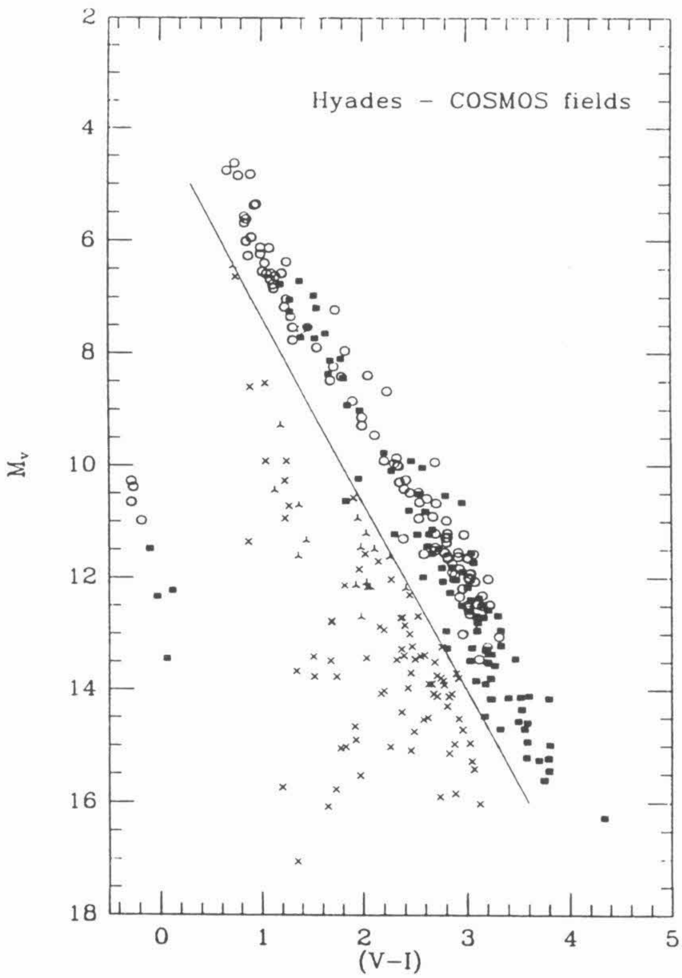

Figure A: the (M_v, (V-I)) colour-magnitude diagram for the candidate Hyades stars (the distances are derived from the proper motions, assuming Hyades membership). Solid squares (P60 photometry) and open circles (other photometry) denote likely cluster members, while the crosses mark background field-stars.

One of the most important parameters that can be determined from our observations is the luminosity function - the number of stars as a function of luminosity. Transformed to a mass function, using the main-sequence mass-luminosity relation, this gives the fragmentation spectrum for star formation - that is, the number of stars forming as a function of mass. There is particular interest in the shape of the mass function at very low mass (VLM), since objects with masses below ~ 0.075 solar masses (brown dwarfs) fail to ignite hydrogen burning in the core and are perennial dark-matter candidates. The Hyades luminosity function (plotting bolometric magnitude, where the Sun has $M_{bol} = +4.64$) is shown in figure B and the mass function in figure C. In both cases, the functions derived from observations of fields stars in the immediate vicinity of the Sun (suitably scaled) are also plotted. (The field-star data are taken from C. Tinney's surveys based on plates taken with the Oschin Schmidt as part of the second Palomar sky survey, POSS II.) Qualitatively, the two functions are similar, reaching maxima at $M_{bol} \sim +10$ or masses of $\sim 0.M_{\odot}$. The important point is that this maximum lies well above the completeness limit of the Hyades survey - the implication is that the number of stars does not continue to increase as we move to lower and lower masses. While a different fragmentation mechanism may kick in at lower masses, simply extrapolating the observed function into the VLM régime predicts only a small number of brown dwarfs.

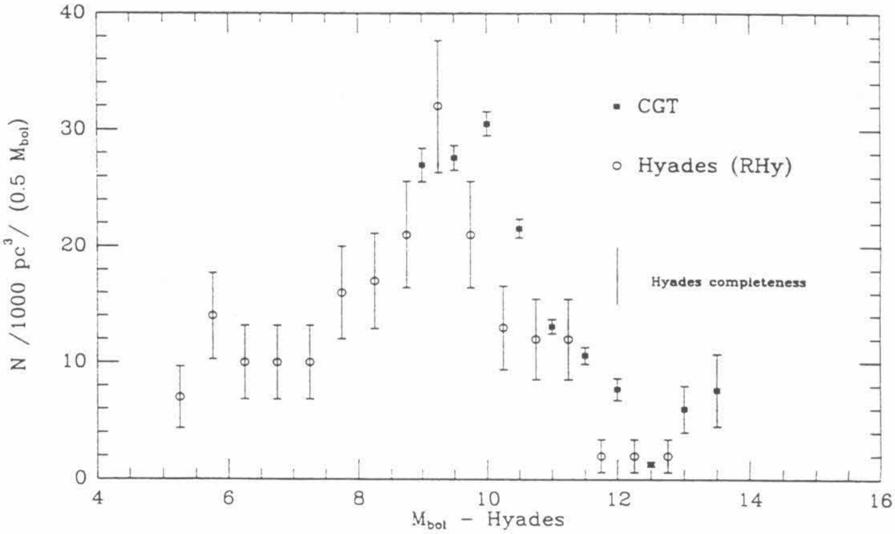

Figure B: the bolometric luminosity function for the Hyades compared with a field-star survey by Tinney (CGT)

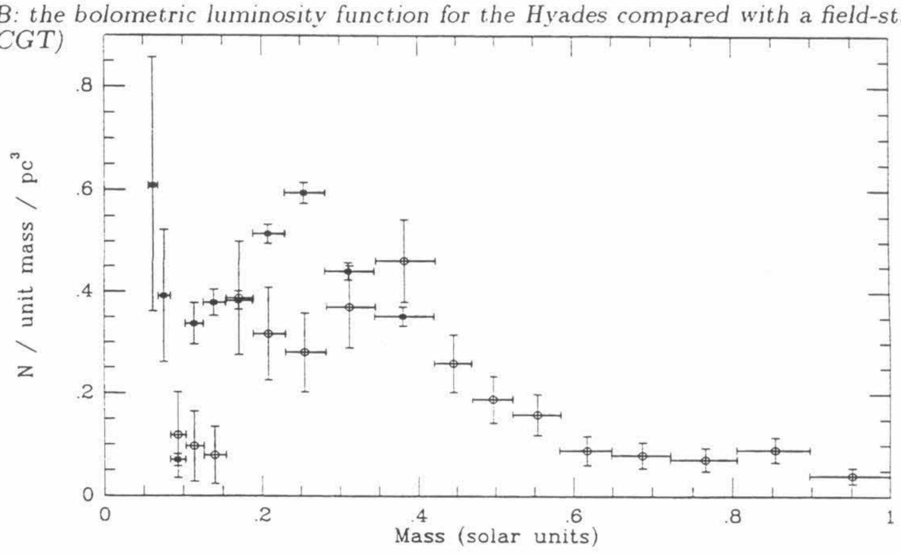

Figure C: the stellar mass function of the Hyades cluster, again compared with analysis of Tinney's field-star survey

On the other hand, there are differences between the Hyades and the field-star luminosity functions - particularly in the ratio between the number of low-mass ($\sim 0.25M_\odot$) and intermediate-mass ($\sim 1M_\odot$) stars. The latter stars are nearly twice as common in the Hyades than in the field, and this probably reflects the dynamical evolution of the cluster. The Hyades cluster $\sim 7 \times 10^8$ years old - old enough for the cluster to have relaxed. Energy equipartition arguments lead one to expect that the lower-mass stars will have a slightly higher velocity dispersion and hence a broader, less concentrated distribution than the higher-mass stars, and our observations confirm this. The core-radius of the former stars is 3.3 parsecs, as compared with 2.1 parsecs for the $1M_\odot$ stars. Since the lower-mass stars have orbits extending to larger radii, these stars are more susceptible to gravitational interactions and tidal stripping. The Hyades cluster as a whole is probably 3-4 times less massive now than at formation, when the total mass was probably $\sim 1500M_\odot$.

As mentioned above, the Hyades K and M-dwarfs have significant Balmer line emission - figure D shows a typical Hyades M-dwarf. The prominence of this emission increases with decreasing mass, mainly because the lower mass stars have lower temperatures and emit less energy in the continuum (hence there is more contrast between line and continuum). Emission of this strength is rare amongst field M-dwarfs (typical age of a few $\times 10^9$ years) but if we look at the lower-mass members of younger open clusters - such as the Pleiades ($\sim 5 \times 10^7$ years)- we find even stronger emission. The obvious conclusion is that $H\alpha$ emission is a time-dependent phenomenon, presumably tied to the decay in the magnetic field strength in these stars. If this could be calibrated, one would have a means of estimating the age-distribution amongst the M-dwarfs in the immediate vicinity of the Sun, and hence trace at least the recent star formation history of the Galactic disk.

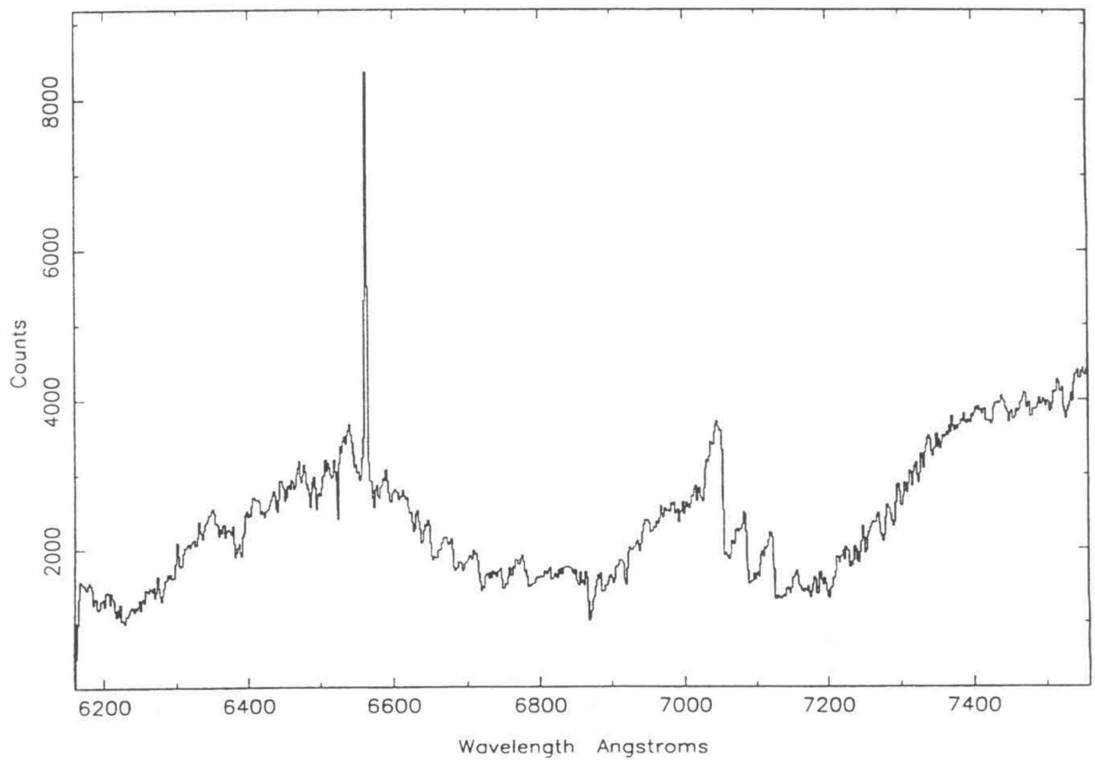

Figure D: a typical late-type M-dwarf in the Hyades - $M_v = +13.3$*, or 0.0003 solar luminosities. The strong molecular bands are due primarily to TiO and the* $H\alpha$ *emission is prominent.*

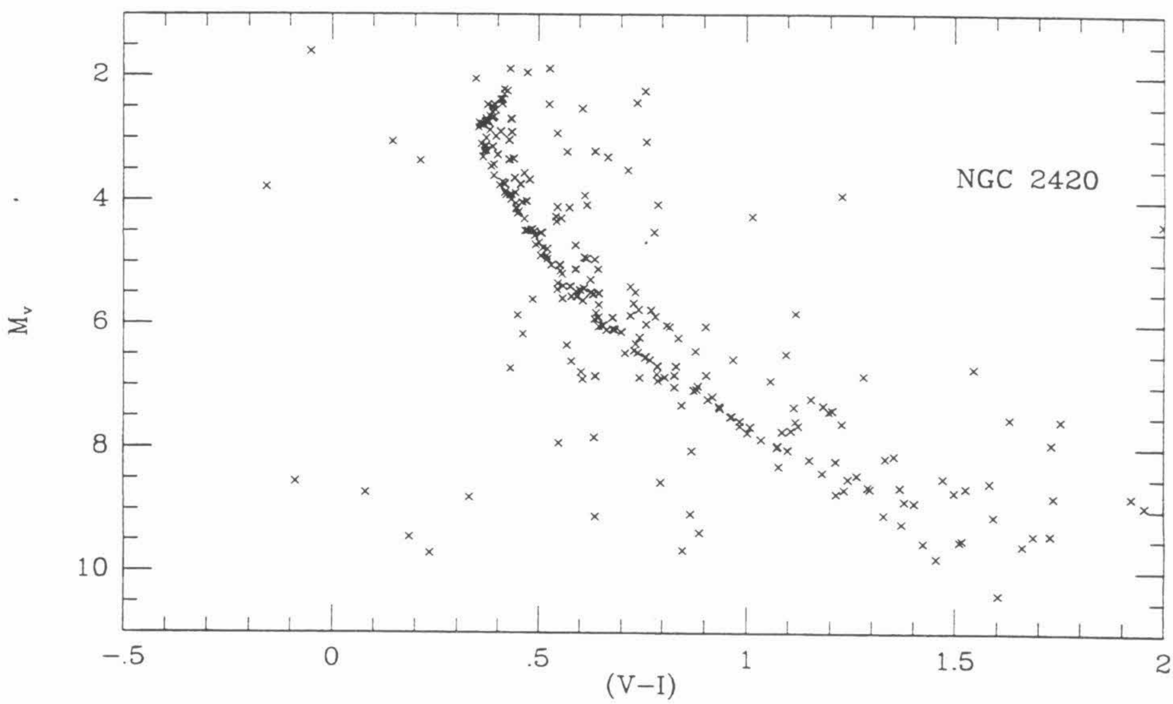

Figure E: the (M_v, (V-I)) colour-magnitude diagram for the old open cluster NGC 2420. The bimodal distribution along the main-sequence implies a significant fraction of equal-mass binaries.

Clearly, to determine the time-scale for $H\alpha$ decay, we require more than two datapoints (Pleiades and Hyades). Open clusters are obvious calibrators, since the ages can be determined with moderate accuracy, and, in collaboration with S. Hawley (Michigan State Univ.), we have been working to extend the observations to cover both more young clusters and a number of older systems. One of the other advantages of studying these (more distant) open clusters is that the systems are relatively compact ($\sim$ 20 arcminutes diameter), and we can use multi-object spectrographs (such as the Norris spectrograph on the P200) to survey 50-100 stars at once. So far we have obtained observations of two southern younger clusters (NGC 2516 and NGC 3680) from CTIO, and will obtain similar data for the older, northern clusters M67, NGC 2420 and NGC 188 with the Norris/P200. NGC 2420 is of particular interest - figure E shows the colour-magnitude diagram, derived from CCD observations with the P60. The main-sequence is clearly bimodal, with the more luminous upper branch being due to binary stars of nearly equal mass. The Hyades do not show this behaviour - although at least 45 % of Hyads are binary systems.

Finally, besides the $H\alpha$ emission, chromospheric activity also produces X-ray radiation from low-mass stars. We (Reid & Hawley) have used the ROSAT X-ray satellite to obtain follow-up observations of some 15 of the VLM Hyades stars confirmed as members through P60 photometry and P200 spectroscopy. All of the stars were detected by ROSAT. Moreover, our observations show that the fraction of the total energy emitted at X-ray wavelengths is constant (within 10 %) as a function of mass. Again, this fraction is lower in the Hyades than for the younger Pleiades. Thus the X-ray luminosity may afford another age-indicator for local stars.

Near-Infrared Line Imaging of PN

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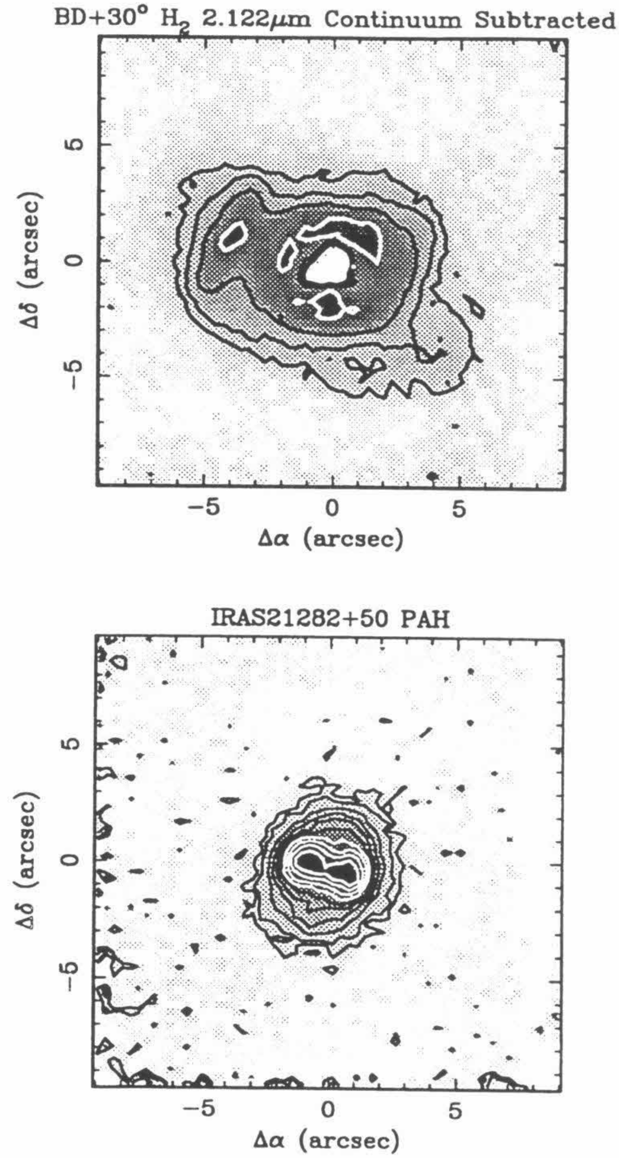
Coinvestigators: J.R. Graham (UC–Berkeley), K. Matthews (Caltech)

In a typical picture of planetary nebula formation, a highly evolved progenitor star experiences rapid mass loss leading to development of a substantial cool, slowly expanding circumstellar envelope of gas and dust. The remnant star evolves toward increasing temperatures until it is hot enough ($T \sim 30,000K$) to produce far-ultraviolet photons, ionizing the gas and heating and destroying the dust as it "eats away" at the envelope of material from the inside. In addition, a fast, hot wind from the star ploughs into the slowly expanding circumstellar material. Study of these interactions in young planetary nebulae is key to understanding both the history of their formation and their later evolution.

The bulk of the circumstellar envelope consists of molecular hydrogen (H_2). In its quiescent state this molecule does not radiate. However, in a planetary nebula, emission from H_2 can be excited by either hydrodynamic "shocks" caused by the collision of the supersonic stellar wind with the molecular envelope, or by absorption of ultraviolet radiation. While H_2 emission is ubiquitous in planetaries, the mechanism of its excitation is not always clear.

Many young planetary nebulae also exhibit a dust feature at 3.3 μm. This broad line is attributed to the ultraviolet excitation of tiny dust particles composed of groups of aromatic carbon rings with attached hydrogen atoms (benzene is the simplest example). These particles are rapidly eroded and destroyed in the ionized gas, and will not be excited deep in the surrounding molecular material–hence they trace the interface between these regions.

We imaged these features in four young, compact planetary nebulae in July 1993 using the Cassegrain Infrared Camera on the Palomar 200-inch telescope. Two representative images are shown in the accompanying Figure. In BD+303639, the H_2 and 3.3 μm emission are mainly distributed in a ring about the central star. This spatial coincidence implies that here the H_2 is excited by UV photons. We show for IRAS 21282+50 a deep image in the 3.3 μm dust feature. A bright torus of emission (seen edge-on) lies close to the central star, with fainter emission extending into the molecular envelope. Despite this evidence for a strong ultraviolet radiation field inside this planetary, curiously, no H_2 emission was detected.



Top: Continuum-subtracted H_2 line image of BD+303639. The 3.3 μm emission (not shown) is largely coincident with the H_2, implying that UV photons are responsible for the excitation of the molecular hydrogen emission. *Bottom:* An image of the young planetary nebula IRAS 21282+50 taken in the light of the 3.3 μm dust feature. A bright torus of emission is seen edge-on, indicating that strong UV radiation is present. Curiously, no H_2 was detected.

SpectroCam-10 Observations of the Galactic Center

Principal Investigator: Susan R. Stolovy
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Cornell University

Coinvestigators: T. Herter, G. Stacey, T. Hayward, and J. Houck
Cornell University

Subject Heading: Interstellar Medium

The Galactic Center has been a region of intense interest in the past few decades due its uniqueness and complexity. In March 1993, we used SpectroCam-10 to probe the nature of three different structures within the Galactic Center:

Imaging the Central Parsec

A strong spatial correlation has been observed between the warm dust emission, $Br\alpha/Br\gamma$ line emission, and the 2-cm radio emission from the ionized gas in the central parsec. In order to derive color temperatures and map the 10-μm silicate feature, we obtained images of the central parsec (~20") of the Galaxy in the 6 different 1-μm-wide filters spanning the 8-13μm window. This was done to identify the sources in the field as stellar or non-stellar. Many of the sources seen in the near-IR are thought to be supergiants, possibly formed as a result of mergers in the extremely crowded central parsec. We had hoped to improve upon previous mid-infrared observations (Gezari and Yusef-Zadeh 1990), but some of our images suffered from astigmatism in the telescope and seeing conditions varied. Nonetheless, we believe that the data are good enough to compare with more recent observations of Gezari (1992). Also, we witnessed the spectacular capabilities of SpectroCam-10 coupled with a 5-m telescope and good seeing: we were able to obtain sensitivities similar to Gezari's even in 40s of on- source integration.

Ionization Structure

At a slightly larger scale (3 x 4 pc), the "mini-spiral" seen in the radio is also traced out by the [NeII] 12.8μm line as observed by Lacy et al (1991) with 2" resolution. In order to probe the ionization structure, we observed this region in the [ArIII] 8.99μm and [SIV]10.5μm lines. Because these species have higher ionization potentials than NeII, the proposed observations will trace any existing ionization gradient in the gas streamers. This is interesting because the UV radiation field derived from this proposed study will help to settle the question of whether the ionization is due to embedded stars or a central source near the dynamical center of the Galaxy. We did not detect either the [ArIII] line or the [SIV] line, leading us to conclude that the gas is rather weakly ionized, and that there is no enhancement of the UV field near Sgr A* at the dynamical center of the galaxy.

The "Quintuplet" and the "Pistol"

Among the unique structures of the Galactic Center, one of the most striking is the system of nonthermal radio filaments extended over 200pc, oriented perpendicular to the Galactic plane, and associated with a large-scale *poloidal magnetic* field. Recently, Okuda et al (1990) observed a "quintuplet" of 5 infrared sources within a 1pc of each other located where the straight filaments intersect the thermal filaments along the Galactic plane. These sources are enigmatic because have very high dust temperatures (500-1000K) and no hydrogen recombination lines or radio continuum emission. It is a matter of debate whether these stars are related to the structure observed in thermal radio emission known as the "Pistol," which is displaced by about 10" from the stellar cluster. It is thought that the quintuplet may be evidence for star formation in an unusual environment, possibly related to the unusual magnetic field in the region. We imaged the quintuplet stars in all six filters, and produced a mosaic of the diffuse emission of the pistol at 11.7μm. The detection of the pistol was not expected, and we were pleasantly surprised. We observed the region again in July 1993 (both imaging and high-resolution spectroscopy), and data analysis is ongoing.

Fig. 1 is an image of the central 15" of the galactic center taken at 11.7 μm. The on-source integration time is only 40 sec. IRS sources 1,3,5 10 and 7 are easily seen.

We thank G. Gull, J. Schoenwald, and T. Herter at Cornell for their support of SpectroCam-10, and the staff of Palomar observatory for assistance with the observations. SpectroCam-10 is supported by grants from NASA and the Department of Astronomy at Cornell University.

