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PALOMAR OBSERVATORY
ANNUAL REPORT
1992

Palomar Observatory 105-24
California Institute of Technology
Pasadena, California 91125

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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 modern, powerful astronomical facilities in the world.

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INSTRUMENTATION

THE NORRIS SPECTROGRAPH

Principal Investigator: Donald Hamilton
California Institute of Technology

Subject Heading: Instrumentation

This preceeding year has seen the routine use of the Norris Spectrograph. This is a multi-object fiber spectrograph designed exclusively for use at The Hale Telescope. There are 176 independently positionable fibers each one that can be placed onto a desired object, star or galaxy, within a twenty arcminute field. This implies that the *observing efficiency* (the amount of telescope time it takes to complete a specific observational program), is increased directly by this multiplex factor. One can then consider that use of this type of instrument allows the effective equivalent of 176 Hale Telescopes each of which observes a single object at a time, as it was in the past.

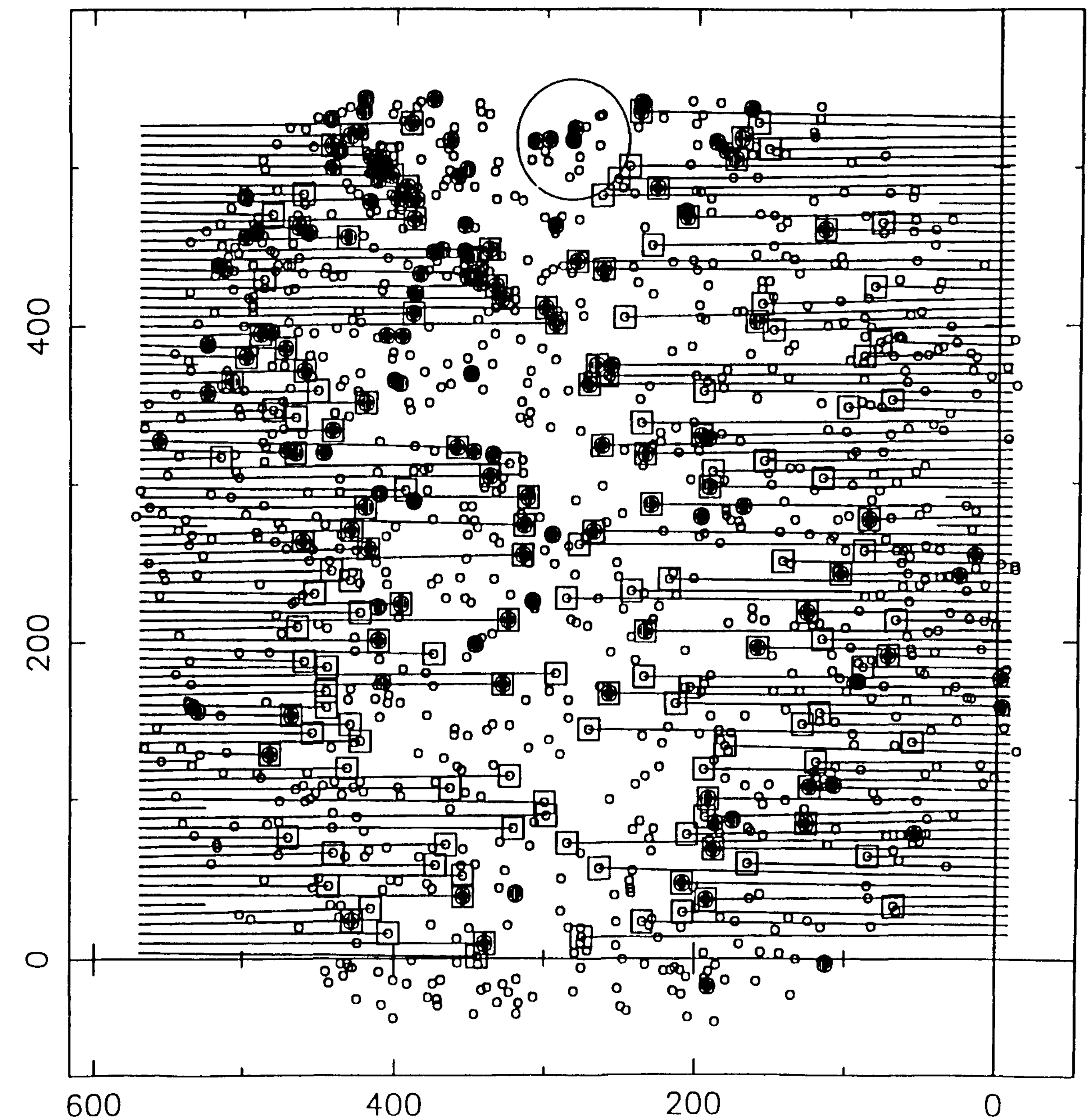
The Norris Spectrograph represents the ultimate in state-of-the-art fiber spectrographs. It consists of an xy stage to position each moveable fiber to its proper place in the $f/16$ Cassegrain focal plane of The Hale Telescope. The light from a star or distant galaxy that enters each fiber is brought to a spectrograph where the light is dispersed by a reflection grating and the spectra imaged onto a modern detector (CCD or charge-coupled device). Unlike other fiber spectrographs, which use an existing spectrograph and are retro-fitted with fibers at a later date, the Norris is an integrated xy stage and spectrograph which keeps the fiber lengths as short as possible. This is an important aspect if precision is required.

Over the past year several improvements have been made in the instrument. We have added hollow-cathode arc lamps so that there are a sufficient number of comparison lines when the high spectral resolution gratings are used. Originally the instrument was designed more for observing distant galaxies with low-resolution gratings, but the extensive use of the instrument for programs that require accurate velocities has been large. We have also incorporated several new features in the software which control the instrument to improve the observing efficiency and its ease of use.