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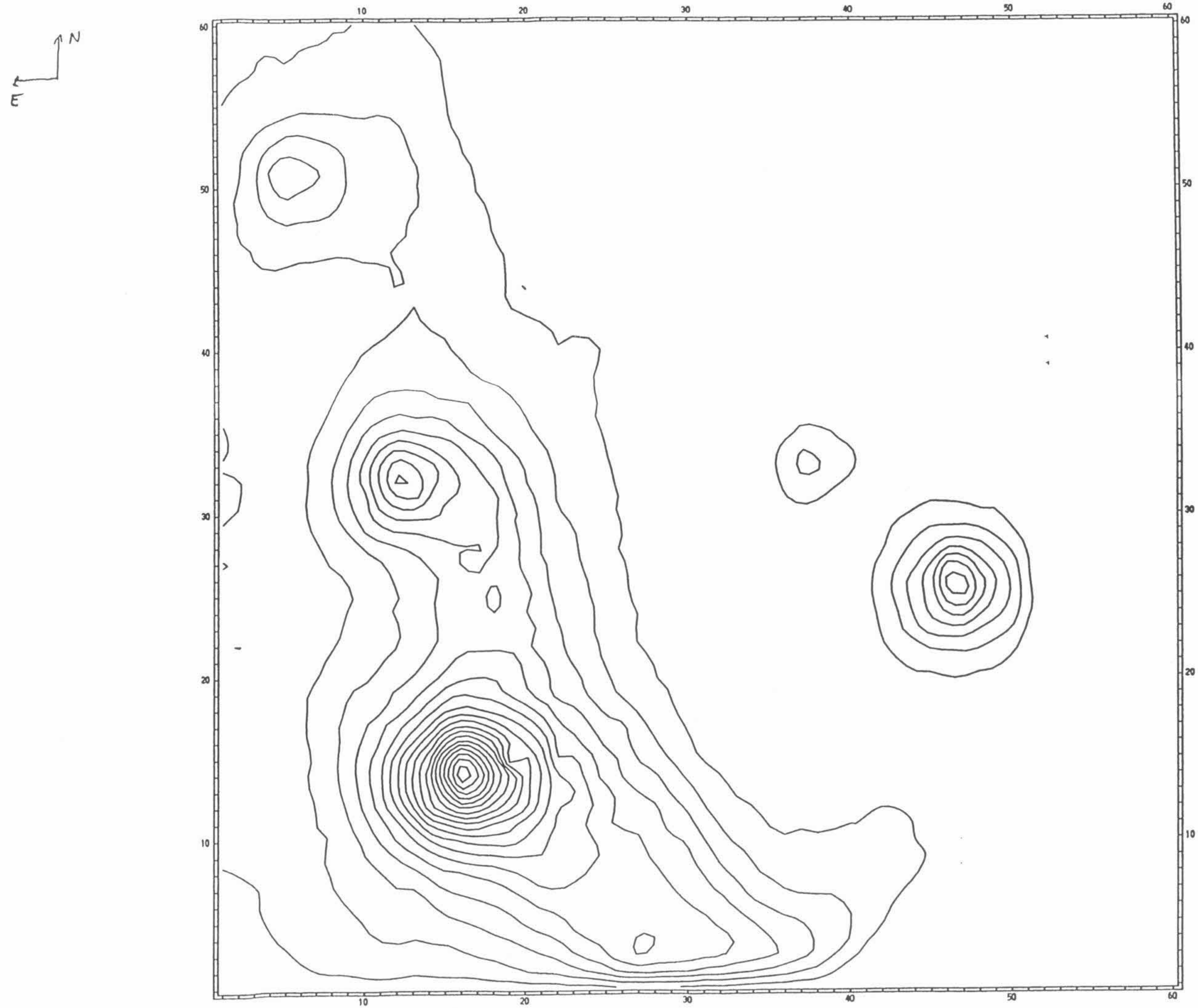
Fig. 1 11.7 microns 15" x 15" field



Radial Velocities of Mark III Binary Stars

Jocelyn Tomkin, Xiaopei Pan and James McCarthy

Subject Heading: Stars

Binaries are the key to our knowledge of the basic properties of stars. Observations of binaries can tell us how massive, how large, how luminous, and even how distant stars are.

It has long been known, by means of spectroscopic observations, that many bright stars are binaries. But, thanks to the extremely small angular separations of their components and the limitations imposed by the Earth's atmosphere, they have never been resolved as visual binaries, even by the world's largest telescopes. In recent years, however, the situation has begun to change; new observational methods are resolving bright stars as visual binaries that until now have been known only as spectroscopic binaries.

The program of optical interferometry being carried out with the Mark III interferometer at Mount Wilson is having particular success in this direction. Accurate orbits are being determined for binaries of unprecedented closeness. For example, the angular semimajor axis of α And, whose visual orbit was recently observed and measured for the first time by Pan et al. (1992, ApJ, **384**, 624), is $0.''02415 \pm 0.''00013$, which corresponds to the angle subtended by a penny at a distance of 95 miles. In terms of the geography of Southern California this is roughly the angular size of a penny in San Diego as seen from Long Beach!

Although the newly resolved Mark III binaries are already known as spectroscopic binaries, in many of them only the spectrum of the bright primary star has been seen, that of the fainter secondary remains undetected. As a result they are still able to hide their secrets from us. We are carrying out a program of spectroscopic observations on the 60-inch telescope aimed at detecting the secondary spectra and measuring their radial velocities for selected Mark III binaries. The combination of visual orbits provided by the Mark III interferometer, and spectroscopic orbits for the primaries and secondaries, provided by our 60-inch observations, will enable us to solve these systems.

For most systems our observations provide good phase coverage of their orbits, especially the crucial phases of maximum velocity separation between the primary and secondary spectra. Data reduction and measurement of radial velocities are in progress.

The reduced spectra of α And and θ^2 Tau reveal the unambiguous presence of their secondaries. This is the first time the spectrum of the secondary has been detected in either system. As a member of the Hyades cluster, θ^2 Tau is of special astrophysical importance. Our preliminary measurements of its primary and secondary radial velocities provide a mass ratio $m_{sec}/m_{pri} = 0.65$.

Star Formation in the Outer Galaxy

Principal Investigator: Stuart Vogel
Department of Astronomy
University of Maryland

Coinvestigator: Eugene de Geus
California Institute of Technology

Subject Heading: Interstellar Medium

Recently, giant molecular clouds have been discovered at kinematic distances of as large as 28 kpc from the Galactic center (Digel *et al.* 1993), placing them well beyond the relatively sharp edge to the stellar disk of the Milky Way that occurs at 14–18 kpc. Locally such giant molecular clouds are the site of most star formation. However, physical conditions, including density, temperature, the radiation field, cosmic ray flux, and chemical abundances, are markedly different in the outer galaxy, and it was unclear whether star formation could occur in the outer galaxy. It was also uncertain whether the large kinematic distances, derived under the assumption of a flat rotation curve, were correct. Our observations, described below, show that giant molecular clouds do indeed at large distances well beyond most of the galactic disk and that massive star formation is presently occuring.

The Palomar 60-inch imaging Fabry-Perot spectrometer is an optimum instrument for studying recombination line emission from the outer Galaxy because of its sensitivity to diffuse emission and because it can discriminate foreground Galactic emission on the basis of velocity. Using the Fabry-Perot we detected Hα emission for which the velocity and morphology unambiguously demonstrate that the ionized and molecular gas are associated (de Geus *et al. 1993*). The shell-shaped morphology of the ionized gas on one side of the molecular cloud was an indication of the position of the ionizing star. The ionizing star was located, and a photometric distance consistent with the kinematic distance was obtained. Therefore, it is clear that giant molecular cloud formation and star formation occur well beyond the edge of the stellar disk.

Since giant molecular clouds usually form clusters of stars, photometry of fainter stars in this region and in other similar clouds will allow more reliable distance determinations and therefore a measure of the rotation of the galactic disk at large galactocentric distances. Also such studies will provide insight into the effect of varying physical conditions on the star formation rate and the initial mass function. Finally, studies of this and other HII regions which we hope to detect will yield chemical abundance measurements which are important for understanding the evolution of the Galactic disk.

de Geus E.J., Vogel S.N., Digel S.W., Gruendl R.A. 1993 ApJ 413, L97.
Digel, S.W., de Geus, E.J., & Thaddeus, P., 1993. ApJ *in press*

"High Resolution Spectroscopy of the Shoched Gas in Supernova Remnant IC 443"

Principal Investigator: Zhong Wang
IPAC, California Institute of Technology

Coinvestigator: Xiaohui Hui
Astronomy Department, California Institute of Technology
Coinvestigator: Bryan Penprase
Physics Department, Pomona College

Subject Heading: Interstellar Medium

Our observations with the Echelle Spectrograph at the Palomar 60-inch telescope have been blessed with two clear nights out of four in Spring 1993. The telescope and instruments worked flawlessly during our entire observation. With the help of the instrument scientist and the Palomar staff, we were able to obtain high S/N and very useful data with the two nights of observing. We observed 22 positions in total, and at least nine of the stronger emission lines (ranging from [OII]λ3727 in blue to SIIλ6731 in the red) are clearly seen in most of the spectra. All of the data have been reduced now, and more detailed data analysis are in progress.

As shown in the following page, optical emission lines are strong at the positions we select to map in the vicinity of the supernova remnant. The line profiles are well resolved, and shows clear changes from one position to the other, representing changes in kinematics in different parts of the expanding shell. In particular, we find the previously unresolved broad lines split into blue and red shifted components as we move our aperture from the edge of the supernova bubble to the interior, suggesting that we are seeing both front and back sides of the shell structure. Beucase in some cases the absorption of the blue shifted part can also be seen, we can measure the optical thickness of the material inside the cavity of the supernova remnant bubble.

The velocity resolution of the optical lines is about 7 km/s, which is the highest available for this paricular object, and compares favorably with the wealth of radio and infrared data recently obtained by us and some of our collaborators. This makes physically meaningful comparisons between the data of different wavelengths. For example, at where the molecular line emission peaks, we find that the optical line width is typically 45 km/s, about half the value observed elsewhere in the supernova remnant at comparable radius. We interpret this as the dramatic slow-down of the shockwave by dense gas, and the fact that faster shocks dissociate the molecular gas rapidly also helps to explain the observed kinematics. We are still in the process of using the measured line ratios to substantiate these interpretations.

Our observations demonstrated the feasibility of high resolution emission line spectroscopy applied to the studies of shocked gas kinematics. The Echelle are different from long-slit observations or narrow-band imaging in that it gains in velocity resolution and spectral coverage at the same time. We believe a fully sampled database for IC 443 would be extremely useful for the detailed studies of supernova-ISM interactions.

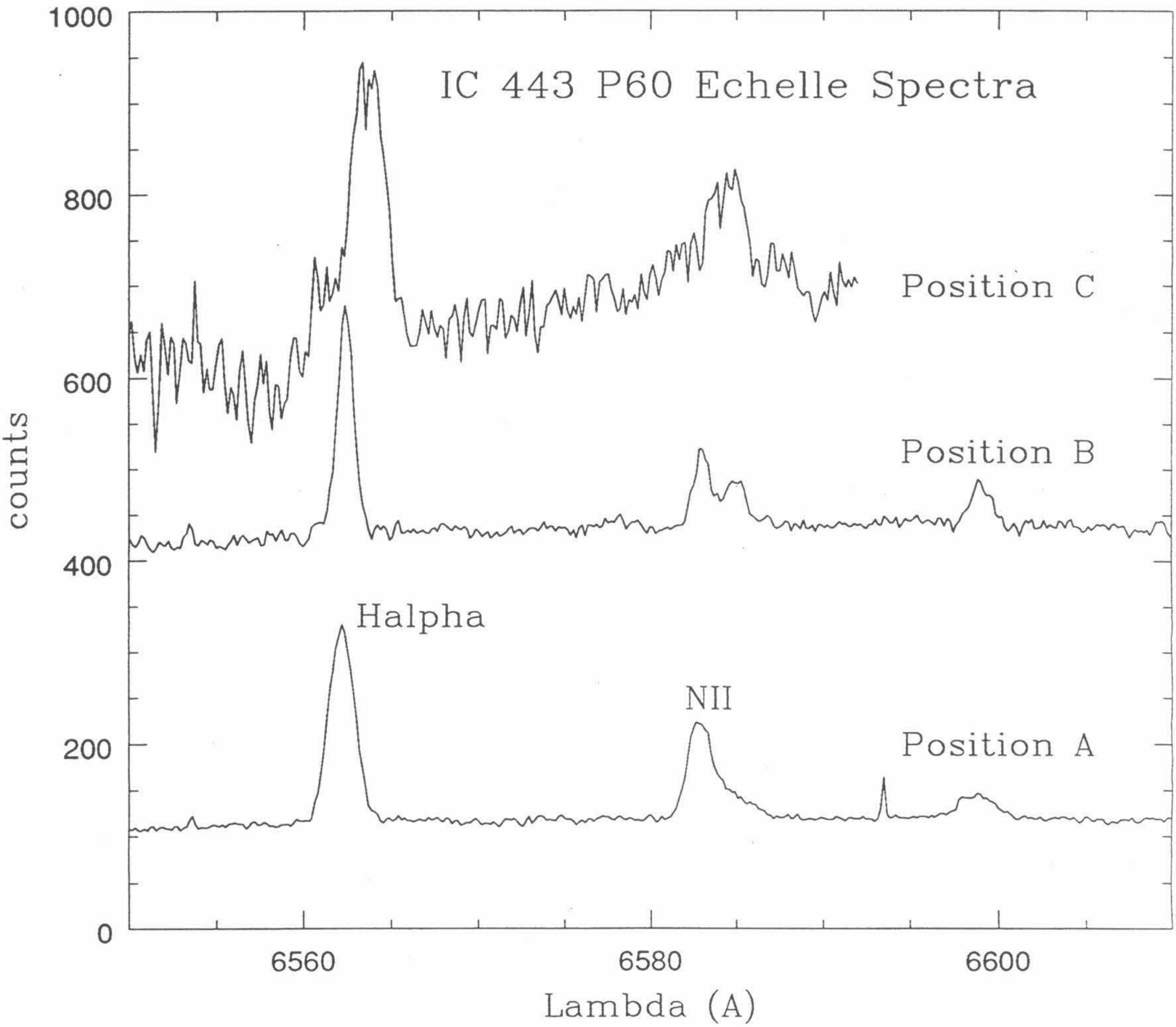


Figure 1 — A typical segement of the spectra in several positions of the supernova remnant. Position A is right at the edge of the shell, where the emission is very bright, and only a single component is seen. Position B and C are somewhat closer to the interior of the remnant, where the line is fainter, and the emission is clearly composed of a blue and a red shifted component. The relative brightness of the two components changes with position, and absorption on the blue side can be seen in some cases.

Discovery of Five Eclipsing Binaries in the Globular Cluster M 71

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Department of Astronomy
California Institute of Technology
Coinvestigators: Mario Mateo
Carnegie Institute of Washington

Subject heading: stars, binaries

We have obtained multi-epoch CCD images of the metal rich globular cluster M 71 to search for short period phototmetric variable stars. The data were taken at the Palomar 60 inch telescope with a Tektronics 1024×1024 pixel CCD. Each image has a $\sim$ 6 '×6 ' field view with a scale of 0.37 "/pixel. Images were centered on the cluster, and had exposures times of 300 and 600 seconds in both filters V and i. The Gunn filter i was chosen because most of the observing runs were during bright time. A total of 169 V frames and 160 i frames were useful from the data obtained on 15 nights (4 nights in 1991, 11 in 1993). The best seeing of the all runs was $\sim$ 0.9 " in both filters. All frames were bias subtracted and flatfielded using standard techniques. Stellar photometry was performed using the photometric reduction package DoPhot (Mateo 1990b). Then, time series analysis was applied to the multi-epoch photometry data to search for photometric variable stars.

We discovered five short period eclipsing stars among the main sequence stars. All the light curves of the variables are shown in Fig. 1. The magnitude in the figure is the intrumental i magnitude (the true i magnitude of the stars are roughly around 18, calibration is still in progress). Of the five variables we discovered, four of them have a light curve typical of W UMa type contact eclipsing binaries. W UMa type systems are contact eclipsing binaries both of whose both components overflow their Roche lobes, forming a common envelope with a contant temperature. The photometric variation is due mostly to a change in the projected area. Star 420_316 has a light curve which is qualitatively different from those of other four candidates. The presence of deep primary eclipse and very shallow secondary eclipse implies that its two components have similar sizes but very different surface brightness. We believe that star 420_316 is a detached or semi-detached Algol type eclipsing system.

The star counts down to Gunn i magnitude < 21 of the CCD images of several control fields shows that about 1700 of the 6700 stars in our M 71 field are background/foreground stars. The relative frequency of occurrence of contact binaries among field stars is about 0.1 percent for F-G dwarfs, and it is significantly lower than 0.1 percent for stars of other spectral types (Kaluzny 1993, Duerbeck 1984). Hence, at most 1 to 2 of the six variables we found in our survey field are likely to be background/foreground stars.

One important question we want to ask is: could these five eclipsing binaries be primordial binaries ? If W UMa type binaries result from the evolution of initially detached systems into contact configurations, they have to lose enough angular momentum in a time scale less than the age of the host globular cluster —probably via magnetic torques from a stellar wind in which the spin angular momentum and the orbital angular momentum are coupled through tides. This idea has been explored by many people (e.g. Eggen & Iben 1989). Estimates based on the level of chromospheric and coronal activity exhibited by components of short-period main-sequence binaries suggest that systems with initial orbital periods as long as 5-10 days may evolve into a contact configuration on a time scale of a few Gyr. Could these short period primordial binaries have survived binary-hardening collisions in the cluster M 71? If we adopt a central density of of 600 $M_{\odot}$ pc^{-3} and a central velocity dispersion of 2.3 km/sec (Djorgovski 1993), the time scale for hardening and destroying binaries with periods less than 5-10 days and component masses of $0.7M_{\odot}$ exceeds 10^{11} yrs (Hills 1990). Thus, the five eclipsing binaries we found could well be results of the evolution of short period primordial binaries, which have survived in the low central density cluster M 71. These six short period binaries thus set a strict lower limit of 0.07 percent to the fraction of primordial binary stars in globular clusters. The timescale for W UMa type contact binaries to merge into single stars is quite uncertain. Estimates range from 10^8 to 10^{10} y, depending on assumptions regarding the relevant angular momentum loss mechanisms (Eggen & Iben 1989, Rahunen 1981). However, most calculations seem to favor $\tau_{\rm merge} \sim 5 \times 10^8$ yrs. Adopting this τ_{merge}, our lower limit of 0.07 percent W UMa binaries would require at least 1.4 percent of cluster stars to have been created in primordial binaries with periods less than 5-10 days. This is in agreement with estimates of the binary fraction from other methods (spectroscopic binary searches, heating, binary pulsar models, etc.; see Hut *et al.* 1992).

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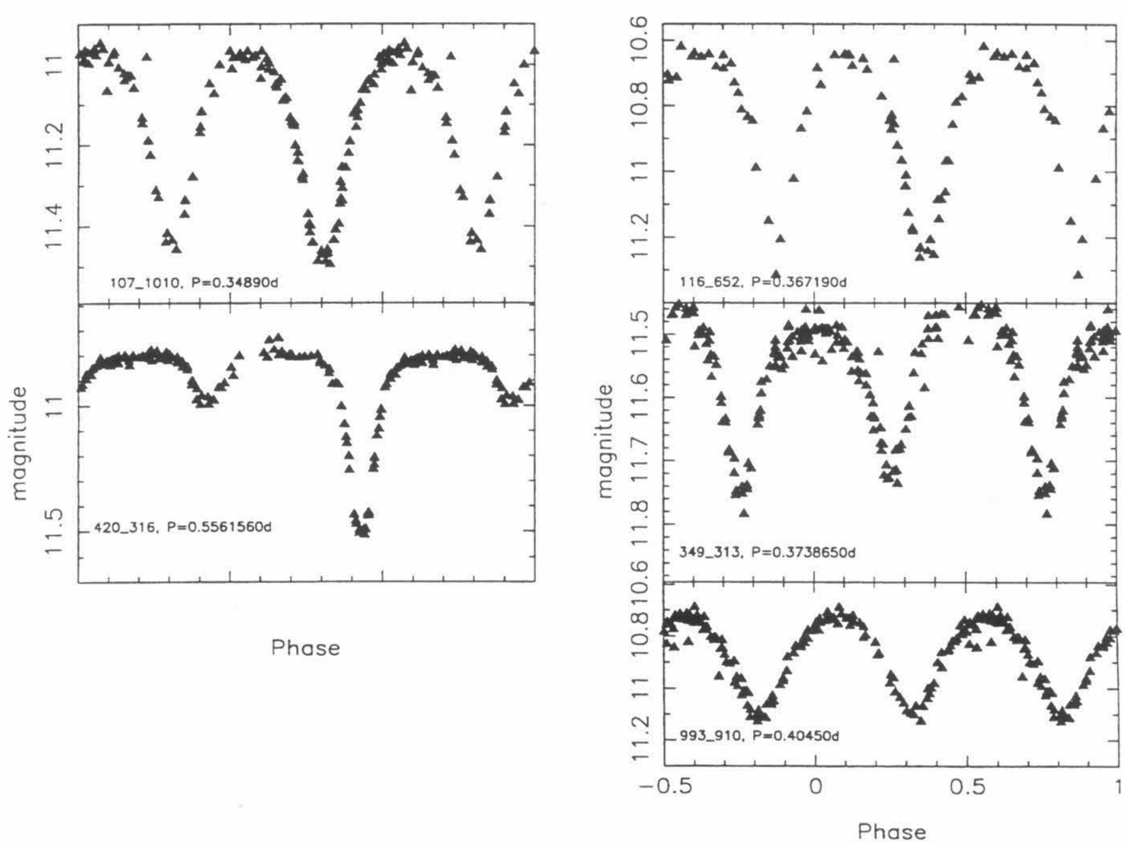
Figure 1: The light curves of five eclipsing binaries.



For the Palomar Annual Report

Study of the 12-Micron Recombination Line in Bright Stars

H Zirin, Caltech; D.E. Jennings, Robert Boyle, D. Deming and George McCabe (GSFC)

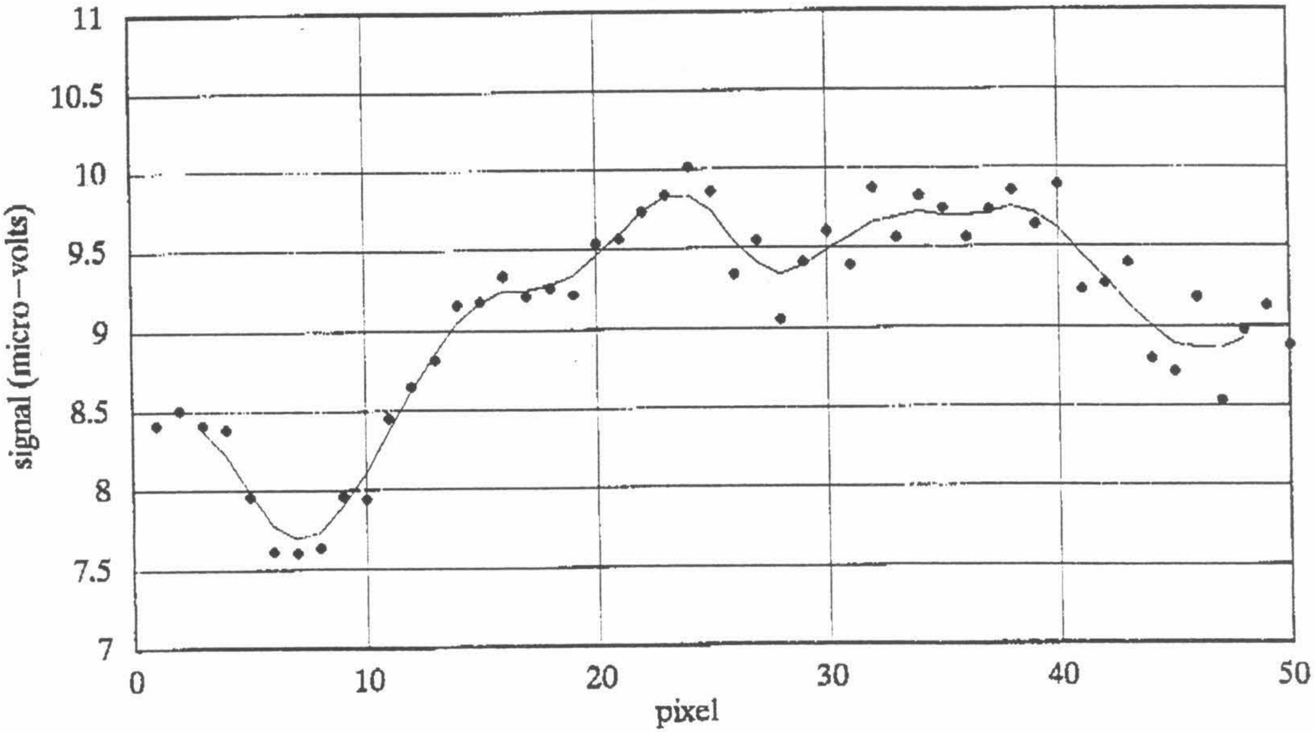
We carried out observations of the 12 micron MgI recombination line in various stars, using an IR array and the Celeste IR spectrograph. This line is seen in emission in the Sun as a result of population inversion near the temperature minimum, and its behavior in other stars is not known. The principal attraction is that the Zeeman splitting for these lines is huge, and the emission peaks in active regions, so it gives the possibility of direct measurement of magnetic fields in stars. However, the photons at this wavelength are hopelessly weak, and without a big improvement in the arrays we will be limited to about a dozen bright stars, which also are of interest.

In three nights in 1993 we obtained, despite the usual instrumental and weather problems, better spectra than anything hitherto obtained for these lines. I believe this is the first application of high-dispersion spectroscopy in this region at Palomar.

The results of our observations in August are shown in the attached figures. The spectral range is 1 cm^{-1}. Only Betelgeuse, the brightest source at these wavelengths, shows a clean spectrum. However, the others sources show some regularities which will become more significant as we get more data. The 811.59 cm^{-1} MgI line is at pixel 28. The absorption feature seen there on α Ori has been seen before, and it also appears to be present in Arcturus. These cool stars probably do not have the reversal found in the Sun. Capella and Procyon, however, should show the emission line. Either the absorption is filled in there, or the data is too noisy.

alpha–ORI, Betelgeuse

Hale Telescope, the night of 8/27/93



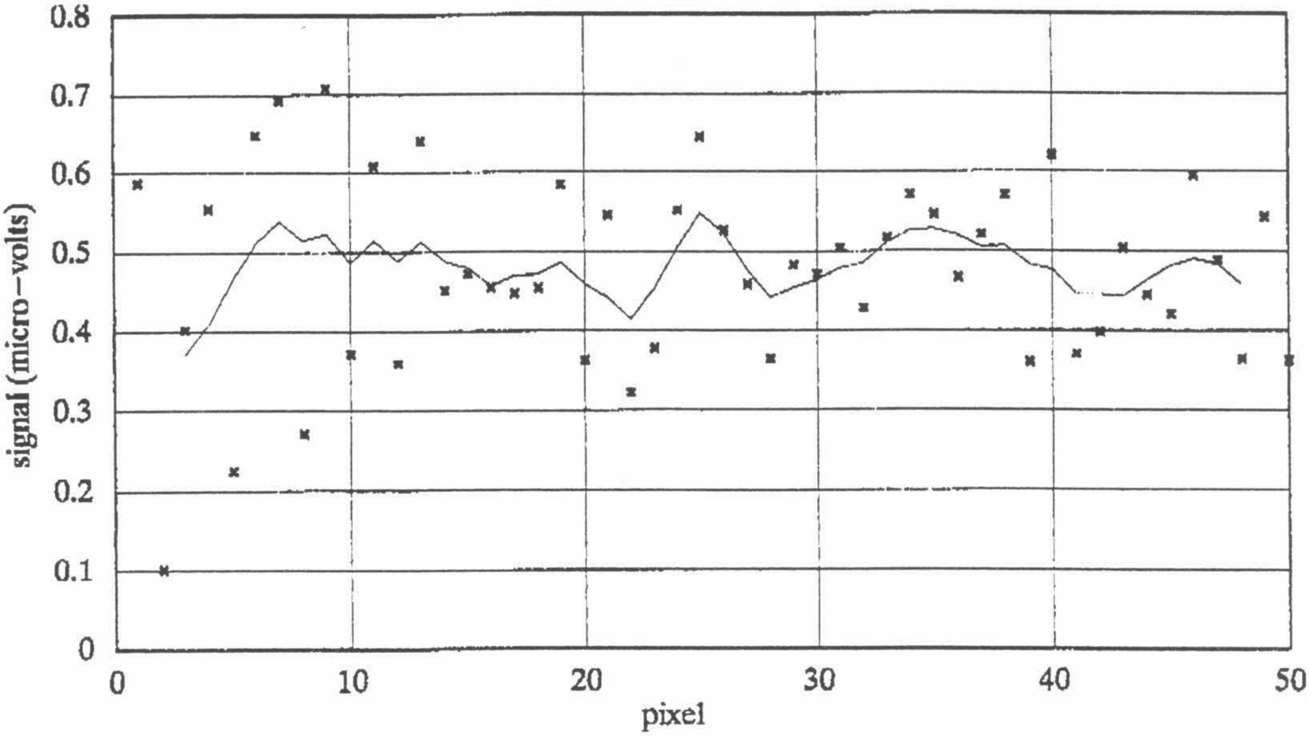
___ smoothed to 4 pixel resolution • raw* data

47min period of observation
avg air mass 1.61

Zirin
3

alpha–BOO, Arcturus

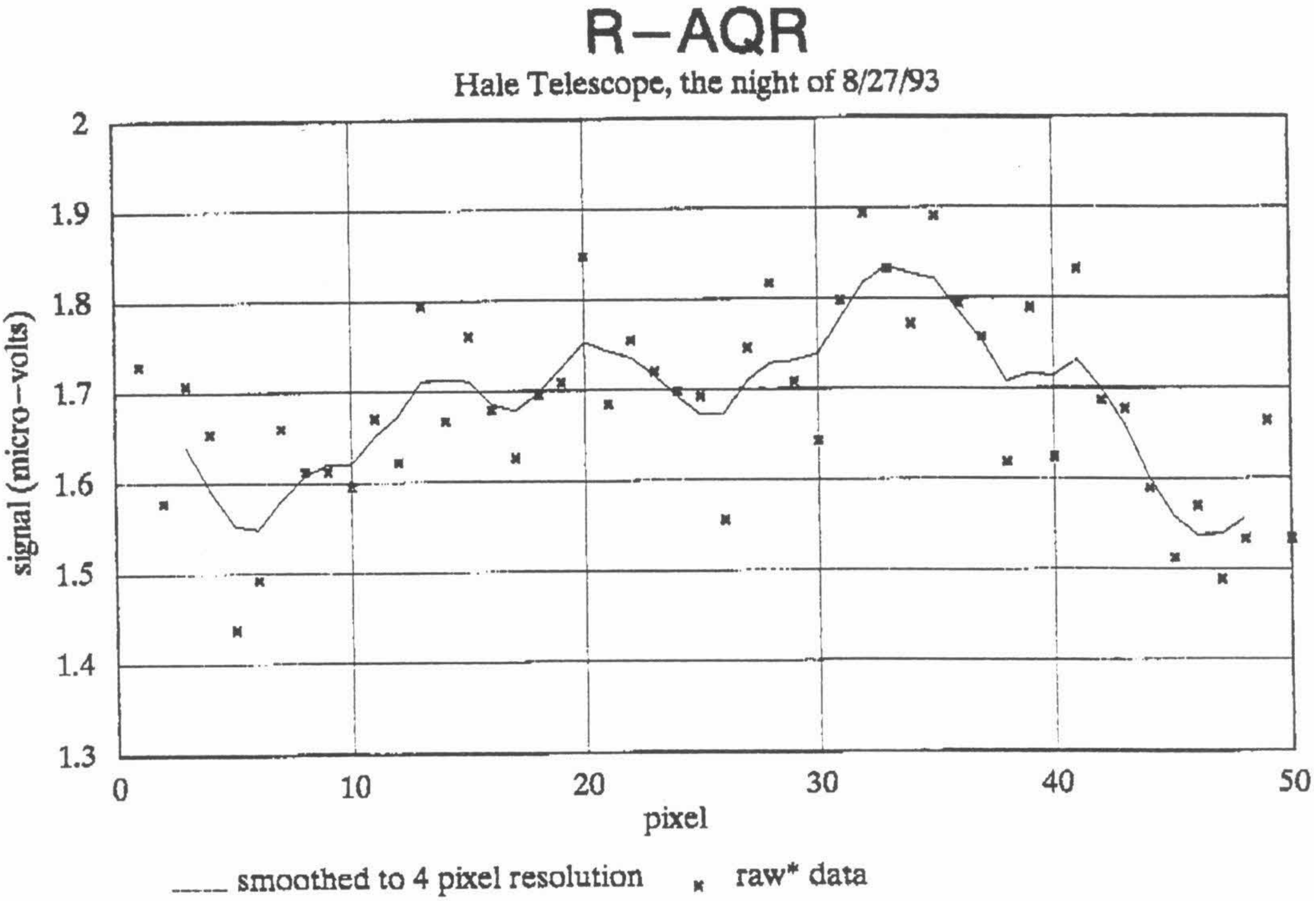
Hale Telescope, the night of 8/27/93



—— smoothed to 4 pixel resolution * raw* data

1hr 20min period of observation
avg air mass 1.98

Zirin 4

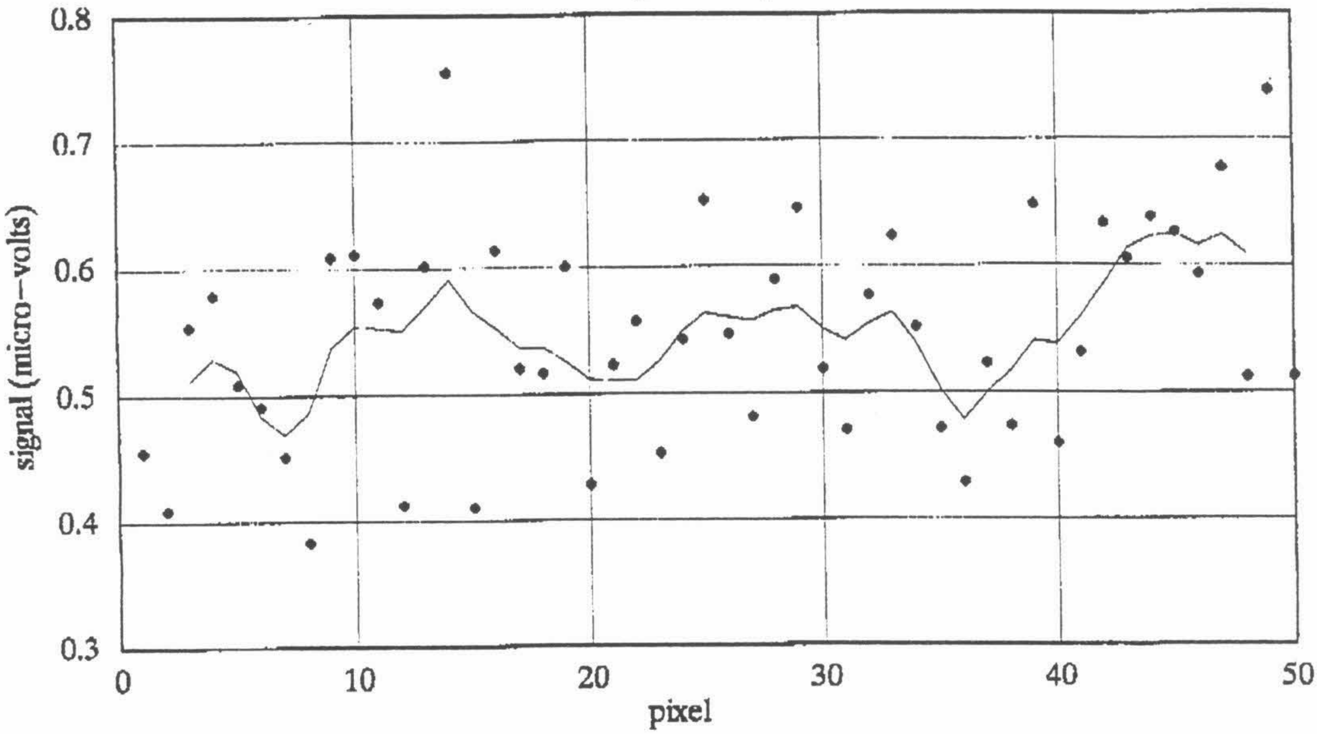


3hr 21min period of observation
avg air mass 1.62

Zwin
5

alpha−CMI, Procyon

Hale Telescope, the night of 8/27/93



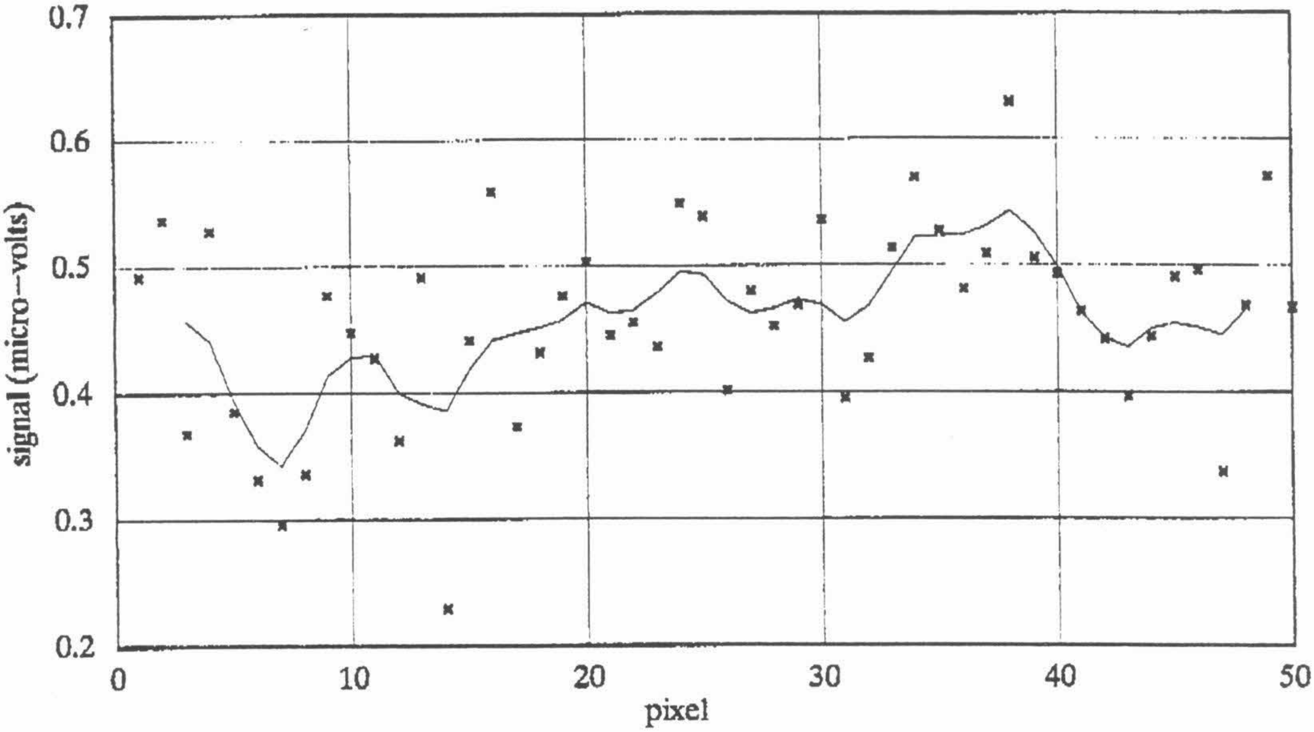
.... smoothed to 4 pixel resolution • raw* data

3hr 3min period of observation
avg air mass 1.56

2 min
6

alpha−AUR, Capella

Hale Telescope, the night of 8/26/93



___._ smoothed to 4 pixel resolution   * raw* data

3hrs 29min period of observation
avg air mass 1.06

GALAXIES AND QUASARS

Near-Infrared 2.2μm Imaging of Ultraluminous Infrared Galaxies

Principal Investigator: Lee Armus
Division of Physics Mathematics and Astronomy
California Institute of Technology

Co-Investigators: B.T. Soifer, J.M. Mazzarella, D.L. Shupe, T. Murphy
(California Institute of Technology)

and M.A. Strauss (IAS, Princeton)

Subject Heading: Galaxies and Quasars

Ultraluminous infrared galaxies produce tremendous amounts of energy, factors of 50-100 more than ordinary galaxies, but because of a great deal of obscuring dust they are difficult to study optically. They do, however, shine brightly in the far-infrared part of the spectrum. Optical imaging of the ten nearest members of the class by Sanders et al. (1988) indicated that all had distorted morphologies, very different from ordered, multi-armed spirals, but similar to what is expected from the remnants of galaxies involved in violent, destructive collisions. Infrared imaging of these galaxies by Carico et al. (1990) found a high fraction (~50%) of close double nuclei, further supporting the model of ultraluminous galaxies as galactic "train wrecks". The galactic collisions help funnel raw material, in the form of molecular gas, toward the centers where huge bursts of star formation produce energies equivalent to that generated by over one thousand billion stars.

Although the model of galaxy mergers generating the ultraluminous galaxies is appealing, there are very few in the local Universe (only 10) - not quite enough to study the nature and origins of these remarkable galaxies in any statistically meaningful sense. We have therefore, begun to obtain infrared images of a much larger sample of ultraluminous galaxies (a total of 53) chosen from the complete, deep survey of Strauss et al. (1990). These galaxies are, on average, a factor of three times further away than the original sample of 10.

Of the 53 ultraluminous infrared galaxies in the Strauss et al. sample visible from Palomar, we have imaged 37 in the near-infrared. Of these 37, 16 appear double, with 10 of these having very close double nuclei - two galactic nuclei closer together than the average size of a single galaxy itself. These objects are undoubtably in the final stages of a merger. The percentage of these ultraluminous infrared galaxies with close, double nuclei is therefore about 30%, comparable to that predicted from the study of the much smaller, nearby sample. In Figure 1, we show 4 of these twin nuclei galaxies, each labeled with their Infrared Astronomical Satellite (IRAS) designation and their distance, in millions of parsecs (Mpc).

A major goal of our study is to determine the lifetime of the ultraluminous galaxy phase, since it has been suggested that these galaxies evolve into quasars after their dust shroud clears. The quasars are the most luminous known objects in the Universe, and it is believed that they derive the bulk of their power from the accretion of gas onto a massive, central black hole. With an average nuclear separation of approximately 5 kiloparsecs (about 15,000 light years) for the 10 close nuclei galaxies, we estimate a lifetime of 100 million years - about 1% of the age of the Universe. Our continuing study of these remarkable galaxies at a variety of wavelengths will undoubtably shed much valuable light on their relationship to both quiescent, and active galaxies.

2.2μ Imaging

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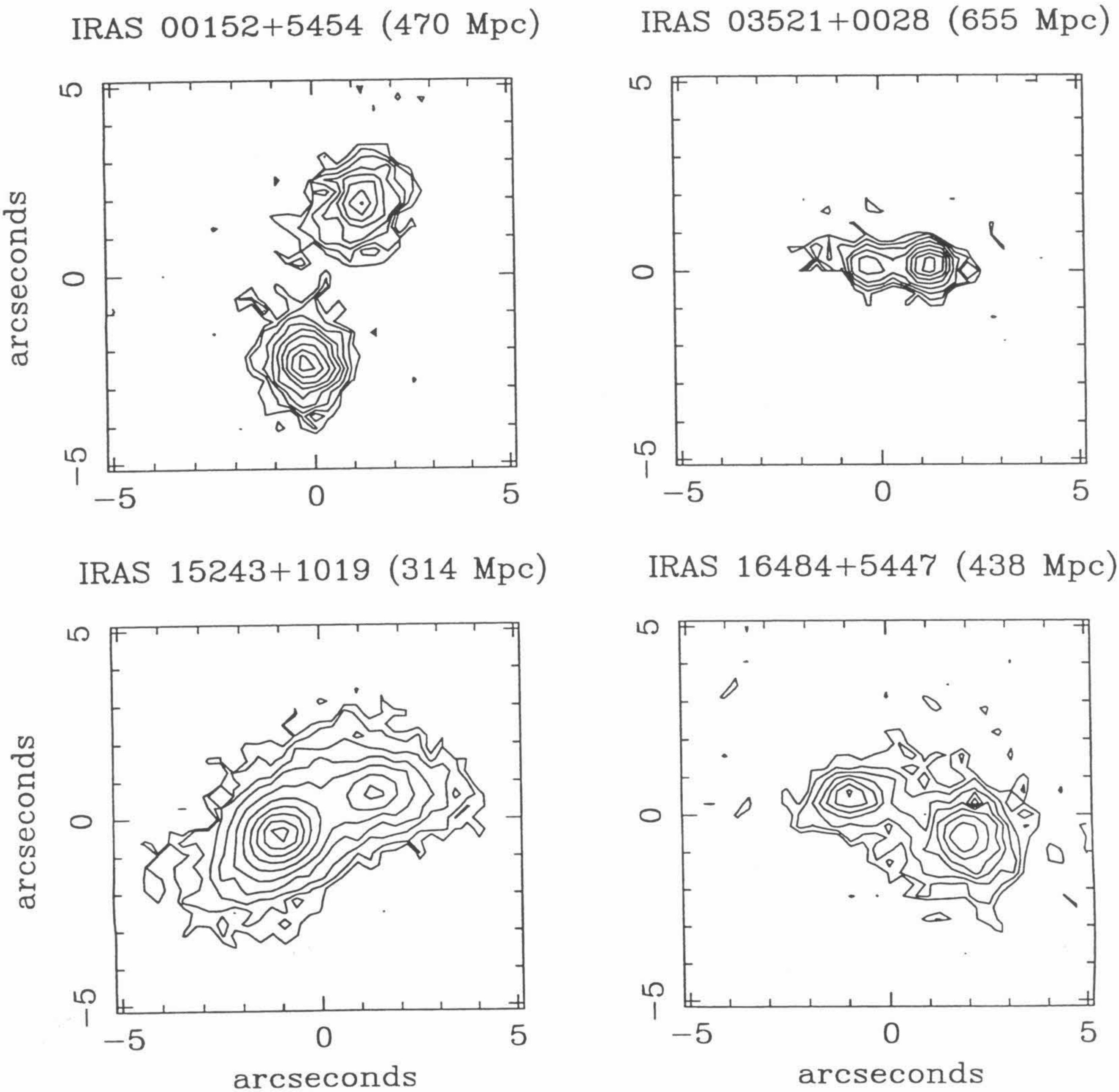


Near-Infrared [FeII] Imaging of Arp 220

Principal Investigator: L. Armus
Palomar Observatory, California Institute of Technology

Coinvestigators: D.L. Shupe, B.T. Soifer, K. Matthews, & G. Neugebauer
Palomar Observatory, California Institute of Technology

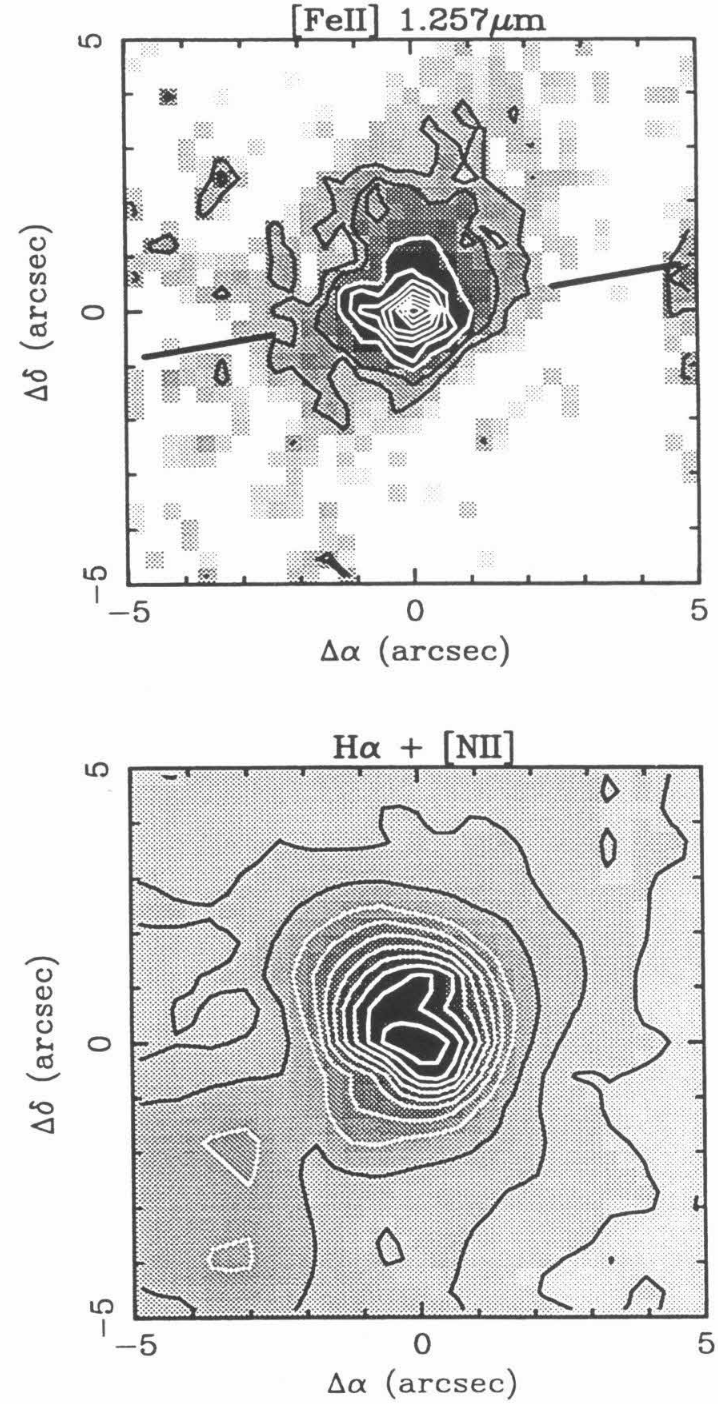
Subject heading: Galaxies and Quasars

Galaxy # 220 in the Atlas of Peculiar Galaxies (Arp 1966) is perhaps the most well studied object in the class of ultraluminous infrared galaxies discovered as a result of the Infrared Astronomical Satellite (the IRAS) mission. It is a highly distorted galaxy which emits nearly 99% of its energy in the infrared part of the spectrum. Arp 220 is as powerful as some of the the most luminous objects in the Universe – the quasars – and it is thought that it draws this power from a combination of both thermal (starlight) and non-thermal (a massive black hole) sources. It is believed that the galactic interaction and merger responsible for the spectacular morphology of the Arp 220 system also plays a major role in driving fresh supplies of fuel to the centers of its now-merging nuclei.