One major area of improvement was in the software that we use to decide how fibers will be assigned to which objects in a given field. The previous programs were rather cumbersome and overly complicated, but with observing experience, more efficient and appropriate software was developed. A schematic of a setup of the Norris xy stage is presented below. The x axis (parallel to the North-South direction) is along the horizontal dimension and the y axis (parallel to the East-West direction) is along the vertical dimension. The units are given in millimeters. This schematic is a representation of a sub-field of galaxies in a cluster of galaxies projected onto the focal plane of The Hale Telescope (which is where the xy stage is placed). The important galaxies to be observed are indicated by the filled circles and the less important objects (galactic stars, background galaxies, for example) are indicated by the small open circles. The two banks of fibers (each 88) are opposite one another and are on the left and right sides. Each fiber that has been assigned to an object has been moved out to that object and is represented by an open square. Given the density of fibers, it is not always possible to assign a fiber to every high priority object. The circular area at the top of the schematic is the entrance to the offset guider. A specific star has been chosen as a guide star.

It its first year of full operation the Norris Spectrograph is being used for three major programs which could not have been conducted without it. One program is studying the frequency of binary stars found in galactic globular clusters (Principal Investigator: J. Cohen). This program is aimed at understanding the dynamical evolution of these clusters. Another program, is studying the globular clusters of the Andromeda galaxy M31 (Principal Investigator: Hamilton) with the goal of increasing our understanding of the formation of galaxies and of globular clusters. In a third, separate program, the confirmation of the existence of dark matter is being undertaken using the Norris by obtaining accurate radial velocities for stars found in dwarf spheroidal galaxies (Principal Investigator: Hamilton). Finally, the original purpose of the instrument, that of surveying thousands of distant galaxies, is underway with remarkable success (Principal Investigator: Sargent). In the Norris Survey for distant galaxies several unusual objects have been located already. These include a quasar at a redshift of 2.9 and two Seyfert galaxies, all three of which are rare objects. Given the success of all of these programs due to the success of the instrument, it is anticipated that during the next observing year Norris will be even more heavily used.

Setup Guide Star OBJ-114984



NORRIS 30-MAY-1992 08:47

A New Echelle Spectrograph for Asteroseismology

Principal Investigator: K.G. Libbrecht
Division of Physics Mathematics and Astronomy
California Institute of Technology

Coinvestigator: M.L. Peri

Subject Heading: Instrumentation

Asteroseismology is the study of acoustic oscillations – sound waves – in stars. Such oscillations probe the stellar interior, and thus carry information on the physical conditions in regions of the star that are not accessible through ordinary observational techniques. Although acoustic oscillations are known to exist in a variety of stellar types, no-one as ever observed them in a solar-type star other than the sun. We hope to be the first to do so.

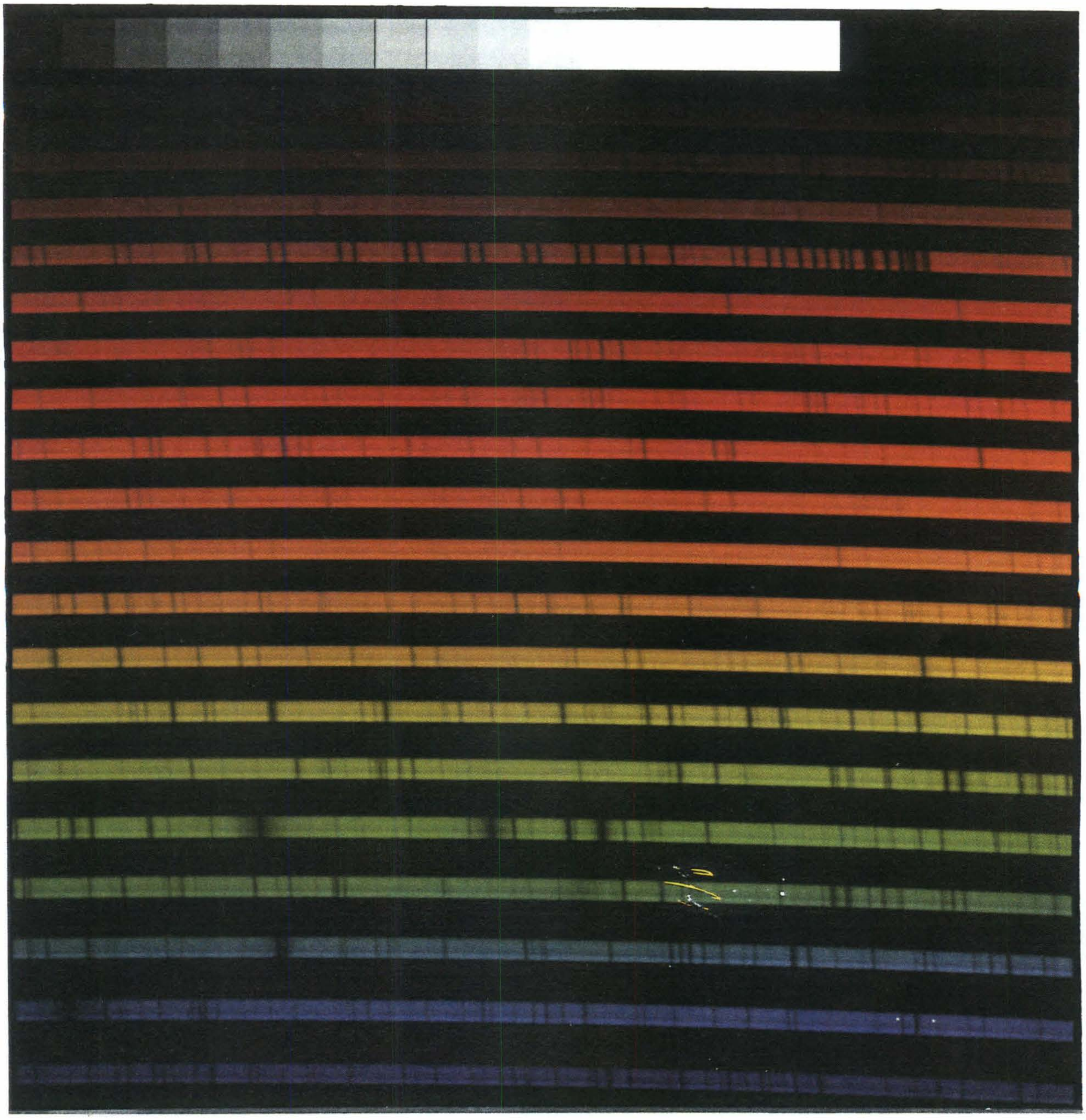
One technique used in asteroseismology is to measure Doppler shifts in the stellar absorption lines caused by gas motions associated with the oscillations. The radial velocities to be detected are very small. In the sun they are on the order of 10 cm/sec per mode of oscillation. Photon noise limitations on the measurements can be alleviated by looking at bright stars with large telescopes, and by observing a large number of spectral lines simultaneously. To enable us to do this we have built a new high-resolution fiber-fed echelle spectrograph for the Palomar 200" Hale telescope. This instrument incorporates state-of-the-art technology for stability and calibration, and is optimized to detect the oscillations in solar-type stars.