The ultraluminous infrared galaxies as a class are very dusty objects, and although they are very luminous, much of the detail on small scales remains hidden from view in the optical portion of the spectrum. It has been proposed that these galaxies may be able to evolve into quasars, and since quasars shine brightly in the optical, a mechanism must exist to remove much of the obscuring dust before this evolution can proceed. Through imaging and spectroscopy in the light of ionized hydrogen, there is evidence to suggest that we have found this mechanism operating in Arp 220 - a galactic "superwind" which is blowing material out of the nucleus at speeds of up to a few hundred kilometers per second, out to distances of over 30,000 light years.

A major prediction of the superwind model is that it drive high speed ($\approx$ 100 km/s) shock waves into the ambient interstellar medium in and around the nucleus of Arp 220. The shocked gas enivironment in Arp 220 is ideal for producing emission in the light of singly ionized iron ([FeII]), which has a strong emission line in the infrared part of the spectrum. We have therefore, imaged Arp 220 in the [FeII] 1.2567 micron line to further elucidate the interaction of the wind with the interstellar medium in this remarkable galaxy. We have discovered that the region of strong [FeII] emission in Arp 220 is extended on scales of over 5000 light years, and that it is roughly (although not exactly) aligned with the much larger scale optical bubbles believed to be "inflated" by the expanding superwind. With an [FeII] luminosity of about 5 million $L_{\odot}$ (it emits more than 5 million times more energy than the Sun just in the [FeII] line alone), Arp 220 is among the 5 most powerful galaxies ever measured in the light of the infrared line of ionized iron. Future work on Arp 220 and similar galaxies will allow us to exploit the dual advantages of very high spatial resolution and dust penetration afforded by our infrared observations, and to gain valuable insight into the superwind process.

Armus
Arp 220



Top: Greyscale and contours of the [FeII] 1.257μm emission line image of Arp 220. The heavy lines indicate the direction of faint Hα "bubbles" believed to be caused by a superwind emanating from the nucleus. *Bottom:* An optical image in the light of Hα + [NII] covering the same region for comparison.

Near Infrared Spectral Imaging of Ultraluminous Galaxies

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Subject Heading: Galaxies and Quasars

"Ultraluminous" infrared galaxies constitute a class of objects discovered by the *Infrared Astronomical Satellite* that emit as much as 99% of their energy at far-infrared wavelengths. Since these galaxies have luminosities equaled only by quasars, they have become a subject of intense study. Current theories suggest that the collision of two gas-rich galaxies may trigger episodes of rapid star-formation (starbursts). A highly luminous "monster," or active galactic nucleus, may subsequently form from remnants of quick-burning, massive stars. During these periods, the system would be obscured by large amounts of dust; this dust would absorb and re-radiate the energy emitted by stars and an active galactic nucleus in the far-infrared. After dust clears from the system, it is thought that the galaxy will have an appearance similar to classical quasars (Sanders *et al.* 1988). If these dust-enshrouded objects are indeed giving birth to quasars, we may be able to establish the evolutionary link between ultraluminous galaxies and quasars by determining the origin of the far-infrared luminosities.

Starbursts, active galactic nuclei (AGN), and collisions between molecular clouds are all capable of producing the observed far-infrared emission. Each of these processes can also drive strong shock waves through the galaxy's interstellar medium. These shock waves can then excite the vibrational-rotational states of molecular hydrogen; strong molecular hydrogen line emission is in fact observed in several of the galaxies. Infrared observations of this emission allow us to probe the heavily obscured galactic nuclei and study the energy sources responsible for triggering the molecular hydrogen emission. We can use this information to distinguish between scenarios where the far-infrared luminosity is powered by starbursts, AGNs, or cloud-cloud collisions.

We have imaged infrared-bright galaxies known to exhibit strong molecular hydrogen emission in an effort to determine the relative roles of starburst, AGN and galaxy merger scenarios. Our technique uses the Cornell Fabry-Perot and Caltech

Infrared Cassegrain Camera to image molecular hydrogen line emission at 2.122 μm. Comparisons of the spatial properties of line and 2 μm continuum emission discriminate between the various energy mechanisms. The spectral line width is also an indicator of the underlying physical processes. We have used our technique to show that global shocks are powering the molecular hydrogen emission in NGC 6240 (Herbst *et al.* 1990).

Two additional ultraluminous galaxies, NGC3690 and NGC7469, have also been studied to complete this program. A paper discussing the results of our observations is in preparation. NGC3690 is a nearby, interacting system containing three bright nuclear sources. One of these sources, also known as IC694, is thought to contain either a compact starburst or a heavily obscured AGN (Condon *et al.* 1991; Sargent *et al.* 1991). We have imaged the 2.122 μm molecular hydrogen line emission from this source. Aperture photometry indicates that the line emission and 2 μm continuum emission are spatially extended and are spatially coincident. The line flux is consistent with the measurements of Nakagawa et al. (1989); the linewidth is consistent with that expected due to galactic rotation. Based on our images, we conclude that this source is powered by a starburst.

In 1992, we imaged the molecular hydrogen line emission from NGC7469. This object is classified as a Seyfert galaxy and probably contains an AGN. However, extended radio emission suggests starburst activity may also be present (Wilson *et al.* 1991). As in NGC3690, the line and continuum emission are spatially coincident and extended. The line emission consists of a nuclear component and two small knots of emission located to the northeast and southwest of the nucleus. These regions appear to be spatially coincident with emission knots observed in the radio. Since the radio emission traces supernovae activity, the spatial correlation of the radio and molecular hydrogen emission suggests that the emission is triggered by shocks associated with the supernovae. We therefore feel that the emission in this source also arises from starburst activity.

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The Discovery of Two New Cepheid Variables

in the Nearby Galaxy M101

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Coinvestigators – The Four Shooter Consortium

Subject Heading: Galaxies and Quasars

The Cepheid variable stars are periodically pulsating variables which obey a well studied and understood period – luminosity relationship. This means that once the period of a Cepheid is known, its distance can be determined from its mean apparent brightness. Since the scatter about the relevant relationship is quite small as judged by analyses of galactic Cepheids and those in the Magellanic Clouds, Cepheid variables are the primary distance indicator to nearby galaxies.

The hard part is finding the Cepheids in the first place and determining their periods. When the Hale telescope was first completed, Sandage and other mounted major campaigns using photographic plates taken at the prime focus to try to find Cepheids in galaxies beyond the Local Group. He was successful for quite a few galaxies, culminating in the discovery of 17 Cepheids in NGC 2403, a galaxy in the M81 group at a distance of about 3.3 Megaparsecs (Tammann and Sandage 1968).

But that was as far as could be reached, and in the intervening 25 years no more distant Cepheid variables were found using photographic techniques. But in the late 1980s, the advent of CCD detectors, with their high quantum efficiency and linearity, made it possible to search more distant systems, and Cook, Aaronson, and Illingworth (1986) found two Cepheids in M101, the nearest ScI galaxy.

In 1985, we began a cooperative program among users of the Four Shooter imaging detector on the 200–inch Hale telescope in an attempt to detect more Cepheids in M101. Each observer was asked to dedicate 30 minutes of time to imaging of the M101 field on every dark clear night. In this way the limitations of trying to carry out a program which has unusual time requirements compared to the standard one that can be completed in several consecutive nights could be overcome. In practice, things did not work out as well as we had hoped. After several years, we accumulated about 35 images of M101, but rejected all but 17 of them because the seeing was not good enough or the sky not dark enough to be useful. These images were analyzed over the past two years, and this effort has resulted in the discovery of two additional Cepheids in M101.

We report the discovery of 2 new Cepheid variables, the first with a period of 36 days and a mean magnitude in the Thuan-Gunn g color of 24.09 mag, while the second has a period of 100 days with a mean g magnitude of 22.48. These magnitudes are transformed in a preliminary way to V, and these data are combined with data

J Cohen
M101

for the 2 variables found previously by Cook, Aaronson, and Illingworth. We derive an apparent distance modulus of 29.4 ±0.15 mag. This is the same value as is deduced from the two variables discovered by Cook, Aaronson, and Illingworth (1986) alone, which enhances our confidence in the validity of this distance determination and the size of its estimated error.

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Polarimetry of Active Galactic Nuclei

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Subject Heading: Galaxies and Quasars

Active galaxies have powerful nuclei (AGN) which radiate at wavelengths from radio to gamma rays. Some of them give evidence of relativistic motions in a beam aligned close to the line-of-sight: at radio wavelengths blobs are seen to move with high apparent velocities, greater than the speed of light (this is called superluminal motion), and at all wavelengths the radiation can be highly variable and partially polarized.

Several varieties of these AGN exist, but at least two of them, in Seyfert I and Seyfert II galaxies, are known to be the same in many cases, only viewed at different aspects. These types differ in the appearance of broad emission lines, which are strong in the type I but weak or absent in the type II galaxies. However, spectropolarimetry, which can emphasize reflected light, has revealed weak polarized broad lines in many type II's, and the interpretation is that these AGN radiate anisotropically because of an obscuring torus around the nucleus. Along the pole (type I) one sees directly into the nuclear region containing the broad-line clouds, whereas from an equatorial direction (type II) the nucleus is obscured but weak polarized broad lines can be seen, reflected from electron or dust clouds along the axis.

Further "unifications" of different types of AGN have been proposed, and one of our goals has been to see if the radio galaxies, which also come in the "type I" and "type II" varieties, can be unified in the same way as the Seyfert galaxies. The radio galaxies are faint and many exposures must be averaged to see these small effects. However, we also have found that their polarizations are variable. Thus another goal has been to study the variability, both for its intrinsic interest and so that we can know whether or not averaging is possible. One curious result we have found is that in several radio galaxies the polarizations of the continuum radiation and of the emission lines vary together - we had expected that the lines would remain constant as the continuum varied. We are now investigating the meaning of this observation.

A second goal of our work is to measure the polarization charactersitics of a number of superluminal radio sources. (We are also studying the radio properties of many of these objects.) The radio velocity and the optical polarization measurements both give information on the geometry of the presumed cones of emission, and their comparison should help to test models of the AGN, both the kinematic and the physical models. To date no clear patterns have emerged, and in particular there does not appear to be any simple connection between the optical polarization position angle and the radio velocity direction. However, these objects are faint and in addition some of them are weakly polarized, so that the statistical significance of our results is still low.

A third category of AGN we are investigating with spectropolarimetry on the Hale telescope is the Broad Absorption Line quasars (BAL). These have deep absorption troughs on the blue side of the broad emission lines, and none of them is a strong radio object. These two properties are probably connected, but they are both mysterious. It will be of particular interest to follow the polarization across the emission line and into the absorption trough, but of course the signal gets very weak there and the observation becomes very difficult. Thus we plan to observe the BAL in detail with the Keck telescope, and are using the Hale telescope mainly to determine which of the objects have strong polarization and will merit time at Keck. So far we have observed five objects, of which two look promising for more detailed study.

A Search for Quasar Protoclusters at z $\gtrsim 4$

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Co-Investigators: J. Smith, D. Thompson (CIT)

Subject Heading: Galaxies and Quasars

Understanding of the formation and evolution of galaxies and large-scale structure, and the understanding of formation and evolution of AGN are key problems in extragalactic astronomy and cosmology today. These problems may be fundamentally connected: it is now generally understood that the same kind of astrophysical processes, dissipative merging and infall, may be central to both formation of galaxies and formation of AGN, and subsequently their evolution. It is likely that AGN at very high redshifts do reside within young galaxies, simply on account of the timing: the age of the universe is at most 1 or 2 Gyr at $z \sim 4 - 5$, depending on the cosmology. The very existence of luminous quasars at $z > 4$ represents a severe timing problem. Moreover, they appear to reside within already considerably chemically evolved stellar populations, presumably cores of giant ellipticals.

Quasars at $z > 4$ offer a possibility to probe the *ab initio* large-scale structure, imprinted by the initial conditions of the primordial density field. The first structures to form via gravitational collapse should be located at the very highest peaks of the initial density field. For just about any reasonable initial density perturbation spectrum, such peaks should be strongly clustered, perhaps as strongly as the bright galaxies today. If this is true, then practically all $z > 4$ quasars should be pointing towards protoclusters in the early universe, and the optimal sites for galaxy formation. This would also be consistent with their interpretation as being the nuclei of young giant ellipticals.

In order to exploit the idea of quasars as markers of protoclusters, we have started a search for faint AGN and star-forming galaxies around the known, $z > 4$ quasars. Our goal is to find less luminous AGNs or starforming galaxies (ostensibly protogalaxies) in fields centered on known $z \gtrsim 4$ quasars. Our first method is multicolor imaging in three bands, e.g., Gunn-Thuan *gri*, where the central bandpass samples the Lyα line, and the other two bracket it and sample the continuum. The "excess" in the Lyα line, and the continuum drop across it (very prominent in high-z quasars) would leave a clear color-color signature. The quasars stand out on the color-color diagrams away from the stellar sequence which is also where most galaxies are clustered in the color-color space (Figure 1). We should be probing the AGN luminosity function nearly to the Seyfert level, and thus practically no unobscured AGNs would escape detection. Whereas this method should work for AGNs where the continuum is easily detectable, it may be insufficient to pick out very faint galaxies at these redshifts. Actively star-forming galaxies (which, at these redshifts, could well be identified as primeval galaxy candidates) should perhaps be even more numerous than faint AGNs. For them, the optimal detection technique may be Lyα narrow-band imaging, where they should stand out, regardless of what their continuum level is. Candidate objects are then followed-up spectroscopically.

To date, we have surveyed the fields of some 15 fields using the multicolor technique to select faint quasars. We are typically complete down to $r \sim 24^m$, which corresponds to nearly Seyfert 1 luminosities at these redshifts. We have also obtained narrow-band imaging data on 6 fields so far, in order to search for Lyα emission line galaxies, powered by star formation. We typically reach the flux limits of a few $\times 10^{-17}$ erg/cm^2/s, which corresponds to an unobscured SFR of $5 - 10\ M_\odot$/yr at these redshifts. So far, we have identified several interesting candidate objects, at least one of which is very likely a faint quasar at $z \sim 4.8$ (Fig.1, Fig.2), and one or two possible Lyα galaxies. These objects are extremely faint, which makes the follow-up spectroscopy extremely difficult.

Using one or two tentative detections above $r \simeq 23.5^m$ as an upper limit, we can place a constraint on the cumulative number density of faint quasars, at the luminosity level never probed before at these redshifts. Our data indicate luminosity-dependent density evolution of faint quasars at these redshifts, in the sense that the numbers of faint quasars drop faster with the increasing redshifts than the numbers of brighter objects.

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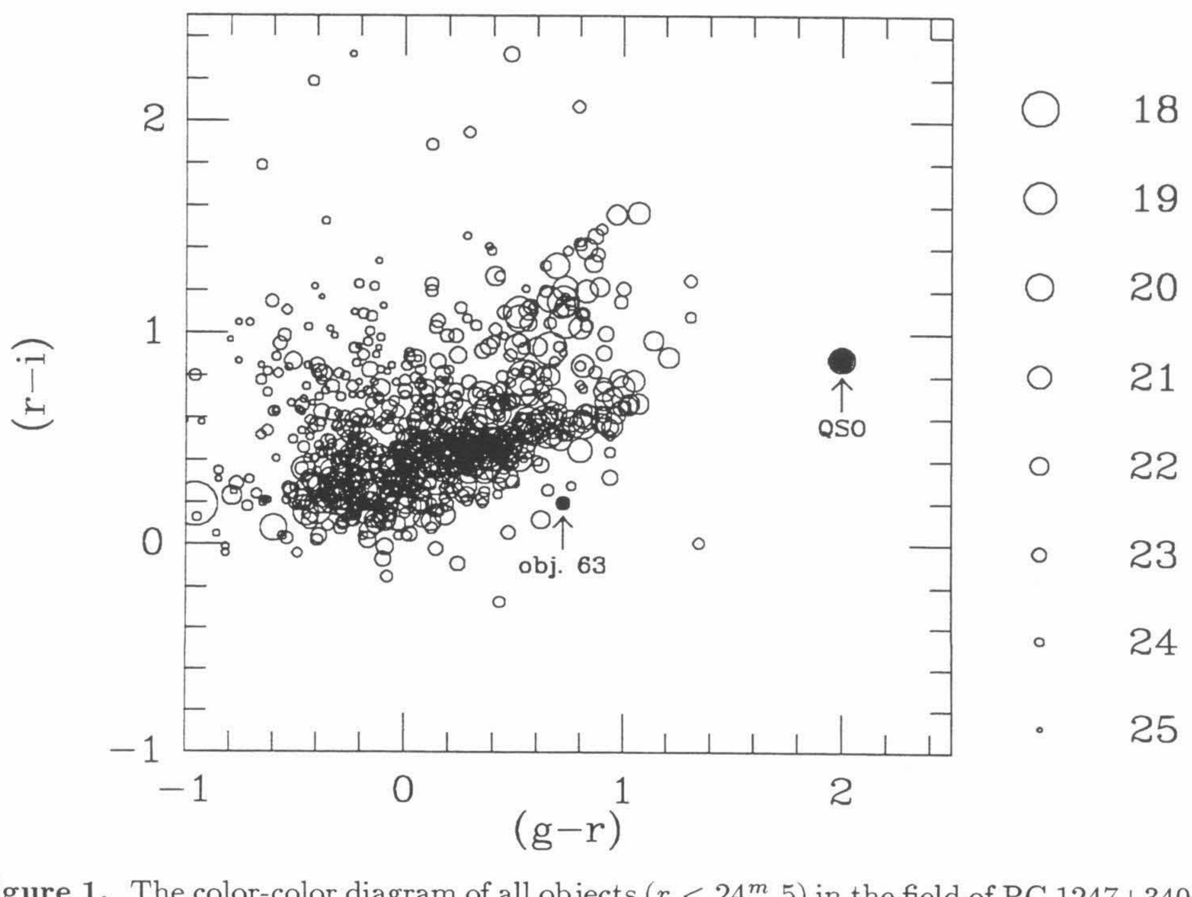

Figure 1. The color-color diagram of all objects ($r < 24^m.5$) in the field of PC 1247+3406, a quasar at $z = 4.897$, obtained at Palomar. Symbol size scales with the r magnitude. The quasar, and the candidate object 63, a possible faint ($r \simeq 23.1^m$) quasar at $z \simeq 4.8$, are marked. Their spectra are shown in Figure 2.

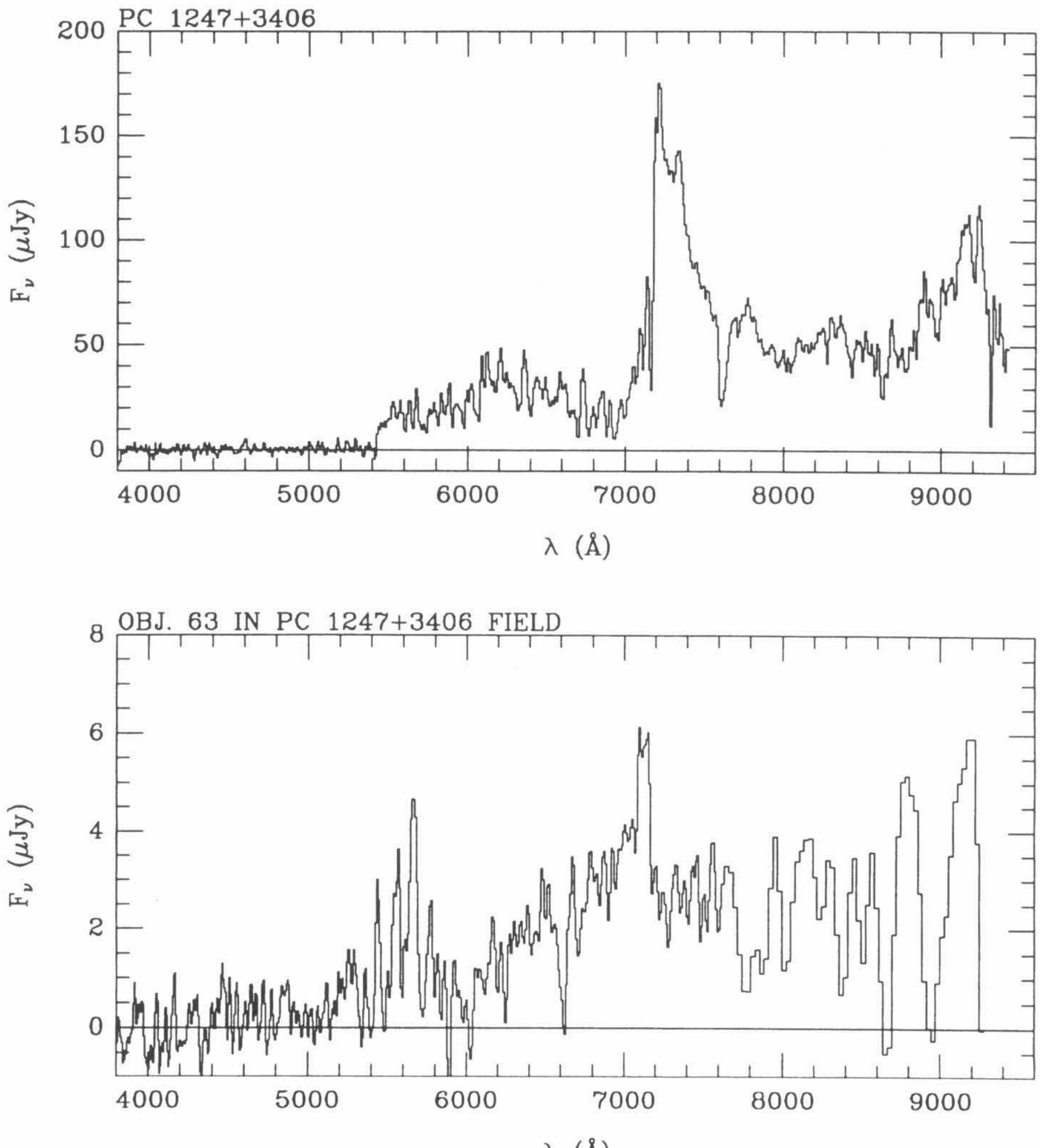

Figure 2. Spectra of the $z = 4.897$ quasar PC 1247+3406 (top), and the newly discovered quasar candidate, object 63 (bottom). Object 63 may be a faint quasar at $z \simeq 4.8$, with a rather peculiar spectrum: the Lyα line may be completely absorbed, with the N V 1240 line (now redshifted to $\sim$ 7000 Å) left over. We believe that the object is a quasar at a high redshift because of the sharp continuum cutoff at $\sim$ 5150 Å, and the continuum drop blueward of $\sim$ 6800 Å, presumably near the Lyα line. The continuum cutoff, probably caused by an intervening hydrogen disk, places a lower limit to the redshift, $z > 4.65$.

Shapes of Quasar Broad Emission Lines

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Subject Heading: Galaxies and Quasars

Broad emission lines in spectra of quasars contain a wealth of information about the physical states and processes in their central engines. Yet, there seems to be surprisingly little systematic empirical data available on their shapes. Recently, Caltech theorists Blandford, Emmering, and Shlosman proposed new models for the Broad Line Regions (BLR). They give several predictions about the line shapes, etc., which could be tested directly with modern spectroscopic observations. In particular, one prediction of their models is that there should be a well-defined minimal line core, corresponding to the typical central velocity dispersions for normal galaxies, i.e., $\sim 200 - 300$ km/s.

We obtained a set of quasar and Seyfert 1 spectra using the McCarthy Spectrograph at the Palomar 60-inch telescope, in the grism + long slit mode, in order to test the predictions of these models. After the continuum subtraction, we model the emission lines by fitting a set of Gaussian components to them (Fig. 1). From this, we can determine and subtract the narrow emission line components, which are of no interest for this project. The remaining broad lines show a range of shapes and asymmetries. They do seem to show the cores with the velocity scales of a few hundred km/s, as predicted by the models. The data have been fully reduced, and are now being interpreted by the theorists.

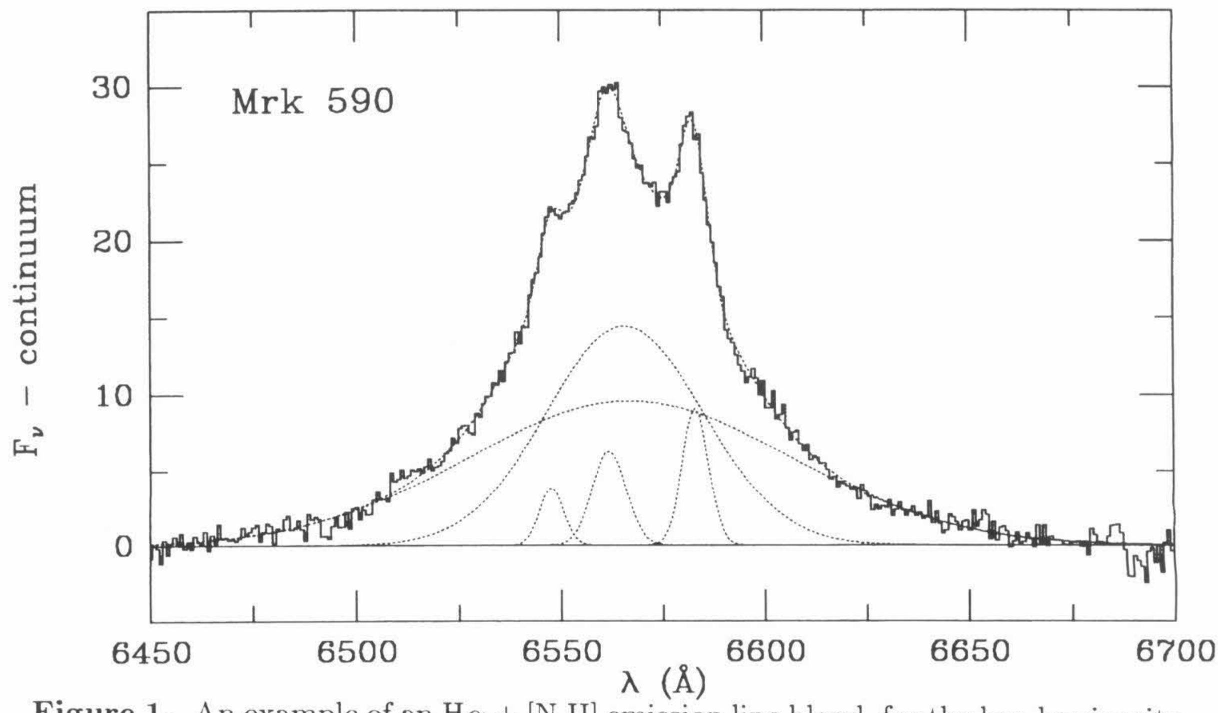

Figure 1. An example of an Hα + [N II] emission line blend, for the low-luminosity quasar Mrk 590. The solid histogram shows the observed line profile, after the continuum subtraction. The dotted lines are the individual Gaussian components from the fit, and their sum, which goes through the data points so well that it is hard to distinguish.

Calibrations and Analysis of the Palomar–STScI Digital Sky Survey

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Subject Heading: Galaxies and Quasars

Digitization of the Second Palomar Observatory Sky Survey (POSS-II) is now in progress at STScI. The resulting data set, the Palomar-STScI Digital Sky Survey (DPOSS), will consist of $\sim$ 3 TB of pixel data: $\sim$ 1 GB/plate, with 1 arcsec pixels, 2 bytes/pixel, 20340^2 pixels/plate, for $\sim$ 900 survey fields in 3 colors. We estimate that ultimately $> 5 \times 10^7$ galaxies and $> 2 \times 10^9$ stars should be detected on the POSS-II plates, reaching down to $B \sim 22^m$. A vast variety of scientific projects will be possible with this data base, including studies of large-scale structure, Galactic structure, automatic identifications of sources from other wavelengths (radio through x-ray), generation of objectively defined catalogs of clusters and groups of galaxies, searches for quasars, etc.

In order to extract useful information from this set of images, we have developed a software system to catalog, calibrate, classify, maintain, and analyze the scans. This system, called SKICAT, incorporates machine learning software technology in order to classify the detected sources objectively and uniformly, and facilitates handling of the enormous (by present-day astronomical standards) data sets resulting from DPOSS.

We are conducting an intensive program of CCD calibrations using the Palomar 60-inch telescope, using Gunn-Thuan gri bands. These CCD images serve both for magnitude zero-point calibrations, and as training and test data for star-galaxy object classifiers. We use both plate overlaps and CCD calibrations to determine and mutually check the magnitude zero-point offsets. The results are excellent for this type of plate material: On average, our magnitude offsets between different plates are uncertain to only a couple of percent, whereas the overall zero-point uncertainty of our magnitudes is not worse than about 5%. As a rule, zero-point accuracy of about 5 - 10% or better is deemed adequate for cosmological studies using this kind of data. The CCD calibration data, which generally have superior image quality, are used to construct the training sets used to train the plate object classifiers. For both J and F plates, the classification accuracy drops below $\sim 90\%$ at about the same equivalent magnitude level, $B \sim 21.2^m \pm 0.2^m$. This is $\sim 1^m$ above the plate detection limits, and $\sim 1^m$ better than what was achieved in the past with similar data. This increase in depth effectively doubles the number of galaxies available for scientific analysis, relative to the previous automated Schmidt surveys.

Our initial results on galaxy counts in two colors (photographic J and F, calibrated to Gunn g and r bands) have been done for a multi-plate region near the north Galactic Pole, covering 4 Survey fields ($\sim$ 100 square degrees). Our data set, truncated at the magnitudes where our star/galaxy classifications become unreliable, consists of $\sim 2 \times 10^5$ galaxies, and a comparable number of stellar objects. Individual plate galaxy counts in both bands are in excellent mutual agreement, and fully consistent with the poissonian and magnitude zero-point errors. The observed power-law slopes of the counts are 0.49 dex/mag in the g band, and 0.46 dex/mag in the r band.

We compare our averaged counts in the g band (Fig.1a, solid histogram) with the data from the APM group (Maddox *et al.* 1990) in the b_J band (Fig. 1a, dashed line), and a "no evolution" model in the B band, taken from Ellis (1987). We assumed the transformation $B \simeq b_j \simeq g + 0.7^m$, which is a reasonable average for fainter galaxies.

We normalized the "no evolution" model at $g \sim 17^m$. Maddox *et al.* made a point about their counts being considerably higher than the "no evolution" model, even at the relatively bright magnitudes, and interpreted that as an evidence for the field galaxy evolution at low redshifts. Our counts are similar to theirs, but with a slightly milder excess. A comparison of our averaged counts in the r band (Fig. 1b, solid histogram) with a "no evolution" model in the Gunn r band (Fig. 1b, dashed line), taken from Koo & Kron (1992), normalized at $r \sim 17^m$ gives a similar result. Here we also see a mild excess over the "no evolution" model at the fainter levels, reaching a factor of 2 at the limit of our data. We are tempted to interpret this as additional, independent evidence for field galaxy evolution at moderate redshifts. This is clearly a very preliminary result. We are now in the process of measuring angular correlation functions for these galaxy catalogs.

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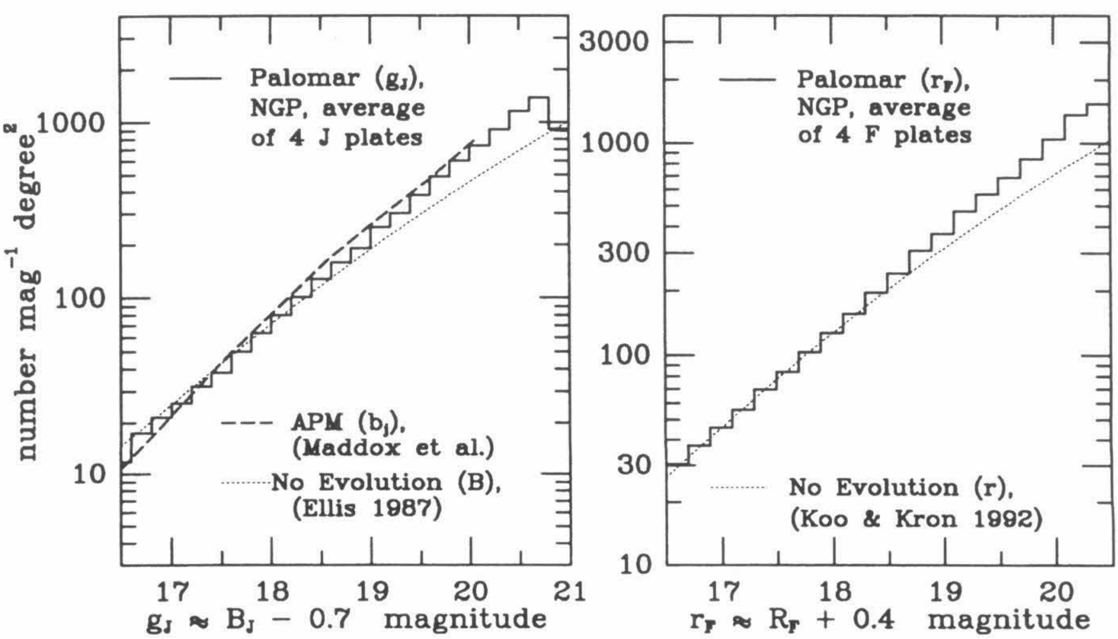

Figure 1. Galaxy counts in 0.2^m bins, rescaled to a number per magnitude and degree^2: (a) average of the four J plates, calibrated to the Gunn g band; (b) average of the F plates, Gunn r band. APM blue counts and no-evolution models are also shown for comparison.

A Search For Primeval Galaxies

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Subject Heading: Galaxies and Quasars

One of the most important experiments in extragalactic astronomy today is the search for primeval galaxies. Their discovery will be a milestone of cosmology. By primeval galaxies (hereafter PGs) we mean young ellipticals or bulges undergoing their first major burst of star formation at large redshifts. In addition to our quasar protocluster search, we are conducting two unbiased field surveys for PGs.

Possibly the simplest strategy is to select *candidate* Lyα emission line galaxies using deep, narrow-band imaging. Simple estimates for Lyα line fluxes powered by star formation and a reasonable range of cosmologies suggest $F_{Ly\alpha} \sim 10^{-16\pm1}$ erg/cm^2/s, which is reachable by present-day technology. We have built a low-resolution Fabry-Perot imaging interferometer for this purpose. The data consist of three-dimensional data cubes (Fig. 1), generated by successive exposures which are spaced by the instrument FWHM ($\sim 10^3$ km/s in the rest-frame). The field of view is ~ 5.5 arcmin square. We use 8 to 12 bands in each sequence, adding up to $\Delta z \sim 0.2$ per datacube. So far, we have searched for Lyα emission in the ranges $z \sim 2.80 - 2.98$, $z \sim 4.42 - 4.61$, and $z \sim 4.75 - 4.90$. The bandpass sequences were chosen to cover intervals between sky emission lines, and to provide a large baseline in redshift. Candidate objects are selected on the basis of both the narrow-band and deep broad-band imaging, and the most promising ones are followed up spectroscopically.

We reach limiting line fluxes of a few $\times 10^{-17}$ erg/cm^2/s. Typically, we find $\sim 10 - 20$ emission-line object per datacube, only a few of which are judged to be high-priority candidates due to their faintness, the absence of a detectable blue continuum, strength of the possible emission line, etc. So far, inconclusive spectra have been obtained for only a few of them. Even if none of our candidates are actually PGs, our limits are already in conflict with the simple CDM-based theoretical predictions.

The experiment is also yielding many foreground emission-line galaxies, in addition to any possible PG candidates (Fig. 2). These are typically galaxies at $z \sim 0.4 - 0.9$, with typical Gunn $r \sim 22^m - 24^m$ and relatively blue colors, which may be representative of the faint blue population found in deep field surveys by Tyson, Cowie and others. We hope to be able to place some constraints on the evolution of field galaxies at intermediate z's, detected through their [O II], [O III], or Blamer line emission.

We are also conducting a serendipitous long-slit spectroscopic search, using data obtained in the course of other projects. After two-dimensional sky subtraction, spectroscopic CCD frames are examined for any possible emission-line objects which may have been covered by the slit. This search complements the Fabry-Perot survey in the coverage of the parameter space: a larger redshift interval, but a smaller solid angle. We typically cover a wavelength range corresponding to Lyα at $z \sim 3 - 6$, and some of our data reach down to $z \sim 2$. Typical $\sim 1^h$ exposures reach line flux limits of a few $\times 10^{-17}$ erg/cm^2/s at best, comparable to the limits from our Fabry-Perot survey.

Only a subset of the available data has been analysed so far, and no obvious Lyα galaxies have been found (however, we *do* find objects with a single emission line, where we cannot determine the redshift unambiguously). We found numbers of faint field emission-line galaxies at redshifts reaching up to 1 (Fig. 3). Their continuum magnitudes vary, from undetected ($r \gtrsim 24^m$) to $r \sim 20^m$, typically with blue colors, indicative of active star formation. These galaxies may be representative of the faint galaxy populations seen in deep field surveys. However, our detections have a median redshift $\langle z \rangle \sim 0.7$, deeper than most field surveys.

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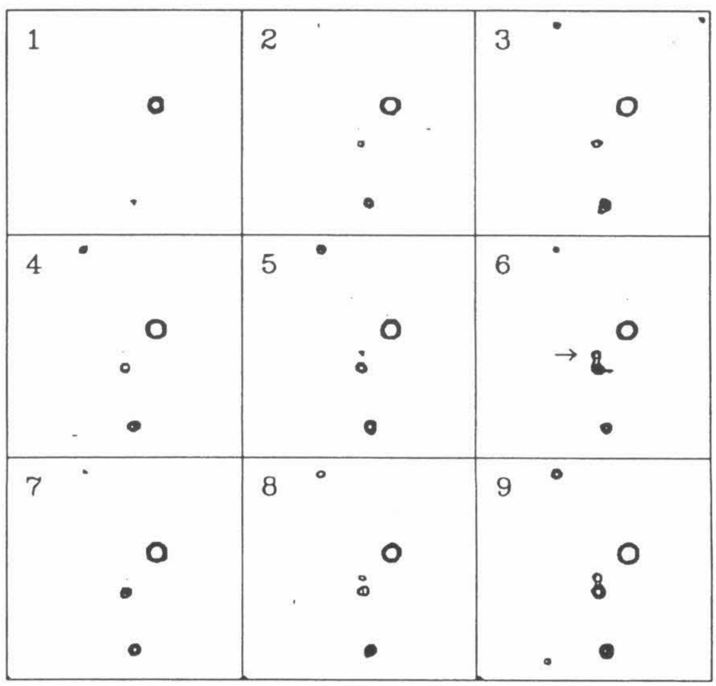

Figure 1. An example of a data cube from our survey area FP0031+34. Panels 1 – 8 correspond to individual wavelength slices; panel 9 is the average. This is a zoom-in on a candidate object (#17), indicated with the arrow in slice 6. This is an unambiguous emission-line detection. Its spectrum is shown in Fig. 2.

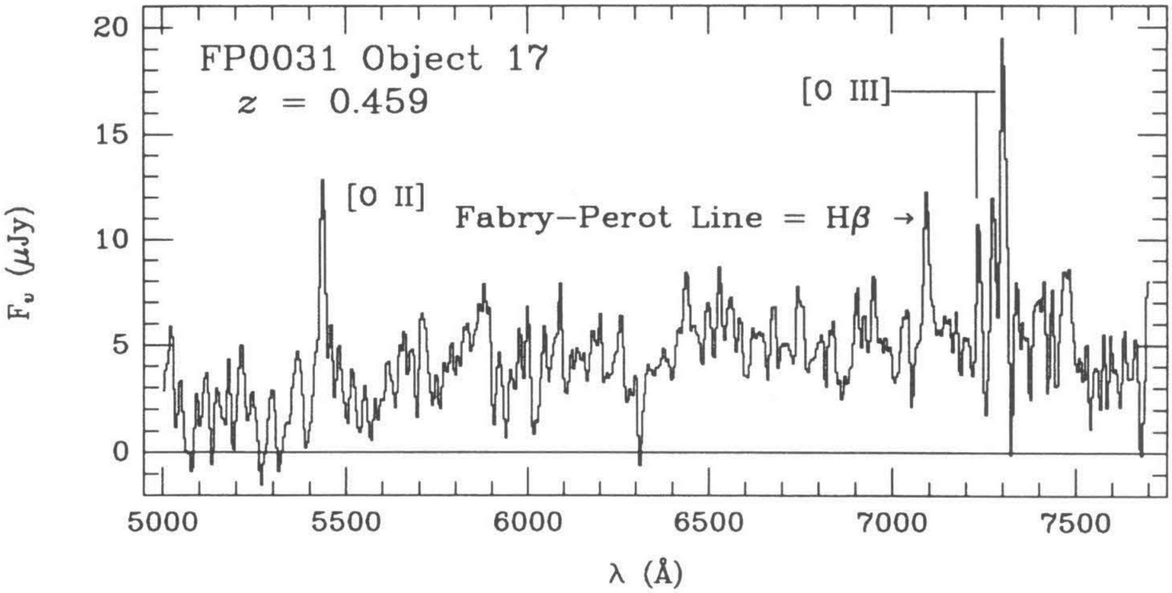

Figure 2. A spectrum of the candidate object #17 from our survey area FP0031+34. It turned out to be an actively star-forming galaxy at a moderate redshift, $z = 0.459$. The emission line which triggered the Fabry-Perot detection is Hβ 4861; other, common emission lines of ionized oxygen are also well detected.

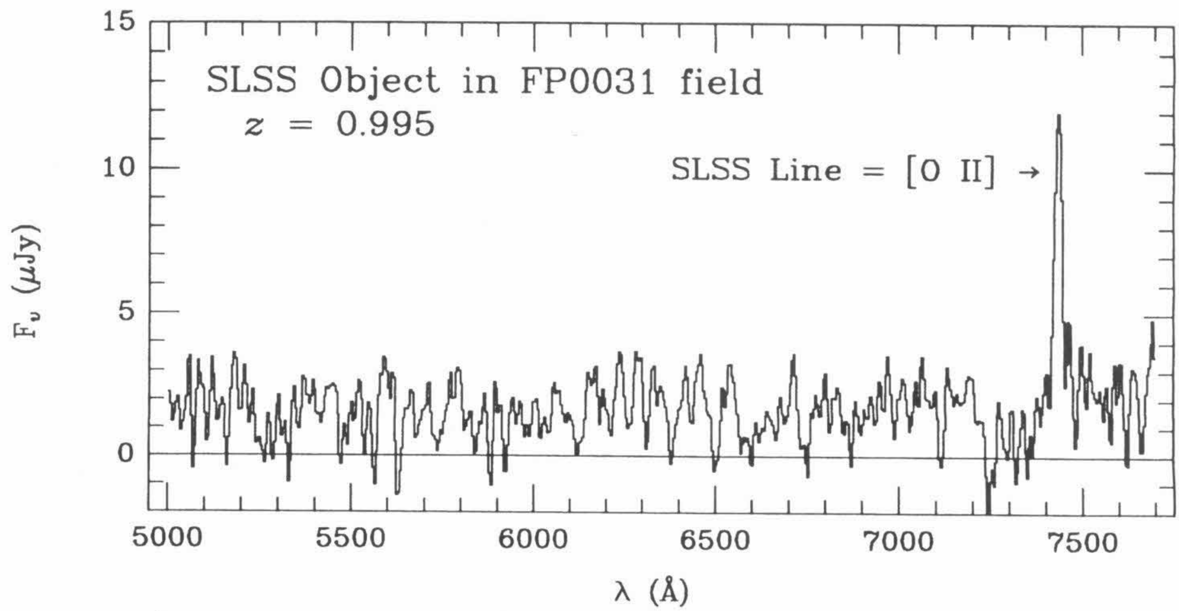

Figure 3. An example of a faint galaxy detected in the serendipitous long-slit survey, a star-forming, $V \sim 23^m$ galaxy at $z = 0.995$, with a fairly blue continuum. The strong emission line, on which the redshift determination is based, is almost certainly [O II] 3727; the shape of the continuum and the absence of other characteristic lines make the identification fairly secure.

SPECTROSCOPIC STUDIES OF THE GLOBULAR CLUSTERS of the ANDROMEDA GALAXY M31

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Subject Heading: Galaxies and Quasars

Globular clusters are known to be the oldest stellar systems and are are believed to have formed during the collapse of their parent galaxy. Our Galaxy, for example, has about 150 globular clusters which have been well studied, not only in attempting to understand galaxy formation, but also their formation as well. They have the distinct advantage of being readily identifiable and are bright enough to permit detailed analysis.

The study of globular clusters associated with other galaxies can supplement and re-inforce our conclusions based upon studies of galactic globular clusters. The nearest galaxy like our own is the Andromeda galaxy (also known as M31). This galaxy is about a factor of two larger than our Galaxy and is only about two million light-years distant. The number of globular clusters known to exist in M31 is about a factor of three more than what has been found to be associated with the Galaxy.

Globular clusters are the principal components of the haloes of galaxies, and have the distinct advantage of capturing and retaining the ingredients of the proto-galactic gas during their formation. The temporal enrichment of this gas by nucleosynthesis can then be traced. An obvious question arises as to whether the chemical enrichment of the protogalaxy gas captured by these clusters is directly due to the epoch of formation. An alternative explanation is that their enrichment is due to a less direct situation, such as being formed out of denser gas, which might have undergone more rapid nucleosynthesis.

Besides serving as fossils of the pre-galactic goo from which they came, globular clusters can also serve as tracers of the gravitational potential or mass of their parent galaxy. The mass of a spiral galaxy is traditionally obtained from an analysis of a galaxy's rotation curve – which is just the coherent distribution of velocities of a certain type of satellite such as a star or cluster of stars which surround a galaxy. The globular clusters of M31 are excellent objects for this type of study as their apparent size is sufficiently small to be observed as a single entity. There are not many galaxies which can be studied in this way, as even for the M31 globular clusters are becoming sufficiently faint that only the largest telescopes can be used.

The Norris Spectrograph, the multi-object fiber spectrograph on The Hale Telescope, has been used in its inaugural program to obtain accurate velocities and chemical abundances for nearly 200 globular clusters found in and near M31. The Norris Spectrograph allows the simultaneous observation of 176 objects at a single time. With this multiplex ability, this large program can be done in only a few nights. If we had used a more traditional spectrograph, such as that of the Hale Telescope's Double Spectrograph, the amount of time required would be around a factor of 50-100 larger.

The Norris Survey of M31 clusters has obtained an excellent data set at high spectroscopic resolution which translates into accurate velocities good to 15 km/sec, and accurate estimates of the chemical composition. All of the data have been reduced and are currently being analyzed. There are a few conclusions that we can deduce rather immediately from the analysis performed so far. The globular cluster system of M31 behaves kinematically as if it were a warm gas with a velocity dispersion of 160 km/sec and the system as a whole rotates with a semi-amplitude of 80 km/sec. Both of these results are similar to what is derived from studies of the globular clusters found in the Galaxy. From an analysis of the velocities of the M31 globular clusters, we have derived that to a mean radius of fifteen thousand light-years the mass contained within that radius is two hundred billion solar masses. This result is consistent with other measurements using different techniques.

It is anticipated that over the next year, additional data will be obtained for globular clusters that are remote from the center of M31. This will not only allow our mass determination to extend to greater distances but also to study how the system as a whole behaves and whether the system can be logically divided into sub-systems which might have formed similarly.

1

Halo Dynamics and Masses in Virgo Ellipticals

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Subject Heading: Galaxies and Quasars

In spiral galaxies, HI rotation curves are measured far beyond the optically bright disks and are usually flat at large radii, indicating a dark halo whose mass is often several times the luminous matter. Because most early type galaxies contain very little gas, and individual stars are too faint to observe, information on the stellar kinematics and mass distribution in these galaxies is usually derived from integrated absorption spectra. However, the rapid falloff of surface brightness limits such measurements, and high signal-to-noise spectra are only possible in the bright central regions. Very little is known about the halos of early type galaxies.

We have undertaken a program to study the halos of early type galaxies using planetary nebulae (*i.e. individual stars*) as test particles. Because planetary nebulae (PNe) are emission line objects, they can be efficiently identified against the sky and galaxy background with [OIII]λ5007 on-band/off-band images. With a multifiber spectrograph, the radial velocities of $\sim$100 PNe can be obtained in a single night. The feasibility of this technique has been demonstrated in our studies of NGC 5128, the nearest giant elliptical galaxy and a merger remnant (Hui 1992, *Ph.D. thesis*). Using the characteristic [O III] λ5007 line, we have measured velocities of over 400 PNe in the galaxy with an accuracy of 15 km s^{-1}. The PNe cover the entire galaxy to a radius of *10 kpc* and extend to *20 kpc* along the photometric major axis. Based on the rotation curve and the velocity dispersion profile, we derived the radial dependence of the mass-to-light ratio by assuming that the velocity dispersion is isotropic. The M/L ratio increases from $\sim$ 4 at the center to $\sim$ 10 at 20 kpc, suggesting the presence of a dark halo around the galaxy. More recently, we have obtained approximately 150 PN spectra in the Sombrero galaxy on the AAT, showing that the method is feasible for galaxies more distant than 10 Mpc.