The new spectrograph resides in the east arm of the 200" telescope, housed on a gimballed table that remains in a fixed orientation as the telescope moves. This eliminates much of the mechanical distortion which often plagues such instruments. Light enters the system through an autoguider assembly at the prime focus of the telescope and is channeled to the spectrograph by an optical fiber feed. An I_2 absorption cell provides instantaneous calibration and a fiber slicer/scrambler enhances the spectral stability. The spectrograph optics include a camera lens system with a 24" focal length and 8" aperture, a prism cross-disperser, and an echelle diffraction grating. The optics cover a spectral range of $4000 - 10000$Å, and currently produce a resolution of $R \equiv \lambda/\Delta\lambda \simeq 35000$. A new fiber slit is being prepared to increase the resolution to $R \simeq 50000$. The new spectrograph shares the camera used by the Norris Multi-Object Spectrograph, which currently employs a thinned CCD with a 1024×1024 array of $24\mu m$ pixels. It records up 20 spectral orders per frame, allowing simultaneous observation of roughly 1000 stellar spectral lines.

Construction of the new spectrograph was completed in early 1992. The instrument was throughly tested at Caltech with sunlight piped in from the Robinson solar tower via an optical fiber test cable. Installation at Palomar Observatory took place in April 1992. We were allocated two nights in June 1992, during which we conducted on-line testing of the prime-focus assembly and fiber feed system. The instrument performed so well that we were able to obtain a time-series of spectra of the Ap star γ Equ, a known oscillator. Our data from γ Equ will serve as a further test of the echelle spectrograph, allowing us to measure the instrument's sensitivity against a known stellar signal.

We plan to complete testing the echelle spectrograph in the summer of 1992, and are scheduled to begin observations of solar-type stars in November 1992.

A New Echelle Spectrograph
K.G. Libbrecht & M.L. Peri



A false-color image of the solar spectrum taken with the new echelle spectrograph shows wavelength converage obtained in a single exposure. Each spectral order appears as a horizontal band in the typical pattern which gives the echelle spectrograph its name. (Echelle means ladder in French.) To detect stellar oscillations we acquire a timeseries of such spectra and look for periodic frame-to-frame motions in the stellar absorption lines.

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The Palomar 200-inch f/9 CCD Camera

Principal Investigator: James K. McCarthy
Department of Astronomy
California Institute of Technology

Subject Heading: Instrumentation

The standard f/16 Cassegrain of the Palomar 200-inch Hale Telescope has a plate scale of 2.54 arcseconds/mm, or 0.061 arcseconds/pixel for CCD pixels measuring 24 μm. It is therefore poorly matched to CCD imaging observations in the absence of any reimaging optics; typical CCDs are 1024 pixels square, and so a reciprocal scale of 16 pixels/arcsecond implies a total field of about 1-arcminute. In order to maximize the imaged field size, most existing CCD imaging instruments (PFUEI and COSMIC at Prime focus, 4-SHOOTER at the f/16 Cassegrain focus) have been designed with reciprocal scales of approximately 3 pixels/arcsecond.

To facilitate an observing program in which a minimum field size of 90-arcseconds was required at an image scale of 0.2-arcseconds/pixel or less, a new CCD imaging instrument was designed and fabricated for the f/9 Cassegrain focus of the Hale Telescope. With a 1024 $\times$ 1024 CCD array of 24 μm pixels, the f/9 focus provides a nearly 2-arcminute field of view at an image scale of 0.11-arcsec/pixel (or 9 pixels/arcsec). A greater number of pixels per arcsecond permits CCD photometry to achieve a greater S/N ratio in a single exposure prior to saturation, an indeed increases the photometric accuracy achieved for the same stellar signal in the high S/N regime where CCD readnoise is insignificant. These two advantages were both crucial to the planned observing program, in which stellar oscillations were to be investigated photometrically, requiring an accuracy per exposure of order 300 μmag and an ultimate sensitivity for a 7-night time series of 20 μmag or better.[†]

The f/9 Cassegrain focus is produced by an 18-inch diameter doublet or triplet lens system (depending upon the wavelength range of the observation; work in the red requiring the triplet configuration) located above the Cassegrain focus in the converging beam from the f/16 secondary mirror. The positive power of these lenses alters the f/ratio from f/16 to f/9, and an unvignetted field of 7.5-inches (14-arcminutes) diameter is available. The 18-inch diameter lenses were fabricated in 1963 and used in conjunction with 8 $\times$ 10-inch photographic plates for some years thereafter. This new instrument represents the first application of the f/9 Cassegrain mode to modern CCD imaging. In September 1992 the three 18-inch diameter lenses were commercially anti-reflection coated with a high-efficiency broad-band coating (0.5% average reflectivity from 3650Å to 9000Å) for utmost performance.

[†] The f/9 CCD camera system was indeed successful reaching this level of precision on the Hale Telescope in January 1992 during a 7-night observing campaign.

Figure 1 is a plan view showing the design of the instrument, which includes an 8-position filter wheel (A) for standard 2 x 2-inch filters (the wheel will however accommodate 3-inch diameter circular filters if a new filter cell is designed), a 64mm diameter shutter (B), and an offset T.V. guider 'periscope' (C). The periscope can be moved in the radial direction through the field (total diameter 28-arcminutes, although only the central 14-arcminutes diameter is unvignetted by the 18-inch diameter lens) to pickup suitable guide stars; if this radial motion is coupled with rotation of the complete f/9 CCD camera on the rotating Cassegrain ring, it is possible for the T.V. guider to search the entire 28-arcminute field around the target being imaged by the CCD detector (D). Most of the moving parts are mounted to the top surface of a 0.75-inch thickness aluminum baseplate (E), so as to function above the focus. Figure 2 shows the f/9 CCD camera as it appears attached to the 200-inch Hale Telescope, as viewed from below.

The f/9 CCD camera proved capable of furnishing image sizes at least as good as 0.8-arcseconds diameter during the periods of best seeing in January 1992, and it is likely that the atmospheric seeing and not the f/9 optical system was still the limiting factor. A Code V raytrace analysis indicates that the 18-inch diameter f/9 lenses introduce aberrations at below the 0.1-arcsecond level. As predicted by the raytrace analysis, the image quality (or point spread function) furnished by the f/9 system proved to be exceedingly uniform across the 2-arcminute field of view of the 1024 x 1024 CCD, and would remain so for much larger CCDs as well.

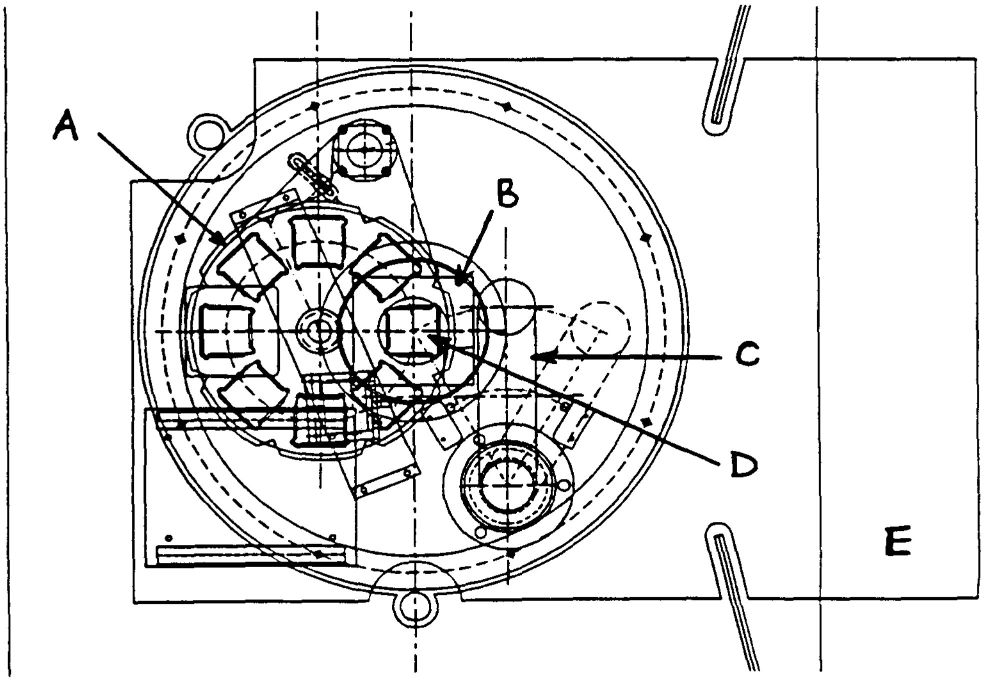

Figure 1: Simplified plan view of the f/9 CCD Camera design for the Palomar 200-inch Hale Telescope. Letters refer to components identified in the text.

Acknowledgements

It is a pleasure to acknowledge fabrication work by Gaston Araya Machining for the Palomar 200-inch f/9 CCD Camera, the drafting services of Ms. Kathy Smart, and the contributions of the Palomar engineering staff, particularly Hal Petrie, Bill Douglas, Ernest Croner, John Cromer, and Mike Carr. The raytrace analysis with Code V was conducted by Caltech graduate student Todd Hunter.

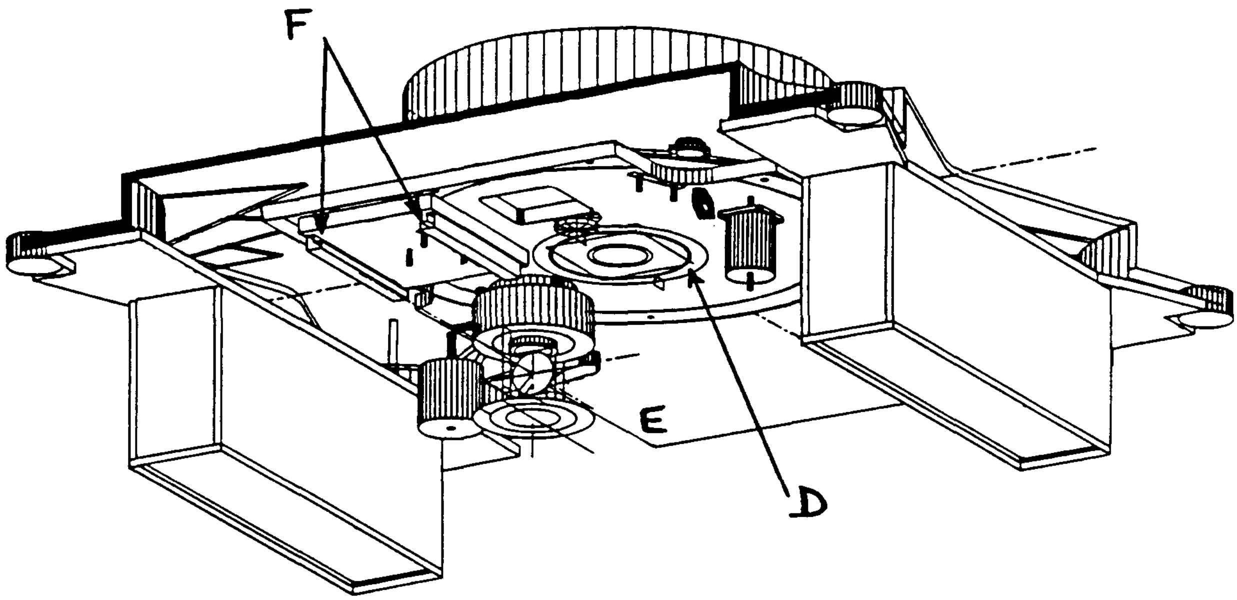

Figure 2: Perspective view of the f/9 CCD Camera system as it appears attached to the Cassegrain of the 200-inch telescope. The CCD detector and LN_2 Dewar attach to the small central ring (D), while the T.V. guider camera attaches to the rails (F). Note that the T.V. camera is stationary while the 'periscope' may move radially in the telescope field. The remaining components seen in Figure 1 are located above the 0.75-inch thick aluminum baseplate (E) and are therefore not visible from this perspective.