It is important to extend the planetary nebula study to the Virgo Cluster, where giant elliptical galaxies are abundant. By studying the planetary nebula kinematics in a half dozen or so galaxies, we expect to infer more generally the halo dynamical properties and mass distributions, hence a better understanding of the structure of giant elliptical galaxies. Last year, we continued our effort to survey for planetary nebulae in the Virgo ellipticals. In the limited time available for real observing, we took approximately 3 hours of [O III] λ5007 on-band exposure of M87, the brightest giant elliptical galaxy in the Virgo Cluster. About 40 planetary nebulae were identified to a galactic distance of 20 kpc. The velocity of these planetry nebulae will be obtained in the future spectroscopy observations.

The H_0 Key Project: The Distance of M81

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Subject Heading: Galaxies and Quasars

The H_0 Key Project for Hubble Space Telescope aims to employ the Cepheid period-luminosity relation to measure galaxy distances out as far as the Virgo cluster, and to calibrate secondary distance indicators to reach to the Coma cluster and beyond. Distances for galaxies at such substantial redshifts will yield a reliable value for the Hubble Constant and the expansion age of the Universe.

Secondary distance indicators are the uncalibrated yardsticks of astronomy and include the Tully-Fisher relation, surface brightness fluctuations, the planetary nebula luminosity function, the type I supernova standard candle, and the study of the expanding photospheres of type II supernovae. The major part of the Key Project has been deferred until the first Hubble servicing mission scheduled for the end of the current year.

In nearby galaxies, however, it has been possible to discover Cepheids with the aberrated Hubble telescope. Photometry with the COSMIC camera in good seeing on the 200 inch telescope has played a crucial role in calibrating our observations of Cepheids in the galaxy M81, permitting the identification and study of these variable stars in significant numbers, and allowing measurement of periods from light curves two magnitudes fainter than has been possible from the ground.

We obtain a distance for M81 of 3.6 ± 0.3 Mpc (Freedman *et al.* 1993, Hughes *et al.* 1993).

After the HST servicing mission in December Cepheids as distant as the Virgo and Fornax clusters should be similarly accessible to the aberration correcting WFPC2 camera (Trauger *et al.* 1992). In the Key Project Cepheid distances to twenty galaxies are designed to calibrate the five secondary distance indicators noted earlier, so that systematic differences between them can be measured and eliminated. The goal of the project is determination of the Hubble Constant to 10% accuracy.

Photometry in M81 was carried out in the course of other programs with the COSMIC camera, in particular during observations for the DEEP survey described in last year's Annual Report.

During one of these observing runs we made a significant photometric contribution to the light curve of the most distant supernova yet discovered (redshift 0.458). The luminosity of this event is consistent with a low value of the cosmological deceleration parameter (Perlmutter *et al.* 1993).

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Follow up Observations of a Deep IRAS Field

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Subject heading: Galaxies and Quasars

A decade ago, the IRAS space mission made an un-biased survey of the sky at infrared wavelengths that cannot be observed with ground based telescopes because of absorption by the Earth's atmosphere. Although the IRAS all sky survey has been published for many years, it has only been recently that a subset of the IRAS observations have been adequately processed to look at the faintest sources accessible to the satellite. This subset of observations was acquired using pointed "filler" mode rather than survey mode observations. The sources found in these pointed observations are typically 10 times fainter than the sources found in the normal survey, but only a small fraction of the sky is covered.

What are these faintest sources? More importantly, are the faint sources found in the pointed mode real or are they artifacts of noise in the detector or of many faint sources adding their signals in the relatively low resolution IRAS detectors?

In order to answer these questions, about half the area covered in the filler mode was imaged in the optical by a mosaic of 11 four shooter frames (each covering 1/16 sq deg). In addition, this same area was observed using the Very Large Array (VLA) in New Mexico at radio wavelengths. The radio survey, in contrast to IRAS, has a small beam and locates radio sources with high precision. It was therefore possible to identify optical counterparts with individual IRAS sources. Using the double spectrograph at Palomar, optical spectra were obtained of each of the sources with an IRAS signal to noise ratio exceeding five. Near infrared photometry was obtained with the Cassagrain infrared detectors at the 200-inch of these same sources.

As expected, each of the brighter (> 50 mJy) sources can be clearly identified with faint galaxies. The galaxies appear to follow the relationship between radio emission and infrared emission established for brighter galaxies. Furthermore, their near infrared colors show they are most likely normal spiral galaxies surrounded by warm dust. The redshifts are consistent with those extrapolated from brighter galaxies detected by IRAS.

It would, of course, have been exciting if the faint infrared sources would have belonged to an entirely new class of object. The Palomar and VLA observations, however, established that most likely there is not an abundant new class. Most importantly, they verified that the faint filler mode observations, in at least this case, are valid. Since one use of the filler fields is in determining number counts of galaxies at low infrared flux levels, this confirmation is essential. The ground base observations thus show the importance to space measurements of follow-up observations at a number of wavelengths using a variety of techniques.

Supernova 1993 J

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Subject Heading: Galaxies and Quasars

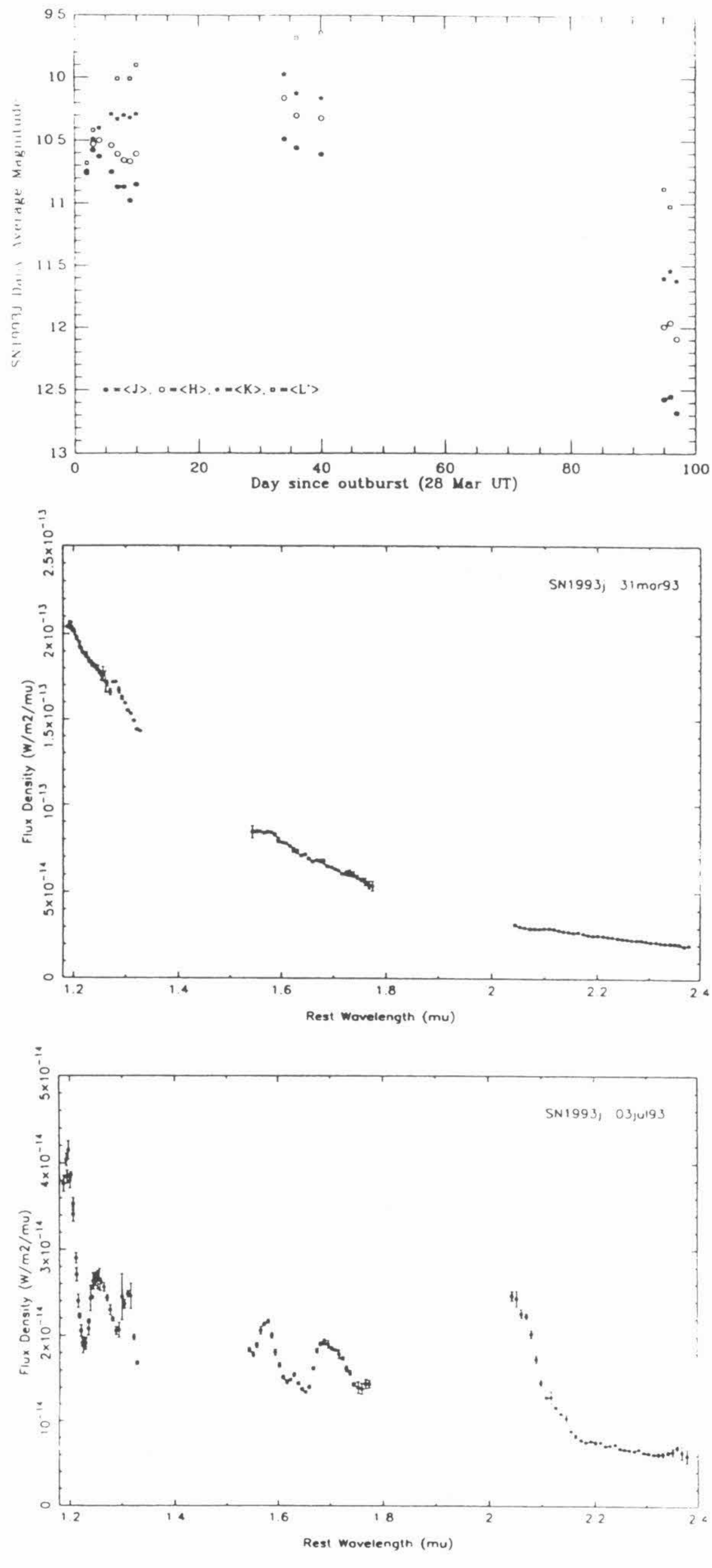
An understanding of supernovae is important for many areas of astrophysics. Unfortunately their occurrence is unscheduled and their appearance changes rapidly with time. Thus their study cannot be planned, but requires an ongoing observational program which is flexible enough to let the observer make the necessary observations. Fortunately we have such a program in place.

Supernova 1993J erupted in the nearby galaxy M81 (10 million light years away) on 29 March 1993. It is a type II supernova, resulting from the core collapse of a very massive ($M > 25 M_\odot$) star which had lost most of its hydrogen envelope prior to the explosion. Because of its nearness, SN1993J will probably become the best studied supernova except for the recent supernova in the Large Magellanic Cloud, SN1987A. Luckily, observers in the infrared group were scheduled on the Cassegrain infrared camera on the following few nights and in light runs in succeeding months. Thus it has been possible to obtain photometry of the supernova at 1.3, 1.65, 2.2 and 3.7 μm. The results are shown in the top panel of the accompanying figure. In addition, it has been possible to obtain low resolution spectra from 1.2 to 2.4 μm on about a dozen nights covering the first six months of the object before it disappeared behind the Sun. Early and late spectra are shown in the bottom panels of the figure.

The near infrared light curve shows an initial sharp rise at day $\sim$3, a second, much broader brightening between days $\sim$15-30, finally followed by a slow decline in luminosity after day $\sim$40. The near infrared colors show a pronounced reddening over the course of this evolution. It is seen that shortly after the outburst the spectrum is featureless corresponding, it is thought, to an initial expansion of a photosphere around the supernova that radiates like a blackbody. Later on, when the gas is cooling and the brightness of the supernova decreases, strong hydrogen lines become prominent (e.g., the Paschen β line at 1.28 μm) and iron lines appear around 1.6-1.8 μm.

This is clearly not a finished story. Observations will resume when the supernova again can be observed. Especially relevant will be the expected onset of thermal emission from dust which might well show up first at 3.7 μm. These infrared data will be combined with data obtained at a variety of other wavelengths in order to present a complete picture of the supernova.

Supernova 1993J
Neugebauer et al



Near-infrared light curve and representative spectra of SN 1993J. The light curve follows the evolution over the first 100 days, while the spectra show the change in continuum slope and line flux at two epochs, 31 March, and 3 July, 1993.

Velocity Shifts in Quasar Broad Emission Lines

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Subject Heading: Galaxies and Quasars

The nature of the close quasar pairs, Q1634+267A,B (separation 3.77 arcseconds) and Q2345+007A,B (separation 7.03 arcseconds), has not been established with certainty. In both systems, the spectra of the two components are remarkably similar and yield the identical redshift within the measurement errors. Since quasar spectra, despite sharing defining characteristics such as strong emission lines with velocity widths of thousands of kilometers per second, are quite heterogeneous, the similarity of the spectra of the two components of these quasar pairs suggests that the two components are in fact two gravitationally-lensed images of a single quasar. However, in neither case has a candidate lensing galaxy been identified, even though such wide separations between the component images require the lensing galaxy to be unusually massive and luminous (Steidel and Sargent 1991, Soifer *et al.* 1993). Accordingly, the possibility is still entertained that the pairs are binary quasars with physical separations of tens of thousands or a hundred thousand light-years. A resolution of the question is of considerable importance because such quasar pairs are essential for measuring the sizes of the intervening systems responsible for the absorption lines seen in many quasar spectra (Foltz *et al.* 1984). Unfortunately, however, the limits determined for the sizes depend strongly on whether a particular close pair is a manifestation of lensing or an actual physical binary.

Steidel and Sargent (1991a) recorded high quality spectra of Q1634+267A,B and Q2345+007A,B in order to examine critically the degree of similarity of the two components of each pair. They found that the continuum shapes of the two spectra were nearly identical, but they also discovered that the ultraviolet emission lines of the two components of Q1634+267A,B exhibited velocity shifts of as much as 1000 km s^{-1}. The overall similarity of the spectra of the components of each pair convinced the authors that the two pairs were indeed the product of gravitational lensing. In order to explain the velocity differences of the emission lines, they predicted that the velocities of individual emission lines in quasar spectra must vary on a timescale which is less than the roughly one year time difference between the light paths of the two images.

There are two indirect arguments for believing that the velocities of the emission lines in quasars must vary. First, it is well known that the velocities determined for different ions in a quasar spectrum often differ by 1000 km s^{-1}. Since the distribution of velocity differences is broad with a mode that is consistent with 0 km s^{-1} (Steidel and Sargent 1991b), it is likely that these velocity differences reflect variability in the velocities of of the emission lines, although on an unknown timescale. Second, variability of emission lines in the spectra of Type 1 Seyfert nuclei, which are believed to be less luminous cousins of quasars, is well established. Notably, an application to quasars of the empirical Seyfert galaxy relation between the timescale of variability of emission lines and continuum luminosity leads to an estimate of the quasar emission line timescale of roughly one year, in accord with predictions of Steidel and Sargent (1991a) based on the gravitational lensing time delay.

We decided to test the prediction of Steidel and Sargent (1991a) by searching for velocity changes in 30 quasars, each of which was observed on two occasions separated by a year or two. An identical instrument setup, the Double Spectrograph attached to the 200-inch Hale telescope, was used for all of the observations. The spectra are all of exceptionally high quality.

Direct comparison of the spectra from the two epochs reveals several emission line velocity shifts ranging from a few $\times$ 10^2 km s^{-1} to 1500 km s^{-1}, although the majority of objects do not exhibit any measurable shifts. The spectra from the two epochs are remarkably similar, except for overall changes in fluxes, which have been reported by many previous investigators, and for minor differences in the shape of the continua, which may be artifacts introduced by the observing procedures. Our results therefore lend support to the hypothesis that the wide-separation quasar pairs with very similar redshifts and spectra, like Q1634+267A,B and Q2345+007A,B, are in fact lensed systems in which the observed emission line differences between the two components are due to intrinsic variations in the single, lensed quasar.

In Figure I below, we plot an example illustrating both the overall similarity of the spectra from the two epochs and the emission line velocity shifts.

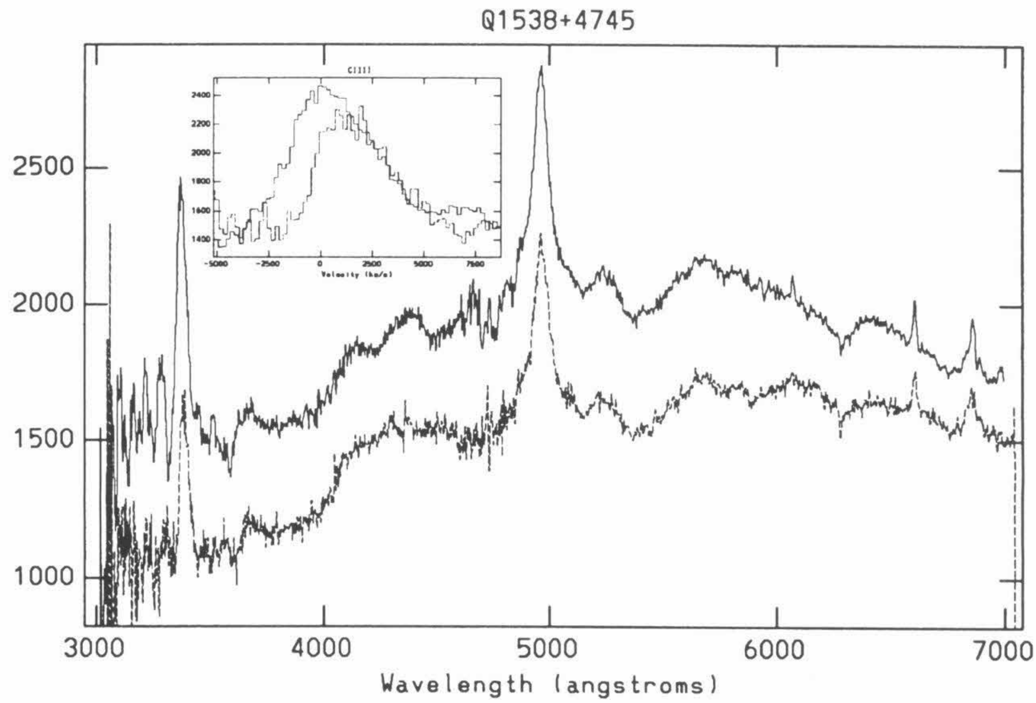

Figure I. Spectra of Q1538+4745 (z = 0.77) recorded on 1989 July 14 (solid line) and on 1992 June 16 (dotted line). The units of the ordinate are micro-Janskys. The inset displays an expanded view of the CIII] 1909Å emission line (cosmologically redshifted to 3379Å), showing a velocity shift of 1125 ± 88 km s^{-1} between the two epochs. The spectra in the inset plot have been scaled so that their continua match.

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High Redshift Quasar Surveys

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Subject Heading: Galaxies and Quasars

Quasars were discovered thirty years ago as star-like objects with large redshifts. Even though they are not much bigger than our solar system, they outshine even the biggest galaxies containing tens of billions of stars. Observations of nearby quasars show that they are located at the centers of galaxies; they probably derive their luminosity from processes associated with the accretion of matter from the host galaxy into a black hole with a mass of a hundred million suns. Some quasars are as much as 1000 times more luminous than the galaxy in which they reside. Thanks to their extraordinary brightness, quasars can be detected to far greater distances than galaxies. Extensive surveys for such quasars, conducted at various observatories (including Palomar) over the last 15 years, have shown that their numbers at given luminosity increase dramatically with redshift: for quasars of average luminosity, the space density at redshift 2 is a hundredfold of that at redshift zero.

Schmidt, Schneider (Institute for Advanced Study, Princeton), and Gunn (Princeton University) have been engaged for ten years in a major program to find out how quasars behave at redshifts larger than 2. They conducted a large survey that has produced hundreds of quasars with redshifts ranging from less than 1 to over 4, including 141 quasars with redshifts between 2.0 and 4.75. At these redshifts, the light from an object takes 12 – 14 billion years to reach us, assuming that the Big Bang, which started the universe, happened 15 billion years ago. Schmidt *et al.* find that the number of quasars was essentially constant in the redshift range 2 – 3, and that beyond redshift 3 a steep decline in the numbers sets in. Translated into cosmic times, the number of quasars rose sharply from 1 billion to 2.5 billion years after the Big Bang, and then declined to the present epoch at 15 billion years.

Schmidt *et al.* are now engaged in a survey based on imaging through four red filters. Comparison of the image strengths on the four images allows the selection of objects that may be quasars with a redshift in the range 4.0 – 5.5. Spectroscopic observations of the candidate objects are required to determine whether or not they are high redshift quasars. This program has produced four quasars with a redshift larger than 4, including a quasar with a redshift of 4.90, the largest on record to date. The survey now covers around 30 square degrees on the sky. Spectroscopic follow-up of the large numbers of candidate objects is continuing.

Young Globular Clusters Formed in Galactic Merger

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Subject Heading: Galaxies and Quasars

Our understanding of how globular clusters formed is still very rudimentary. In our own Milky Way galaxy, all such clusters of about 10^5–10^6 densely packed stars are quite old (~12–17 billion years), implying that they formed very early in the history of the Universe. Yet, during the past few years, tantalizing evidence has suggested that some globular clusters may form as part of the bursts of star formation that accompany collisions and mergers of spiral galaxies. If so, this might explain why many more globular clusters are observed per unit luminosity in elliptical galaxies, now increasingly thought to be the remnants of merged spirals, than in spiral galaxies themselves.

As part of a long-term spectroscopic study of merger galaxies, we obtained first spectra of two faint bluish knots in NGC 7252, a prototypical remnant of two spiral galaxies that began merging about 1 billion years ago (Schweizer 1982). These two knots are merely the brightest of a half dozen knots discovered in the early 1980's and long suspected to be young star clusters because of their blue colors and extremely high intrinsic luminosities. We used the Double Spectrograph of the Hale 5-meter telescope in August 1992 to record the spectra, knowing that *Hubble Space Telescope* was scheduled later that year to obtain direct images of NGC 7252 that would hopefully yield diameters for the candidate star clusters.

The spectra of the two knots show unmistakably that the knots are, indeed, extremely luminous clusters of young stars in NGC 7252. They show strong Balmer absorption lines ($H\alpha$, $H\beta$) due to hydrogen in the atmospheres of massive young stars as well as various weaker lines due to iron, magnesium, and calcium. From these absorption lines and the absence of any emission lines, we conclude that the clusters are relatively young (10–500 million years), have ceased forming stars, and are moving within the halo of NGC 7252 with velocities of the order of 100 km s^{-1} (Schweizer & Seitzer 1993). The luminosities of these clusters of young stars are extraordinary: the two observed clusters are about 600 and 150 times as luminous as ω Centauri, the brightest globular cluster in our Milky Way (corresponding to absolute magnitudes $M_V = -17.1$ and -15.5 for a Hubble constant of 50). These extreme luminosities do not necessarily indicate that there are more stars in these distant clusters than in Milky Way globulars, only that there are still many bright, young stars in them. Model calculations suggest that these clusters of young stars will fade by $3\,^1/_2$–7 magnitudes, or factors of 25–600, as they age over the next 10–20 billion years.

The only question that our spectroscopic observations from Palomar could not address concerns the sizes and shapes of these clusters: are they globular clusters of densely packed stars that will continue to gravitate together for a long time, or are they more open clusters that will disperse with time? Happily, observations with the ***Hubble Space Telescope*** made in October 1992 have not only answered this question, but also led to the discovery of many more similar clusters in NGC 7252: the average diameter of some 40 blue knots detected from space is 10 parsec, or just about the mean diameter of the old globulars in our own Milky Way (Whitmore *et al.* 1993). Therefore, there can be little doubt that these blue knots in NGC 7252 are, indeed, young globular clusters.

These young globulars must have formed during the galactic merger, since their ages are less than the age of the merger itself. The clusters' likely progenitors in the precursor galaxies were giant clouds of molecular gas, which were triggered into collapse and star formation by the high pressure of the surrounding gas during the merger (Jog & Solomon 1992). These violent events of the recent past in NGC 7252 may offer us a valuable glimpse of much more ancient events that led to the formation of the Milky Way globulars during the early collapse of our own galaxy.

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Thermal Imaging of Ultraluminous Galaxies

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Coinvestigators: L. Armus, B.T. Soifer, G. Neugebauer,
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J.W. Miles, T.L. Hayward, J.R. Houck, Cornell University

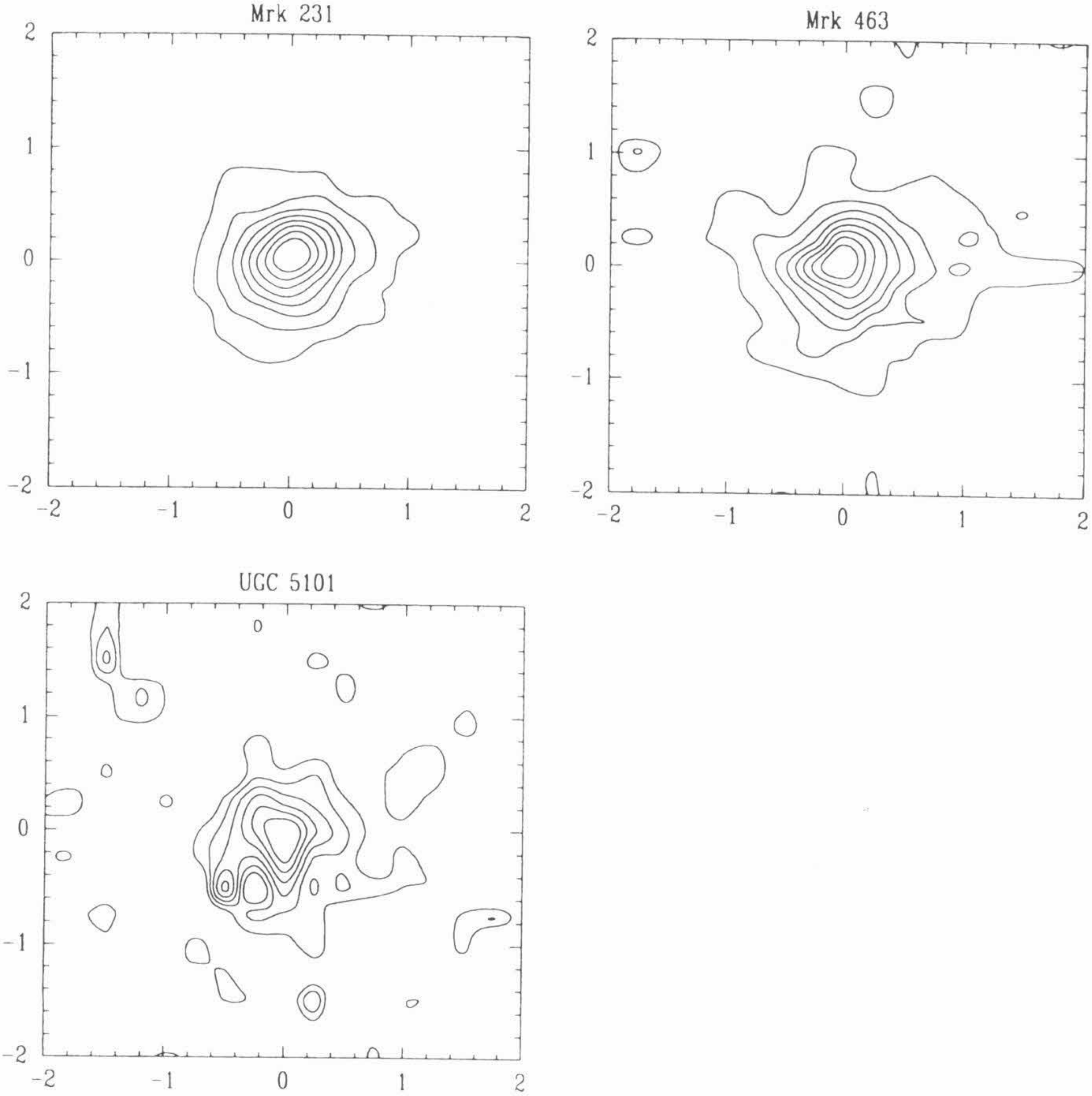
Subject heading: Galaxies and Quasars

One of the major discoveries of the *Infrared Astronomical Satellite* was a class of galaxies with very high far-infrared luminosities. These "ultraluminous" infrared galaxies can emit as much energy as the most luminous objects in the Universe–quasars. The mechanism that powers the tremendous infrared emission from these galaxies is not yet established. The luminosity could originate from a burst of star formation, or from a dust-enshrouded active nucleus powered by a massive black hole. Imaging of infrared-luminous galaxies at 10 μm can provide important clues as to which of these mechanisms are at work, since it is sensitive only to warm (30-50 K) dust grains. Extended mid-infrared emission must be due to a starburst, since even a very luminous active nucleus cannot heat dust past a distance of more than about 100 parsecs (about 30 light-years). If the 10 μm emission is unresolved, it suggests an active nucleus as the engine, although a very compact nuclear starburst could also be present.

In 1993 we began a project of 10 μm imaging of ultraluminous galaxies using SpectroCam-10, the new facility instrument provided by Cornell University. At these long wavelengths, the limit on spatial resolution is not set by atmospheric distortion, but instead is due to diffraction and hence the size of the primary mirror. The combination of SpectroCam-10 and the 200-inch telescope therefore currently provide the highest spatial resolution in the 8-13 μm atmospheric window.

As of this writing we have used SpectroCam-10 for one night in March 1993. We obtained images of Mrk 231, Mrk 463, and UGC 5101 in each of three filters chosen to sample a strong dust absorption feature at 9.7 μm and the continuum on either side. These images have a spatial resolution of 0.8 seconds of arc, and comprise the highest-spatial-resolution mid-infrared image of Mrk 231 ever obtained, and the only 10 μm images of Mrk 463 and UGC 5101 that we are aware of. The accompanying Figure contains contour maps of the 11.7 μm images of these galaxies. Mrk 231 and Mrk 463 appear to be unresolved, indicating that the warm dust lies no further than 300-400 pc from the nucleus. The 10 μm emission from UGC 5101 is too weak to definitively determine whether it is unresolved. The concentration of luminosity in Mrk 231 and Mrk 463 implies that the luminosity density near the nucleus is at least 100 times higher than that found in classical starburst galaxies such as M82. A paper discussing these results is currently in preparation.

Shupe



Contour maps of the images of Mrk 231, Mrk 463, and UGC 5101 taken through the 11.7 μm filter. The contours are spaced by 10% of the peak flux, with the lowest contour at 20% for Mrk 231 and Mrk 463, and 40% for UGC 5101. The graphs are labeled in seconds of arc. The contour map of UGC 5101 is distorted by noisy pixels.

GRAVITATIONAL LENSING BY CLUSTERS AND SUPERCLUSTERS: DEEP IMAGING WITH COSMIC ON THE 200″

Investigators: Ian Smail, Jeremy Mould, and Roger Blandford (Caltech).

Subject Heading: Galaxies and Quasars

Two sets of very deep images have been obtained by our collaboration using the COSMIC imager at the prime focus of the 5m Hale. COSMIC is an efficient high-throughput wide-field imaging spectrograph built by Alan Dressler and co-workers at OCIW. The field of view is $9.6' \times 9.6'$ with high spatial sampling, allowing us take full advantage of the excellent seeing available at Palomar.

One of the sets of images is of a so-called blank field. This is a region of sky free of bright stars and galaxies, chosen for the study of very faint galaxies. These observations were made during periods of sub-arcsecond seeing during nights allocated to us in the Summer. This data is primarily intend to be used to select targets for a very faint galaxy redshift survey to be undertaken with the Keck telescopes (the DEEP project).

The main dataset consists of a 26,500 sec integration taken in Gunn r. This frame is of extraordinary depth and quality – being probably one of the deepest exposures ever taken. We detect every galaxy in the field to a limiting brightness of 0.1% of the night sky – in excess of 6000 over a field of only 90 square arcminutes. The faintest reliable detections have blue magnitudes of ~28–29, by which point the extrapolated number counts predict a surface density of galaxies of over 300 galaxies per square arcminute.

This single field has been analysed to search for the signature of gravitational lensing by large scale structure (Blandford et al. 1993). The signal we are looking for is a coherent alignment of the images of faint galaxies within the field. This would result from the distortion of the galaxy images by weak gravitational lensing from intervening mass structures on a range of scales – from clusters through superclusters and on up to the scales probed by the COBE microwave background experiments. The mass associated with such structures weakly distorts the path of light coming to us from distant background galaxies and this distortion makes the galaxy images appear to point in the same direction on the sky. With so many faint galaxies in our field and such good image quality this dataset appears ideal to use in a test for this effect.

In reality this test is extremely difficult to undertake as a large number of other non-cosmological effects may produce a similar signal. In particular problems with tracking the telescope on the sky may result in trailed images – giving the impression of a cosmological signal. Aberrations in the telescope optics and non-linear features of the detector may also produce similar signals. We have calibrated a number of these systematic effects using images of globular clusters. However, removal or calibration of *all* these observational effects is very difficult and as such we only claim an upper limit on the observed cosmological signal – a limit which is in accord with currently fashionable cosmogonic models, although it does not yet constrain them. A paper on this work has been completed and will be submitted shortly. The work being undertaken by the Palomar staff to improve the shape of the 5m Hale's primary mirror will much reduce the strength of the systematics in these measurements.

The second set of images are deep multi-color observations of a distant rich cluster of galaxies; Abell 2218. These observations were also taken with the COSMIC imager under similarly good conditions. The motivation for these observations was a study of the gravitational lensing effect of the cluster on background faint galaxies. In the case of a massive centrally concentrated structure such as a rich cluster gravitational lensing tends to transform the images of the distant faint galaxies into short arcs ("arclets") curved about the center of the cluster. A number of highly distorted giant arcs are visible in the cluster center as well as a complete ring – formed when a galaxy is seen directly behind the center of the lens. While these giant arcs are very striking more information is carried in the miriad faint galaxies which have suffered only marginal distortions. Using newly developed analytic tools we intend to analyse these images to map the distribution of mass in the cluster and throw much needed light on the nature of the dark matter which is known to pervade clusters.

Star-Formation Histories of Luminous Starburst Galaxies

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Coinvestigators: Terry Herter and Martha Haynes
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Subject Heading: Galaxies and Quasars

In 1983, the *Infrared Astronomical Satellite* discovered a population of galaxies emitting up to 99% of their energy in the far-infrared (Soifer *et al.* 1987). These objects are thought to contain large amounts of dust; this dust absorbs the light emitted by a galaxy at optical and ultraviolet wavelengths and re-emits it at longer wavelengths. The total energies of these objects range from levels characteristic of "normal" galaxies to those of quasars. Some of the more luminous sources may be powered by a rapid burst of massive star-formation known as a "starburst." The origin and subsequent evolution of star-formation in these systems is currently not well understood. In some cases, starburst activity may be triggered by interactions between galaxies or by stellar bars. The prototypical starburst galaxy M82 possesses a stellar bar that may have resulted from an interaction with M81, a nearby galaxy (Telesco *et al.* 1991). Interactions between the bar and interstellar gas may have then triggered the massive star-formation observed in this system. Stellar population models suggest that this galaxy may be preferentially forming high mass stars, that is, the formation of solar mass stars is suppressed (Rieke *et al.* 1980; 1993). This is a controversial result and needs confirmation in other starburst systems.

We are studying the star-formation histories of 20 nearby interacting starburst galaxies to determine if starburst activity is indeed biased against the formation of low-mass stars and to determine how star-formation properties change with the interaction strength and age. At radio wavelengths, spatially extended emission arises from star-forming regions and supernova remnants and thus directly traces starburst activity. To select active nearby starburst galaxies, we therefore chose the twenty starburst galaxies from the *Uppsala General Catalogue of Galaxies* with the highest radio (6 cm) luminosities. In the past year, we have completed imaging these galaxies and two "normal" comparison galaxies at 1.25, 1.65 and 2.2 μm with the Prime Focus Infrared Camera. The 2.2 μm images are being examined for the presence of multiple nuclei, bars, and other morphological features obscured at optical wavelengths. These features are used to identify the mechanism triggering the starburst activity and measure the strength and age of galaxy interactions. Since the primary contribution to the 2 μm continuum emission arises from old giants and supergiants, the images also map the spatial distribution of the underlying stellar population and the mass distribution prior to the burst. The 1.25 and 1.65 μm images are used with the 2.2 μm images to estimate the amount of dust emission and obscuration. In March 1993, we also obtained high-resolution optical spectra of 10 of the galaxies with the Double Spectrograph. We will extract rotation curves from these spectra in order to estimate the underlying galaxy mass. Comparing the rotation curves to those of "normal" galaxies will show how interactions influence the galactic dynamics. To determine if young supergiants are present in these galaxies, we have also obtained 2.2 μm spectra of 10 sources at Kitt Peak National Observatories. The galaxy mass, supergiant population and extinction corrected 2.2 μm luminosity will constrain stellar population models and thus determine if low mass star-formation is suppressed.

This project is the subject of D. Smith's PhD thesis and will be completed in the summer of 1994. D. Smith presented a poster describing the project and images obtained at Palomar at the 182nd meeting of the American Astronomical Society in June 1993; a paper discussing our results for UGC8387, a moderately luminous starburst, is currently in preparation. Preliminary analysis of the sample shows that thermal dust emission contributes significantly to the 2.2 μm emission in several galaxies. Upon completion of our program, we will be able to determine and compare the history of star-formation in starburst galaxies. Comparing star-formation properties as a function of interaction strength and duration will show how interactions influence starburst activity and determine if starbursts are generally biased against low mass star-formation.

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A Search for $z \gtrsim 4$ BRI Quasars

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Co-Investigators: S. Djorgovski, D. Thompson (CIT)

Subject Heading: Galaxies and Quasars

Quasars at $z \approx 4$ had already formed when the universe was only 5-10 percent of its present age. These high redshift quasars can therefore be used as probes of the universe at early epochs, while absorption from objects along the line of sight to the QSO's can give information about conditions in the universe throughout its history. We are conducting a multicolor search for quasars, AGN, and star-forming galaxies near *known*, $z > 4$ quasars at the Hale 200-inch telescope, using these early quasars as markers of possible protoclusters. Preliminary results are given in Smith, Thompson, & Djorgovski (1993).

Irwin *et al.*(1991) reported on a multicolor photographic survey for bright ($R > 19$) $z > 4$ quasars using APM measurements of UK Schmidt Telescope B_J, R, and I plates. They have discovered at least 20 new $z > 4$ quasars with this technique. However, they have published only rough coordinates, redshifts, and m_R magnitudes for 9 of them (Irwin & McMahon 1990). We thought this would be a good opportunity to test our CCD multicolor technique by trying to "rediscover" these BRI quasars. At the same time, this will open these objects to investigations by the entire interested community, and allow us to include them in our Hale 200-inch survey for clustering around $z > 4$ quasars. A simple method to discover high-redshift quasars is to use the Johnson BRI or Gunn-Thuan gri bands, and look for objects where the Lyα line is in the red band. The line, and the continuum drop across it would leave a distinct color-color signature.

We obtained imaging data on 4 of the 9 target quasar fields on UT 1993 March 23 to 25 and May 18 to 20. The possible coordinates of the quasars form a box 60 arcmin in declination and at most 15 arcmin in right ascension. The initial imaging data were taken at the Palomar 60 inch telescope using reimaging optics giving us an 18.4 arcmin field of view with 1.08 arcsec/pixel. Therefore, four pointings were necessary in order to cover the desired range. Three of these quasars have been recovered so far. The combined color-color diagram for two of these quasars is shown in figure 1. The two quasars are well separated from the stellar locus. Candidates were chosen by visually examining all objects with appropriate colors. Several candidates were chosen in each field and ranked by position in color-color space and stellar morphology. Follow up spectroscopy revealed in both cases that our highest ranked candidate was indeed the quasar.

Spectra of these two quasars (figure 2) were obtained at the Hale 200-inch telescope, using the 4Shooter spectrograph on the nights of UT 1993 May 26 to 27 and June 10. We derive a redshift of 4.381 ± 0.010 for BRI 1013+00. We see some evidence for a damped Lyα absorption system roughly centered at $\lambda 5909$ ($z = 3.86$), and possibly a second at $\lambda 5748$ ($z = 3.73$). For BRI 1050–00 we derive an emission-line redshift of 4.291 ± 0.002. Two Lyα absorption lines, at $\lambda 6350.5$ and $\lambda 6372.8$ ($z = 4.224$ and 4.242, respectively), can be seen immediately blueward of the Lyα emission line (figure 2). A group of faint, presumably foreground, galaxies is seen within a few arcsecs of the quasar. It is possible, although highly speculative, that this bright quasar has been gravitationally magnified. High resolution imaging of the field, and spectroscopy of the galaxies are clearly desirable.

We hope to obtain imaging data on the additional target quasars in our search this October at the Palomar 60-inch telescope.

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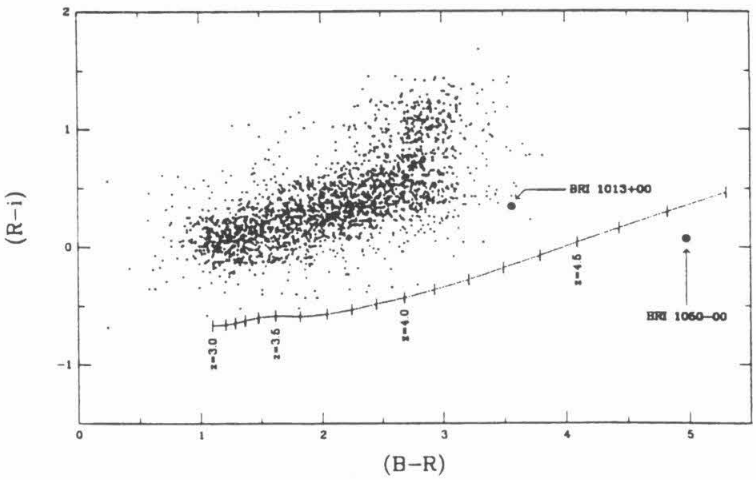

Figure 1: The BRi color-color diagram of all objects with $17.5 < m_R < 20.5$ in the 8 fields around BRI 1050−00 and BRI 1013+00. The solid circles represent the two quasars which are well separated from the stellar locus. The curve represents predicted quasar colors for the redshift range 3.0 to 4.8 calculated using a composite quasar spectrum.

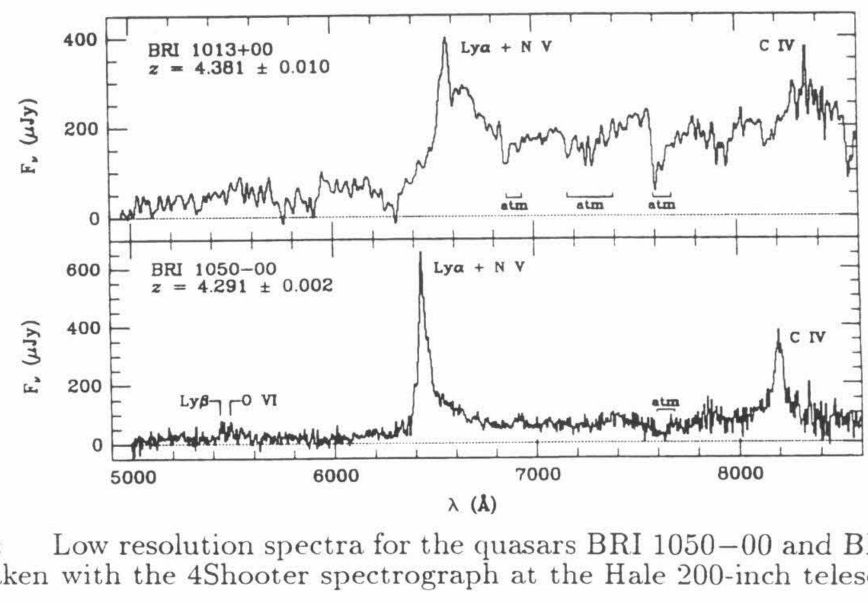

Figure 2: Low resolution spectra for the quasars BRI 1050−00 and BRI 1013+00 taken with the 4Shooter spectrograph at the Hale 200-inch telescope.

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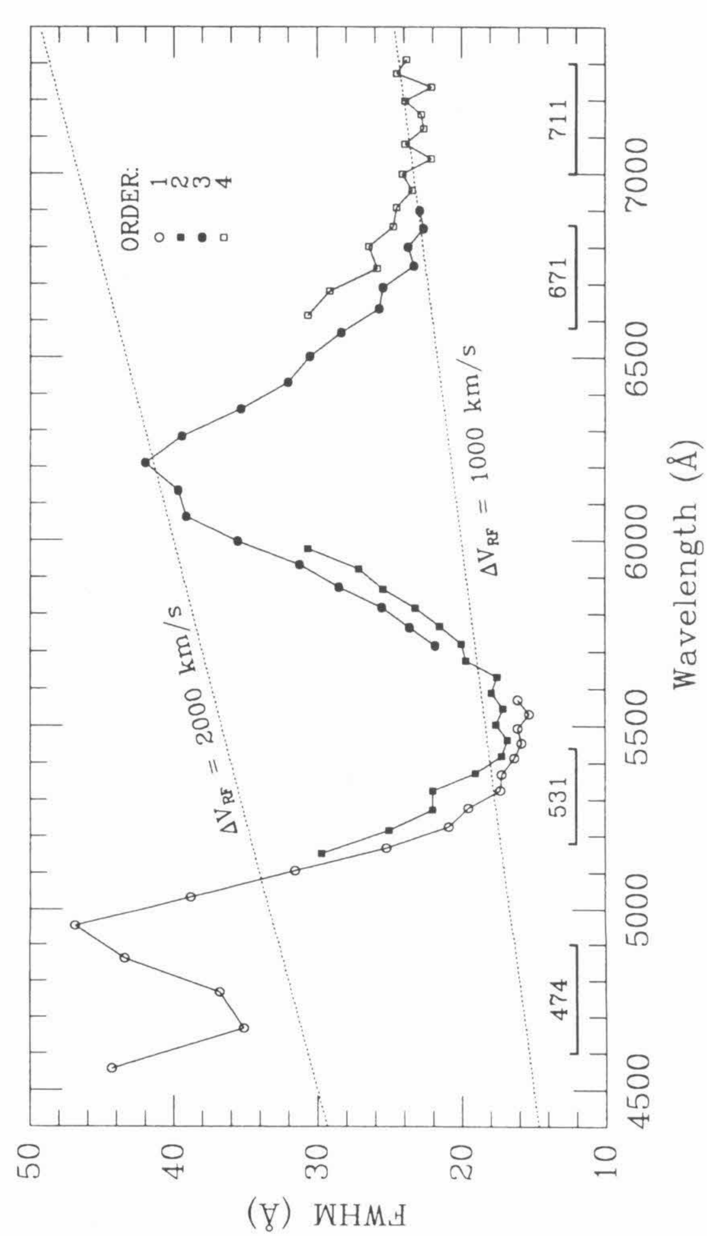

FWHM (Å)
Wavelength (Å)
ORDER:
1
2
3
4
ΔV_RF = 2000 km/s
ΔV_RF = 1000 km/s
474
531
671
711
50
40
30
20
10
4500
5000
5500
6000
6500
7000

Near Infrared Spectroscopy of Infrared Bright Quasars and Ultraluminous Galaxies

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Co-Investigators: L. Armus, K. Matthews, G. Neugebauer, J. Mazzarella, and J. Graham

Subject Heading: Galaxies and Quasars

One of the most important discoveries of the IRAS all sky survey was that there is a class of colliding/merging galaxies that emit at infrared wavelengths as much luminosity as the most energetic objects in the universe, the quasars.

A major unanswered question raised by these Ultraluminous Infrared Galaxies is what powers the infrared emission? Two processes are thought to be most likely to explain the luminosity, either an intense period of star formation that converts most of the gaseous matter in these galaxies into stars in a very short time span (a "starburst") or an accretion disk surrounding a massive black hole (a quasar). In either case, the power is generated out of sight of astronomers that study visible light, because the energy generating environment is enveloped in a massive cloud of gas and dust that effectively absorbs the visible light and reradiates the power in the infrared portion of the spectrum.

We have been embarked for the last several years on the study of the question of what powers these Ultraluminous Infrared Galaxies. The answer to this question relates to several fundamental problems in astrophysics. If the power is generated by a quasar, then it is likely that quasars, the most luminous objects in the universe, are formed in the collision of two gas rich spiral galaxies. On the other hand, if the power is released in a burst of star formation, then these galaxies are showing that major stages in the evolution of galaxies result from the collision of two gas rich galaxies.

One of the most promising techniques for addressing this question is near infrared spectroscopy. The near infrared light generated in these environments much more readily escapes the surrounding gas and dust, because the dust is much less opaque at near infrared wavelengths than in the visible. Spectroscopic diagnostics, such as recombination lines of hydrogen, emission lines of highly ionized species, and lines of hot molecules permit us to assess the physical conditions in these dust enshrouded regions, and thereby gain a fuller understanding of the sources that are powering the enormous luminosity.

The accompanying figure shows spectra obtained as part of our effort to study the ultraluminous infrared galaxies and quasars via this technique. The objects on the left are quasars that show strong lines of Helium, atomic hydrogen and in some cases molecular hydrogen and neutral oxygen. One of these quasars were found by IRAS to be very bright in the far infrared, and so have large amounts of dust and gas in the environment of the quasar. The objects on the right are all of similar luminosity to quasars, but were selected to be bright in the infrared. These systems show the same strong lines of hydrogen and helium, but also show a very strong line of molecular hydrogen. Probably the most exciting and puzzling result to date from these studies is the presence of strong molecular hydrogen emission in the environment of the nuclei of the quasars and ultraluminous IRAS galaxies. The environment of quasars is an exceedingly harsh one for the survival of molecular gas, and yet many of these systems show strong lines that demonstrate the presence of such gas. What this means for the transport of molecular gas to the nuclei of galaxies, and the survival of this gas in such harsh environments is not yet understood.