The Second Palomar Sky Survey

I. N. Reid - for the sky survey team [1]
Palomar Observatory, California Institute of Technology

Subject Heading : Instrumentation

During 1992 the Oschin telescope continued to be devoted exclusively to taking photographic plates for the second Palomar Sky Survey (POSS II). Started in late 1985, this survey, when complete, will provide complete coverage of the northern celestial hemisphere in blue (IIIaJ emulsion), red (IIIaF) and infrared (IVN) passbands and will match in depth the southern sky surveys currently being undertaken by the UK Schmidt telescope in New South Wales, Australia. The new survey extends 2.5 magnitudes fainter in the blue (a factor of 10 in luminosity) than the original POSS I survey, completed in 1957, while the red plates are $\sim$ 1 magnitude deeper - there is no previous northern-sky near-infrared survey.

There are 894 separate fields set at 5^o spacing, allowing sufficient overlap between adjacent fields to cross-calibrate - a factor of considerable importance for programmes such as investigations of the large-scale structure of the universe, which depend on excellent uniformity over tens of degrees on the sky. During the past year (Sep 13, 1991 to Sep 12, 1992), we obtained a total of 348 plates (the 1991/2 winter was particularly poor weather-wise), of which 297 are of sufficient quality to be included in the survey - an acceptance rate of 85 %. This brings the total number of accepted plates to 490 IIIaJ (52 %), 597 IIIaF (67 %) and 190 IVN (21 %). In addition, short-exposure (3 minute) unhypered IIIaJ plates have been taken to match the deep J-band survey - this is to allow the U.S. Naval Observatory to tie together the faint, radio-star astrometric reference frame and the brighter fundamental reference stars.

The survey plates are being copied by the Photolabs of the European Southern Observatory in Garching and three shipments, each of 100 plates, were despatched during the course of the year. The first set of film copies (50 IIIaJ plates) was issued by ESO. In addition, the past year saw an agreement reached with the Space Telescope Science Institute, Baltimore, by which the survey plates will be scanned 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.

Survey plates have been used for several scientific projects during the year, notably Tinney's (CIT) search for very low mass M dwarf stars. The luminosity function derived from this study, currently covering nine 6 x 6 degree fields, shows a luminosity that declines in number density by a factor of 5-10 from the well-known maximum near $\sim 0.25M_{\odot}$ and is flat or decreasing at the lowest luminosities. These data are also being applied to a study of the frequency and extent of chromospheric emission amongst earlier-type M stars (Hawley (Lawrence Livermore), Tinney & Reid). In addition, Serabyn (CIT) has used POSS II material to study the optical structure of the bright-rimmed globule IC1396E. Finally, Mueller has discovered a further 8 supernovae, bringing the total discovered during the course of POSS II (including historical, i.e. POSS I, supernovae) to 56; two Apollo asteroids (1991BB and 1991TB2); and two comets (1991h1 and 1992g), making a total of nine discovered during the course of the survey.

[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

SOLAR SYSTEM

Infrared observations of planets, rings and satellites.

Principal Investigator: Philip D. Nicholson
Astronomy Department,
Cornell University

Coinvestigators: Keith Matthews & Stephen Leroy
California Institute of Technology,
Doug Hamilton, Cornell University, and
Anne Skrutskie, U. Massachussetts

Subject Heading: Solar System

Since 1988, Philip Nicholson and Keith Matthews have collaborated on a program of planetary observations using the 58 × 62 pixel Cassegrain Infrared Camera at Palomar. These observations exploit the strong $\lambda 2.0 - 2.4$ μm absorptions by methane and molecular hydrogen in the atmospheres of the giant planets to study the rings of Saturn and Uranus, the faint inner satellites of Jupiter and Saturn discovered in spacecraft images, and the smaller classical satellites of Saturn and Uranus. The 1–5 μm spectral region accessible to the InSb detectors in the IR camera also offers opportunities to study the atmospheres of the outer planets themselves, especially in the 5 μm region where thermal emission from relatively deep tropospheric levels can be sensed, and at 2.2 μm where stratospheric hazes are prominent.

In 1991/1992, six nights on the 200-inch telescope were devoted to this program, including observations of Neptune, Saturn's rings and inner satellites, and the satellites of Uranus. The scientific goals and results obtained to date from these data are summarized below.

(a) Satellites. In July 1991, we obtained near-IR photometric observations of the inner Saturnian satellites, Mimas and Enceladus, in order to define their near-opposition brightening (diagnostic of unusual textures in their icy surfaces), as well as spectroscopic observations of the icy Uranian satellites Miranda, Ariel and Titania, and Neptune's single large satellite Triton.

Initial reductions of the Enceladus images show only minimal (~ 0.1 magnitude) brightening between phase angles of 0.09° and 0.06° at 2.10 μm, but what appear to be substantial 'opposition surges' of 0.4–0.5 mag. over this same range at 2.24 and 2.40 μm (see Figure). This behavior is not consistent with our expectations, as the satellite's albedo is relatively low at 2.10 and 2.40 μm and high at 2.24 μm, and most physical models predict a correlation between albedo and opposition brightening. It is possible that our measurements are affected systematically by the very strong scattered light from Saturn's rings, and we are currently exploring more sophisticated approaches to removal of this background.

Although not yet reduced to final form, our infrared spectra of Triton were taken on each of 6 consecutive nights and therefore cover one complete rotation of the satellite (its orbital and rotation periods are 5.8 days). Many of the spectra show evidence for the feature at 2.15 μm discovered by Cruikshank et al. (1984), and attributed to liquid or solid nitrogen on the satellite's surface. Our observations may help to specify the distribution of nitrogen in longitude on Triton, as well as serve to confirm the previous detection. As anticipated, the new spectra of the Uranian satellites are dominated by absorption bands due to water ice or frost, and no obvious unusual features were seen. No good published spectrum of Miranda exists, due to its faintness and close proximity to Uranus.

(b) Neptune. Our previous observations of Neptune in 1990 had revealed the presence of one or more bright 'spots' in the planet's southern hemisphere at a wavelength of 2.2 μm, as well as a general northern hemisphere brightening (Leroy et al. 1990). Because of the great opacity of Neptune's atmosphere in this wavelength region, we believe these features reside in the stratosphere, perhaps 50-100 km above the cloud tops visible in *Voyager* images. During our 6-night run in July 1991 we systematically imaged Neptune at 2.2 μm at least twice per night, in order to track the motions of the southern spots. Our data demonstrated the presence of *two* spots, with rotation periods of approximately 18.5 hours and 16.5 hours. Although the identification of these features is uncertain, the periods match those of the Great Dark Spot and the smaller spot known as D2, as measured from *Voyager* images (Smith et al. 1989). These observations would not

have been possible without both the great sensitivity of the Hale Telescope and the IR Camera, and the ability to make regular observations over almost a week, which permitted us to make initial estimates of the spot rotation periods, and then test these by predicting their next appearance.

(c) Saturn's rings. Although it has long been known from their near-infrared spectra that Saturn's rings are composed primarily of water ice, images taken by the *Voyager* spacecraft in 1980 suggested that there may be subtle compositional variations between the major ring components known as the A, B and C Rings (Cuzzi et al. 1984). Unfortunately, the spacecraft carried no spectrometer capable of verifying this possibility, and published Earth-based infrared spectra combine light from the whole ring system (Clark 1980). By using a tunable filter within the Palomar IR camera, we were able to obtain a sequence of 60 images of the rings, each in a narrow wavelength band, which together cover the spectral range 1.80 – 4.10 μm. This set of images, when correctly registered spatially with respect to one another, will permit us to obtain complete spectra for each of the major ring components separately, and thus to search for tell-tale features in the spectra which might provide a hint as to the nature of the compositional variations. Similar types of observations are planned for NASA's *Cassini* mission to Saturn in the next decade, of which P.D.N. is a science team member, and the Palomar data will serve to test the utility of such measurements.

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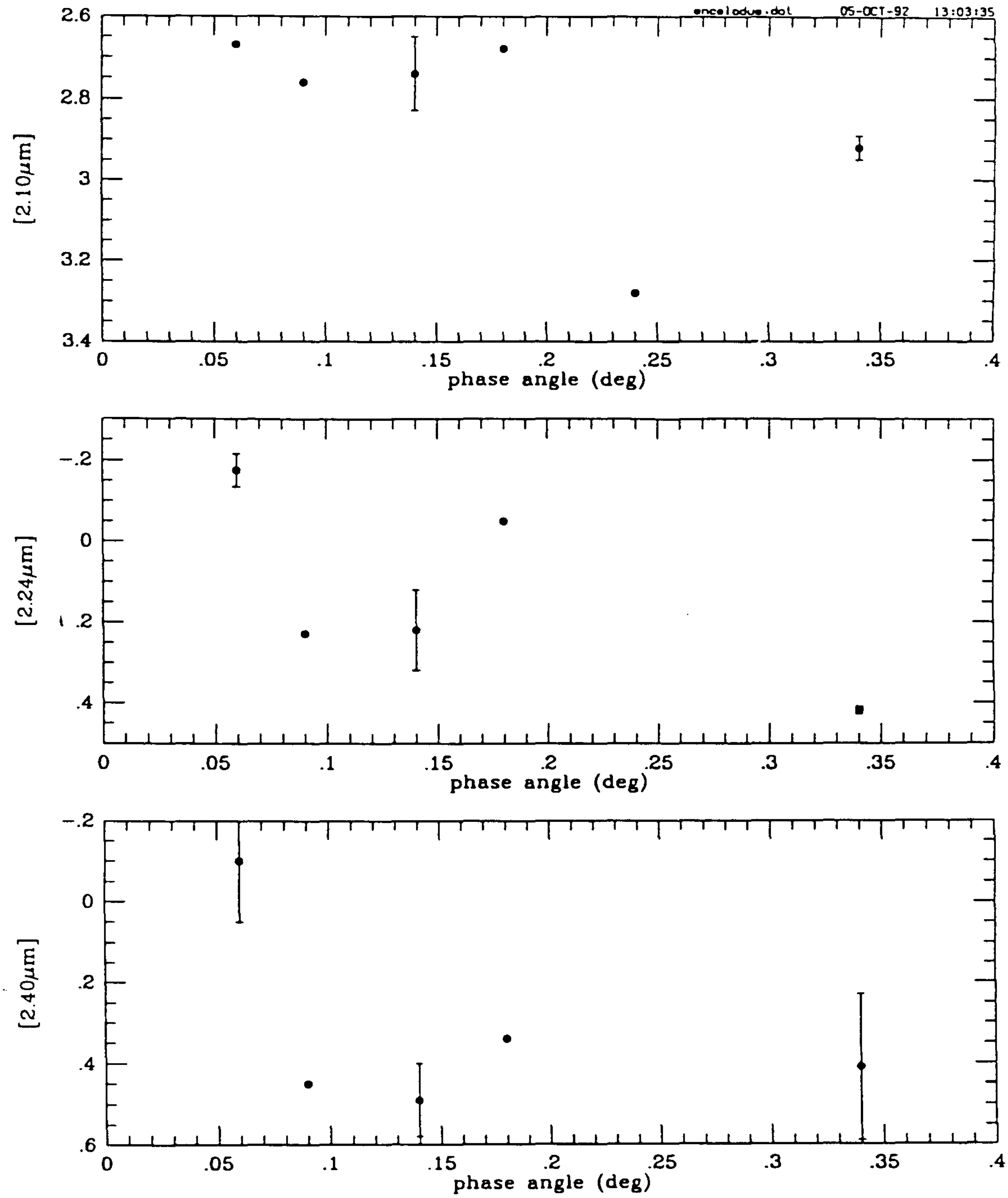

Figure 1. Near-infrared phase curves for Saturn's inner satellite Enceladus at wavelengths of 2.10, 2.24 and 2.40 μm, based on IR camera images obtained on 25–30 July 1991 at Palomar. The magnitude difference between Enceladus and the larger satellite Titan, used here as a photometric reference, is plotted as a function of phase angle, the angle at Saturn between the directions to Sun and Earth. The anomalous 2.10 μm measurement at 0.24° is probably in error, and should be disregarded.