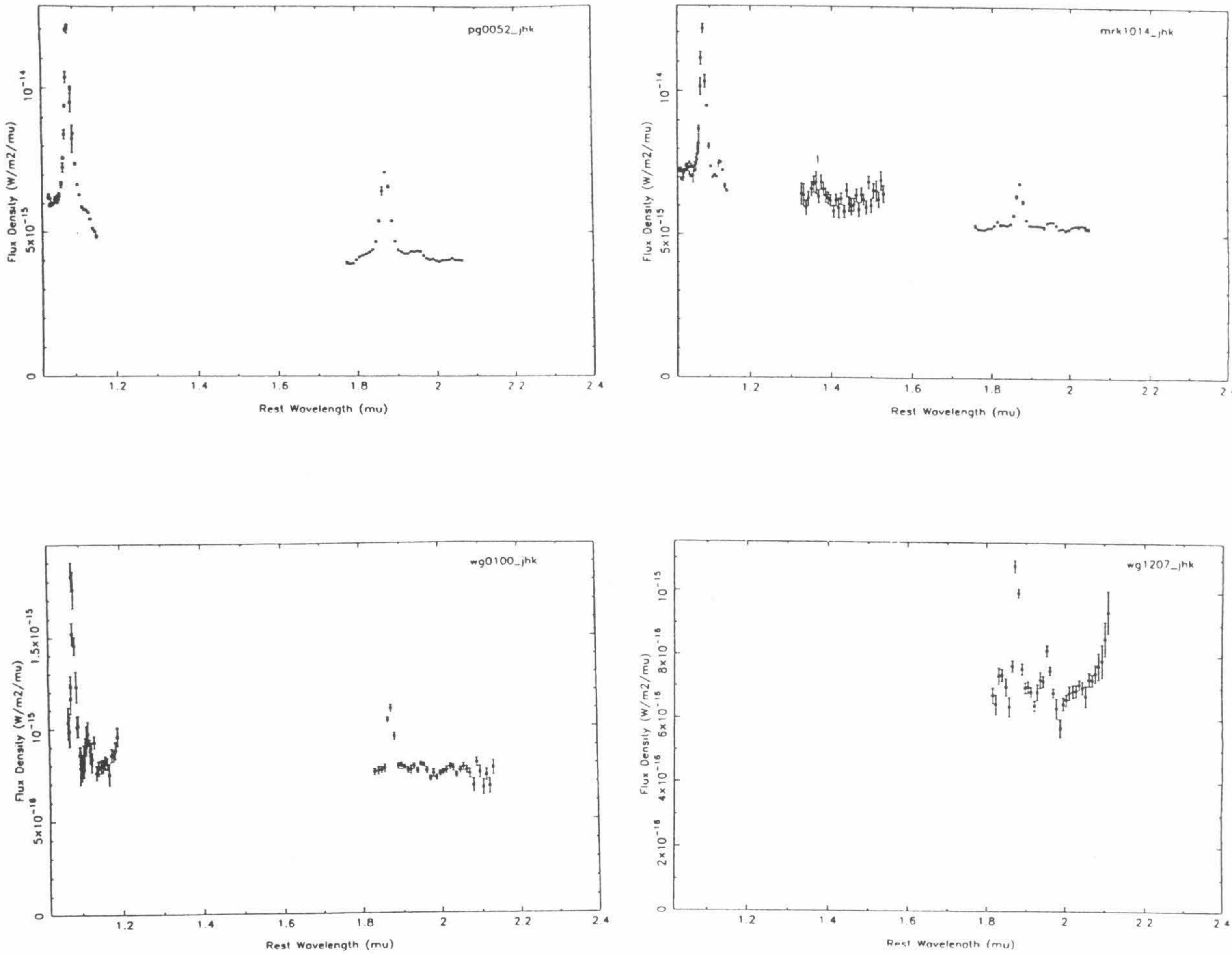

Figure 1: The near infrared spectrum of three quasars and three highly luminous objects found in the IRAS all sky survey. The panels on the left show the spectra of two quasars: PG0052+25 and Markarian 1014, while the panels on the right show the spectra of two IRAS selected Ultraluminous Infrared Galaxies, IRAS 0100-22 and IRAS 1207-04. The spectra were obtained from 1.0 – 2.4 μm using the grism in the Cassegrain Infrared Camera on the 200-inch telescope. The spectra are plotted as flux vs. wavelength, where the wavelength plotted is in the rest frame of the object. The strongest lines in the spectra are the Helium resonance line at 1.083 μm, the Paschen α recombination line of hydrogen at 1.875 μm, the neutral Oxygen line at 1.129 μm, and the line of H_2 at 1.958 μm.

Optical Identification of Faint Radio Sources

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Co-Investigators: L. M. Maxfield and S. G. Djorgovski (CIT)
M. Vigotti and G. Grueff (Bologna)

Subject Heading: Radio Galaxies

Samples of radio sources have always been good hunting grounds for distant galaxies, and the most distant galaxies now known were picked through their radio emission. So far, only the samples of the most powerful radio sources (e.g., the 3CR sample) have been completely identified. They show very prominent evolutionary effects, and even contain several possible primeval galaxies, but they are almost certainly atypical: their enormous radio powers label them as suspicious, probably very different from the bulk of more normal galaxies at comparable redshifts. One must try to identify galaxies with lower radio powers, closer to the objects which we know exist at low redshifts. The third Bologna sample of radio sources (B3VLA) fits the requirements perfectly: the flux levels are about a hundred times lower than those of the 3CR sample, corresponding to the levels where radio source counts deviate most from simple predictions based on euclidean geometry and thus likely probe a large span in redshifts; the radio data are of high quality and already in hand; and the selection criteria are such that one can hope to find many galaxies at large redshifts, where the evolutionary and cosmological effects are the strongest. Indeed, the B3VLA survey has already netted one galaxy at a redshift of 3.22 (B3 1232+397B), one of the most distant radio galaxies now known and one that is considerably more distant than the highest redshift object in the 3CR sample!

In collaboration with the team from Bologna, led by Drs. Grueff and Vigotti, who provide the radio data and some astrometry, we are continuing a program to identify a complete subsample of 118 B3VLA sources. As of the beginning of 1993, we have identified optical counterparts to about 25 B3VLA radio sources, with follow-up spectroscopy for 8 of them. Seventeen new fields have been imaged with the 60-inch telescope in 1993 so far, with 13 of these yielding firm optical identifications of the radio sources. Reduction of the 60-inch data was completed as part of a Caltech SURF project for L. M. Maxfield.

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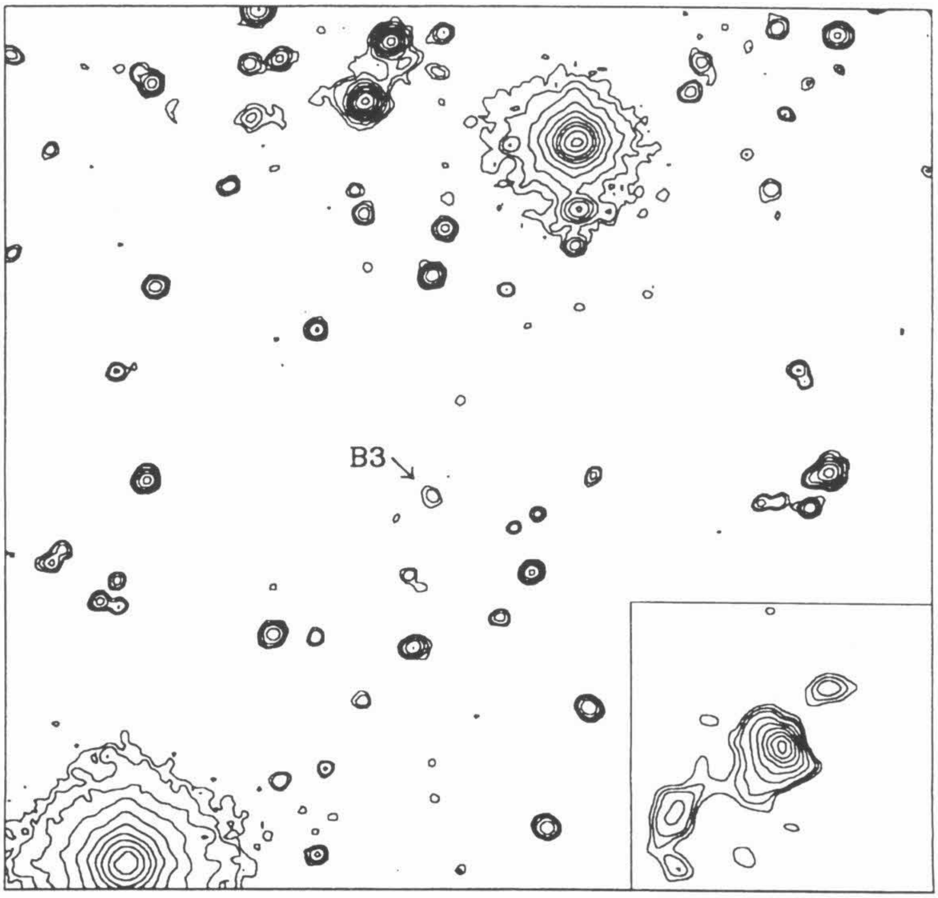

Figure 1. B3 1350+432, an r=22.1 magnitude radio galaxy identified from the 1993 P60 imaging data. Follow-up spectroscopy will be done at the 200-inch in the near future. North is up and east is to the left in this 3 arcminute field of view. Inset: detail in the 20 arcsec square field centered on the radio galaxy.

Spiral Structure in Galaxies

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Subject Heading: Quasars and Galaxies

Remarkably, spiral arms, a defining characteristic of spiral galaxies, are poorly understood. For example, the origin and longevity of spiral arms remain uncertain, as does their effect on the different components of the interstellar medium and on stimulating star formation. Using the Palomar 60-inch imaging Fabry-Perot spectrometer, we are mapping the Hα kinematics in several spiral galaxies in an effort to understand the effects of spiral arms on the interstellar medium in galaxies and factors that influence the spiral arm morphology.

In addition to studying classic spiral galaxies, we are also observing spirals with unusual morphologies. For example, the distinctive bow-shock shape of NGC 2276 has been attributed to a ram pressure interaction of the galaxy with relatively dense intergalactic gas as the galaxy plows through the sparse NGC 2300 group of galaxies. Alternatively, the leading edge of the apparent "bow-shock" might be a sharply defined spiral arm generated by tidal interaction. However, Mulchaey *et al.* (1993) detected hot, dense gas in the intragroup medium with ROSAT observations; the high temperature of the gas requires a large amount of dark matter to explain how the hot gas can remain in the group. They proposed that apparent bow-shock morphology might be an indicator of the presence of a dense intragroup or intracluster medium.

Observations of Hα emission from NGC 2276 with the Palomar 60-inch imaging Fabry-Perot spectrometer show that the kinematics of the galaxy are complex, with line-of-sight peculiar motions that are a significant fraction of the line-of-sight component of the rotational velocity (Gruendl *et al.* 1993). Ram pressure interaction can be ruled out as the cause of the distinctive bow-shock morphology in this galaxy. More likely, tidal interaction with the nearby elliptical galaxy NGC 2300 explains the unusual morphology and kinematics. Therefore, the morphology of the spiral arms and stellar disk is not a reliable indicator of ram pressure interaction.

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Mulchaey, J.S, Davis, D.S., Mushotzky, R.F., & Burstein, D., Ap.J. 404, L9, 1993.

Rotation Curves of Spiral Galaxies in the Hercules Supercluster

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Co–Investigators: Terry Herter (Cornell University)
Martha Haynes (Cornell University)

Subject Heading: GALAXIES AND QUASARS

The Tully-Fisher (T-F) relation is currently one of the most promising methods of accurately determining astronomical distances. There is a strong correlation between galaxy luminosity and velocity width, simply put, because they are both dependent upon galaxy mass. The T-F relation combines observations of optical brightness and rotational velocity to determine the distance to a galaxy.

We can derive an accurate measure of the distance to a cluster by applying the T-F relation to a set of galaxies within it. The 21 cm HI line width should be adequate in principle to measure velocity widths (Aaronson and Mould 1986) and is being extensively used by us. HI widths at the larger distances ($z > .02$) can only be measured with the Arecibo radio telescope, however, and since the portion of the sky visible to Arecibo lies nearly perpendicular to the Great Attractor region the sensitivity to the interesting components of our peculiar motion is significantly reduced. Further cluster work to derive the local motion must rely on the corresponding D_n–σ (or L–σ–Σ) relation for ellipticals, and on the optical rotation curve version of the T-F relation.

The Hercules supercluster is comprised of seven Abell clusters in the range ($.030 < z < .037$). The seven clusters divide themselves into three subconcentrations of two or three clusters joined by a lower density enhancement in the galaxy distribution (Freudling 1990). It is relatively isolated, flanked in front and back by the Hercules and Bootes voids. As the clusters fall at the same distance and suffer the same absorption effects, they represent a very large uniform sample on which to perform statistical analysis with regards to the T-F relation.

Observation of the Hercules supercluster is also of interest for purely morphological considerations. The contrasting environments found in the different clusters are ideal for the comparitive study of the causes and effects of such cluster attributes as local galaxy density, cluster morphology and dynamics, the presence of hot X-ray gas and/or H I deficient galaxies, and how these relate to changes in the distribution of light and mass in galaxies, the former derived from optical rotation curves. The Hercules clusters A2147 and A2151 serve as a case in point. A2147 has a moderate X-ray source and contains many H I deficient spirals, while its neighbor A2151 has a higher density and less H I deficiency. A deeper study of these clusters can lead to identification of the role that such mechanisms as stripping via galaxy-intracluster medium interactions and galaxy-galaxy interactions play in producing such conditions (Haynes 1988).

This examination of the Hercules supercluster is also part of a large program to obtain the optical rotation curves of spiral galaxies in a significant number nearby clusters of galaxies and combine them with optical CCD imaging at I-band and HI line emission observations of galaxies in clusters. Only a few studies to date have addressed the possibility of environmental variations in the distribution of mass within galaxies, and the results are conflicting (Chincarini and de

Souza 1985; Guhathakurta *et al.* 1988; Whitmore *et al.* 1988; Forbes and Whitmore 1989). The question of the universality of the mass distribution in spirals seems still to be an open issue and is of particular significance for studies of the deviations from pure Hubble expansion using the T-F relation for galaxies in clusters. Our overall program goals are threefold:

1. to calibrate the radio and optical applications of the T-F relation for a sample of galaxies observed with both techniques;
2. to investigate the environmental dependence of the T-F relation by studying the optical rotation curves of HI-deficient objects; and
3. to combine both radio and optical techniques to derive a solution for the local motion to clusters at a distance of $z < 0.04$.

This program was started in April 1990 using the Double Spectrograph on the Hale 5.08 meter telescope. To date optical rotation curves have been obtained for over 288 spiral galaxies located in 11 different clusters. The data has been reduced and rotation curves extracted. Optical imaging of these galaxies has been performed at KPNO and MDM. In addition, over 400 H I spectra have been obtained at Arecibo over this time in support of this project.

A significant amount of software has been developed at Cornell to support our T-F relation work. This includes routines to extract rotation curves from the long slit spectra and to model the effects of pointing and slit angle errors on the deduced rotation curve of a galaxy, and an analysis of the optical images via a decomposition technique which separates the contributions of the bulge and disk components of the galaxies. Mass models have been fit to the rotation curves, and the gradient of the velocity profile and terminal velocity point can be evaluated relative to the limiting surface brightness of the optical image and as a function of disk scale length.

We are currently analyzing our data to look for systematic changes in the shapes of rotation curves of galaxies in clusters and correlating HI line widths with optically determined galaxy widths (Vogt *et al.* 1993). We hope to exploit the combined radio and optical data to improve the T-F technique and find more accurate distances to clusters of galaxies and to measure distance to clusters which are outside the Arecibo declination range.

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Rotation Velocities of Galaxies in Intermediate Redshift Clusters (0.1 < z < 0.4)

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Subject Heading: GALAXIES AND QUASARS

We have been conducting a study of the mass–to-light ratios of galaxies in nearby Abell clusters ($z < .04$). One goal of the project is to derive TF distances to the clusters themselves in order to examine deviations from Hubble flow over a volume signficantly larger than that dominated by the Local Supercluster and the Great Attractor. A fundamental limitation of the TF method for peculiar motions is that the scatter in the relation (about 0.3 to 0.4 mag) translates to a constant error of about 15% in the distance. At distances larger than $z = 0.03$, this uncertainty exceeds the largest peculiar motions expected within the constraint that the Hubble law holds even approximately. Nonetheless, the refinement of the method proposed here permits the determination of redshift–independent cluster distances and thus evaluation of the Hubble contant H_o to larger distances (van der Kruit and Pickles, 1988).

The application of the TF relation to distant clusters is identical to the one we use at low z. We employ I-band images together with velocity widths determined from optical lines. By averaging over measurements of many galaxies within a cluster a more refined distance estimate is obtained. Current observations indicate that evolution does not affect the shape of the galaxy luminosity function but only the normalization. Thus, evolution should not be a factor in estimating cluster distances. With our observations we will determine H_o at different redshifts. Since these measurements extend to intermediate distances we will obtain H_o as a function of z for the range $z < 0.4$. Using this technique we expect to ultimately measure q_o.

In 1993 we implemented a pilot program of observations of distant clusters in the range ($0.1 < z < 0.4$). The results of the observations were very promising, and resulted in the immediate publication of the most striking data (Vogt *et al.* 1993a). One field galaxy and three cluster objects known to have strong emission lines were observed over wavelength ranges covering the redshifted lines of [OII], Ca II K, Hβ, and [OIII] (Hα having been redshifted into the night-sky contaminated portion of the optical spectrum). Two of the objects show extended line emission that allows the tracing of the rotation curve in one or more lines. A line width similar to that obtained with single-dish telescopes for the 21 cm HI line observed in lower redshift galaxies can be derived from the observed Hβ, [OII], and [OIII] emission by measuring a characteristic width from the velocity histogram. These moderately distant galaxies have much stronger emission lines than typical low-redshift spirals but they appear to be kinematically similar. Application of the Tully-Fisher relations suggests that the two galaxies with rotation curves are intrinsically brighter at R–band than nearby galaxies.

These results demonstrate the potential in investigating the kinematics of galaxies at intermediate redshift via long–slit spectroscopy. Given very good seeing ($< 1''$) and adequate weather conditions, this project confirms the efficacy of the measurement of rotation curves in distant galaxies. The derived rotation curves are well-defined and appear to flatten, characteristics seen in nearby normal spiral galaxies. At the same time the presence of strong emission in the objects makes them quite unusual compared to low redshift galaxies. Although both galaxies showing extended emission appear to have nearby companions, there is no evidence of interaction in their rotation curves.

Measurements of the velocity widths allow estimation of galaxy properties and/or distances via application of the TF relation. Since most TF studies of nearby galaxies have been calibrated using radio 21-cm line widths, the optical widths were transformed to a system appropriate to the radio TF relation (Vogt *et al.* 1993b). Using this transformation, we derive an equivalent corrected (for turbulent broadening) 21-cm line width W_c^{21} of 185 $\pm$ 15 km s^{-1} for Galaxy 2545.3 and 264 $\pm$ 11 km s^{-1} for BOW 85. The corrected 21-cm width derived for 2545.3 is rather small, particularly relative to the mean expected for a large sample of low redshift objects (Roberts and Haynes 1993). It is possible, given the uncertainties, that this object may be less inclined than the current estimate, or that the rotation curve continues to rise significantly, beyond the radius at which line emission is detected.

Using the TF relation, the intrinsic brightness of distant galaxies can be compared, albeit crudely, to those nearby. Using standard calibrations and a Hubble constant of 75 km s^{-1} Mpc^{-1}, we estimate that BOW 85 and 2545.3 are 0.9$\pm$0.4 and 3.1$\pm$0.7 magnitudes brighter respectively than predicted from the nearby galaxy sample. (Another 0.3 magnitude error should be added in quadrature with the quoted errors to account for the intrinsic scatter in the TF relation). Given the various uncertainties and complications in comparing the distant galaxies to the nearby ones, this increase in the brightness of distant galaxies relative to nearby ones of the same velocity width should be considered preliminary.

Because of our galaxy selection process and the potential for galaxy evolution, use of the TF relation to derive a Hubble constant is not justified at this time. In the future a better statistical sample will allow a comparison of the slope of the TF relation at high and low redshift and the evaluation of the importance of merging in the blue galaxy population. If the effects of galaxy evolution can be disentangled and the local calibration of the TF relation verified, the Hubble constant can be determined.

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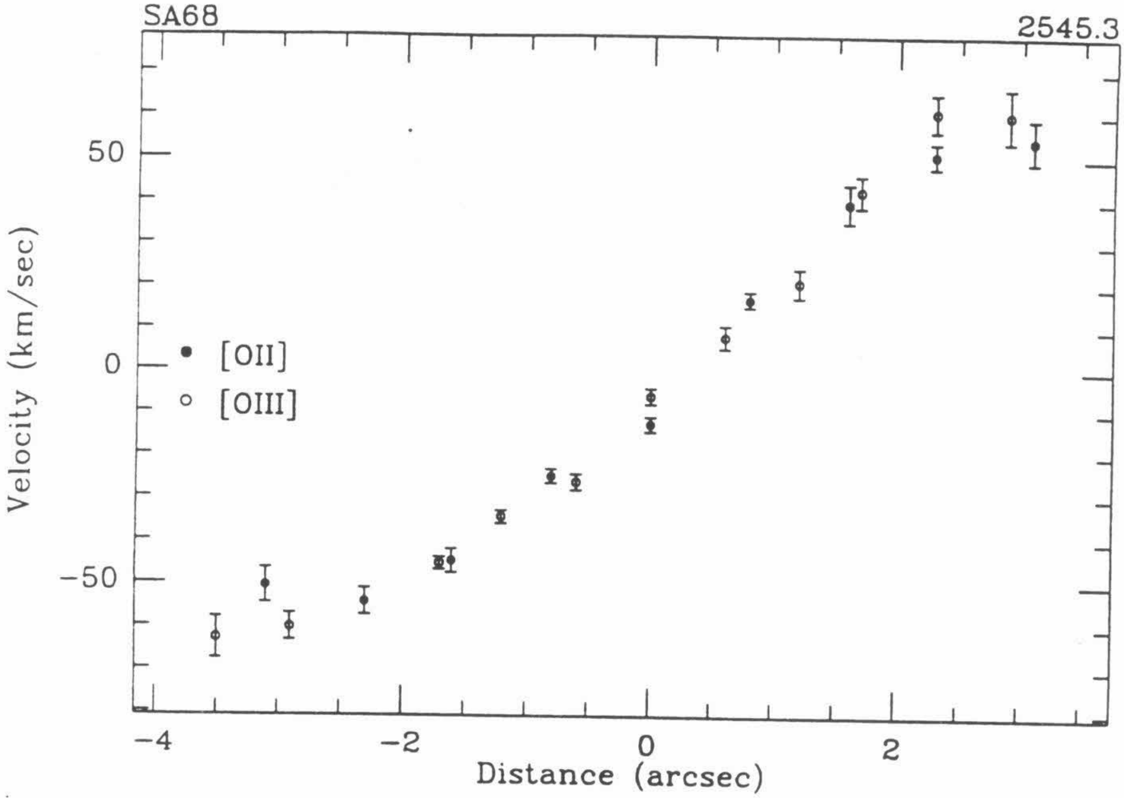
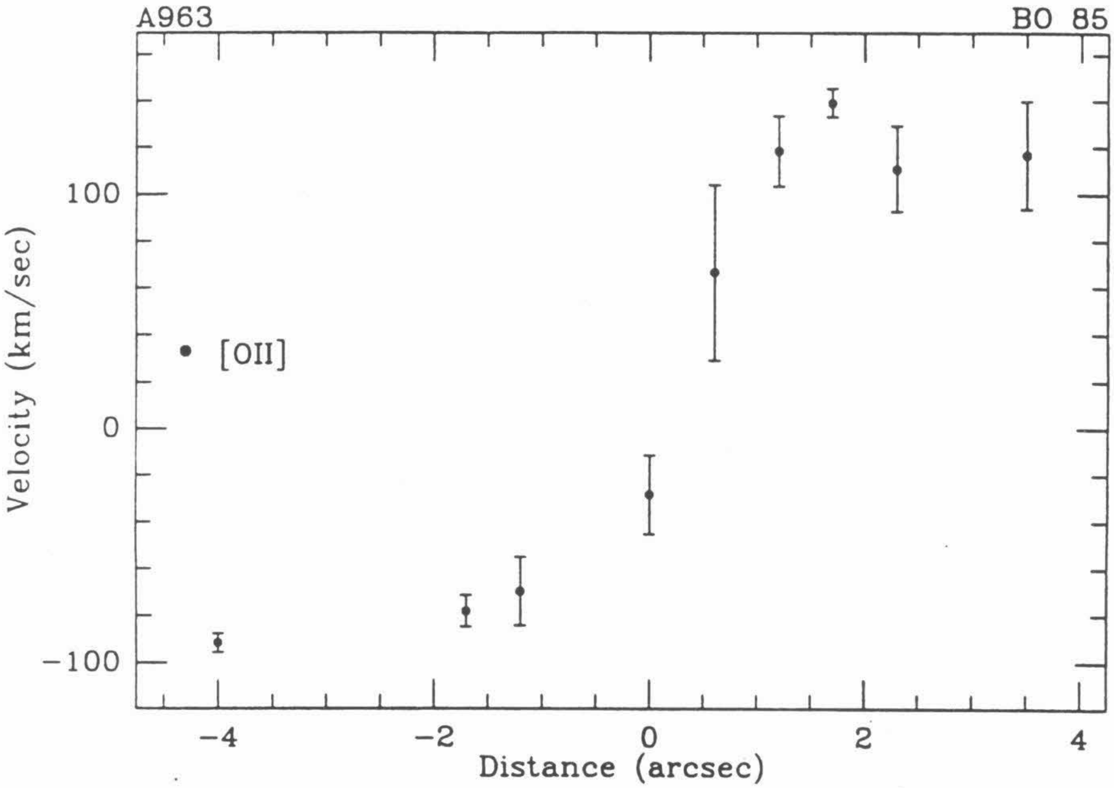


The spatial variation in the velocities in the rest frame of the galaxy derived from the [OII] and [OIII] line profiles for 2545.3 in the SA 68 field ($z = 0.211$).



The spatial variation in the velocities in the rest frame of the galaxy derived from the [OII] line profiles for the No. 85 in Abell 963. The data at -3″ fell onto a bad column on the chip and was distorted ($z = 0.201$).