Dynamical Evaporation of the Jupiter Trojan Swarms

Principal Investigator: Eugene M. Shoemaker
U.S. Geological Survey

Coinvestigators: Carolyn S. Shoemaker
Department of Physics and Astronomy
Northern Arizona University

Henry E. Holt
Department of Geology
Northern Arizona University

Subject Heading: Solar System

From a combination of observations and theoretical studies, a major advance in the understanding of Trojan asteroid swarms has been made in the past year. Our observational program with the Palomar 46-cm Schmidt telescope has led to the discovery of 63 Jupiter Trojans over the past seven years. These objects are among the larger members of the two Trojan swarms, one preceding Jupiter and the other following Jupiter in its orbit. The Jupiter Trojans are surviving fragments of the small solid bodies formed in the region where the giant planets accumulated, and our objective has been to assess, from the evidence of these survivors, the initial mass of solids that condensed from the solar nebula in this region. In the past year, we made substantial progress in the astrometry of the discovered Trojans. In this time period, 36 additional Trojans have been numbered. Typically, for each Trojan, numbering requires about 25 to 30 accurate positions properly distributed over at least three and generally four or more years. Most of these positions have been measured with a Mann comparator from our films taken at Palomar over the years 1987 to 1992. Our Palomar program has now yielded more new numbered Trojans than were known at the beginning of our systematic Trojan search in 1985. The precision of the orbit solution required for numbering is also the precision required for secure proper elements, which is the goal of our astrometry program. In a parallel effort, we developed a refined method for estimating the proper elements of Trojans from their osculating orbits, and derived proper elements by this method for all known Trojans with sufficiently precise orbits.

In order to better understand the limits of stability of Trojan orbits, our colleague Harold Levison numerically integrated the orbits of 270 Trojan-like particles in three dimensions under the influence of the Sun and the four giant planets. The orbits of the Sun and planets were integrated as a full N-body system in a barycentric frame. The equations of motion for the Sun, planets, and particles were integrated using the second order leapfrog simplectic scheme recently developed by Wisdom and Holman (1991). The integrations lasted until the particles escaped or for 10^9 years. In addition, six of the particles were integrated up to 4.5 x 10^9 years.

The results of these integrations have enabled us to contour the dynamical lifetimes of Trojans with respect to their initial proper eccentricity and libration amplitude. The surprising finding is that about 8% of the presently observed Trojans have dynamical lifetimes less than a billion years. All have lifetimes greater than 100 million years, however. One large Trojan, 1991 XX discovered by us in December 1991, has the largest orbital eccentricity of any known Trojan and one of the shortest dynamical lifetimes. The clear implication from the observations and the numerical investigation of orbital stability is that the Trojan swarms are evaporating with a half-life of the order of the age of the solar system.

Because many Trojans that had dynamical lifetimes much less than those of the surviving bodies probably were present in the early solar system history, the early Trojan swarms probably were many times more massive than the present swarm. This leads us to conclude that the mass of condensed solids in the region from which the Trojans were captured was many times greater than we first estimated (Shoemaker et al., 1989). Several hundred Earth masses of solids may have been present in the region in which Jupiter accumulated, and a very massive protosolar nebula is implied.

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STARS AND THE INTERSTELLAR MEDIUM

Baade-Wesselink Distances for the Globular Clusters M5 and M92

Principal Investigator: Judith Cohen
Division of Physics, Mathematics, and Astronomy
California Institute of Technology

Subject Heading: Stars

The distances to globular clusters are usually determined by fixing the absolute magnitudes of their horizontal branch stars at the location of the RR Lyrae variable stars. The assumed value for the absolute luminosity of the RR Lyrae variables rests upon statistical parallaxes for field RR Lyrae stars and on variations of the Baade-Wesselink method for field RR Lyrae variables. Distances to globular clusters which rely on main-sequence locations as defined by field subdwarfs suffer from the serious limitation of the exrtemely small number of field subdwarfs which have accurate parallaxes, and of the need to include corrections to the luminosity for varying metallicities.

These cluster distances are then used to determine cluster ages, and small errors in distance propagate into substantial age uncertainties. In addition, the absolute magnitude of the RR Lyrae variables directly calibrate the extragalactic distance scale. RR Lyraes have been detected in the Magellanic Clouds, in M31, and in several other galaxies of the Local Group, and will undoubtedly be found in additional galaxies by the Hubble Space Telescope, once it is repaired.

I have completed a major effort to recalibrate the absolute magnitudes for RR Lyrae variables in globular clusters. I am using the Baade Wesselink method, which requires two color photometry over the approximately half day period combined with radial velocities. These data are used to construct two independent angular diameter – phase curves. Matching of the two curves yields the distance and mean radius of the pulsating variable star.

This effort began 5 years ago with an analysis of the variable stars in M5 with SURF student Gabrielle Gordon. But we ran into problems with the visual photometry (we were using V (5500 A) and i (8500 A) photometry) which we believed arose because of the influence of shock waves on the atmospheric structure of the star near the phase of minimum radius. The major improvement in the preent investigation was the use of V (5500 A) and K (2.4 μ) photometry using the new infrared array camera. Keith Matthews collaborated in obtaining the infrared photomery. Approximately 10 nights of time on the 5–m Hale telescope, half with the infrared array camera and half with the Double Spectrograph, as well as ten nights on the Palomar 1.5–m telescope, in the period from 1988 to 1990 were involved in this effort.

I have analyzed two RR Lyrae variables in the very metal poor globular cluster M92, as well as the same four RR Lyrae variables in the intermediate metallicity globular cluster M5 studied earlier by myself and Gabrielle Gordon. I find that a distance to M5 of 6.9 $\pm$0.45 kpc, and to M92 of 7.85 $\pm$0.45 kpc. With these distances I obtain an absolute mean magnitude corrected for interstellar reddening of M_V^0 of 0.86 $\pm$0.14 mag for the M5 RR Lyrae stars, while M_V^0 = 0.62 $\pm$0.11 mag for the M92 RR Lyrae variables.

These results are in excellent agreement with previously published distances based on matching the globular cluster main sequence to that defined by the field subdwarfs of known distance. In addition, the metallicity dependence of M_V^0 agrees well with that determined from Badde-Wesselink analyses of field RR Lyrae stars. So I conclude that the globular cluster RR Lyrae variables behave identically to the much better studied field RR Lyrae variables. Calibrations and relationships established from the extensive data for field RR Lyrae stars can now be applied with confidence to the globular cluster RR Lyrae variables, where such data are much sparser and harder to obtain.

Studies of Magnetic White Dwarfs

Principal Investigator: Marshall Cohen
Division of Physics Mathematics and Astronomy
California Institute of Technology

Coinvestigators: Angela Putney, James McCarthy
California Institute of Technology

Subject Heading: Stars

In 1992 we began a study of magnetic white dwarf stars (MWD) by measuring the spectrum of polarization. The polarization arises from very strong magnetic fields, up to a billion Gauss, which is enorously stronger than the fields on the Sun. 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 the MWD are probably the magnetic A stars, but the statistical association is not well-defined. One of our goals is to make a survey of 55 white dwarfs with a nearly featureless spectrum (classification DC) to increase the sample of known magnetic stars and thereby improve the statistics for evolution studies. Some DC stars have faint spectral features indicative of strong magnetic fields, but their recognition and interpretation is greatly improved with spectro-polarimetry. This survey will be conducted by a graduate student, Angela Putney.

A second goal is to use the magnetic field as an aid in understanding the atmosphere and possibly also the interior of the strong-field stars. To do this we first have to establish a good model for the magnetic field. In the observations of seven strong-field stars which we have made to date, we have seen that three have important spectral features not seen before, and we have not yet studied the other four in detail. We believe that our data are better than any which have been obtained heretofore. We should be able to establish good models for the magnetic field in a number of stars, and that should provide data for extensive studies of the atmospheres.

The atmosphere studies are done with large computer codes, and we are establishing a collaborative program with the white-dwarf group at the University of Kiel for that purpose. They have the appropriate codes, and we will have the observational data. Ms. Putney will spend part of 1993 in Kiel.

PROGRESS REPORT FOR PALOMAR OBSERVATIONS

IMAGING OF MILLISECOND PULSARS AND THEIR SURROUNDINGS

James Cordes (Cornell), Scott Lundgren (Cornell), Roger W. Romani (Stanford)

Subject Heading: Stars

15 OCTOBER 1992

We have made imaging observations to probe the optical counterparts of a number of energetic and recycled pulsars. Searching for nebular excitation in the fields of PSRs 1257+12, 1534+12 and 1853+01 provides information on the interaction of the pulsar wind with the surrounding interstellar medium. We have identified putative counterparts in the PSR1953+29 field.

FILAMENTS NEAR THE YOUNG PULSAR IN W44

Recent work (Wolszczan, Cordes, and Dewey 1990, Ap. J., submitted) has shown that the pulsar 1853+01 is clearly associated with the X-ray and radio supernova remnant W44. The SNR and pulsar both have distances of 3 kpc and ages of $\sim$ 20 kyr. Another nearby older pulsar appears to have originated from the same binary as 1853+01. The binary was evidently disrupted by the explosion that produced W44. Most of what is known about W44 is from Einstein X-ray imaging (Smith et al. 1985, *M.N.R.A.S.*, 217, 99) and radio imaging (Clark, Green, and Caswell 1975; *Aust. J. Phys. Suppl.*, 37, 75). In contrast to the Crab nebula and pulsar, the X-rays appear to be predominantly thermal, with no point source counterpart to the pulsar. However, the rotational energy loss from slowdown of the pulsar spin is sufficient to excite nearby nebular material.

We have detected and mapped Hα nebulosity in this obscured supernova remnant. This represents the first optical detection of W44. The association of the filaments with the adjacent molecular cloud should help illuminate the remnant-cloud interaction, as well as allow study of the pulsar's influence on its immediate surroundings. Calibrated follow up observations of the region will give a detailed picture of the energetics and could help confirm the origin of these two pulsars in the same binary system.

OBSERVATIONS OF NEARBY, SPUN-UP PULSARS

Recently, at Arecibo radio observatory a binary pulsar 1534+12 was discovered with a 38 millisecond spin period in a 10 hour eccentric orbit (Wolszczan, IAU circular #5073). It seems likely that the companion is also a neutron star (based on the eccentricity), but it has not yet been seen as a radio pulsar. We have obtained a deep optical image to detect an optical counterpart, which may be due to pulsar wind-driven excitation of interstellar material or a synchrotron nebula.

Surprisingly, we found what appears to be a star of normal spectral type within the error circle for calculation of the pulsar position. No nebulosity was detected. Further observations are necessary to improve our estimate of the pulsar position and to determine whether this is a chance coincidence or whether the observed object is related to the pulsar system.

In a similar vein, we made observations of the recently discovered nearby, single 5 ms pulsar 1257+12. This system is particularly intriguing because it is the first planetary system found outside our own solar system. We imaged this object in the hope of seeing the remnants of the disk that formed the planets. Unfortunately, our observations show no signs of nebulosity in the vicinity of the pulsar, suggesting that whatever remains of the protoplanetary disk is too faint to see from Earth.

Finally, we made images of the binary millisecond pulsar 1953+29 (P_{spin} = 6.1 ms, P_{orb} = 117 days) that has a non-neutron star companion, almost certainly a white dwarf owing to the near perfect circularity of the orbit and the mass. A previous attempt to detect the companion (Loredo 1984, in *Millisecond Pulsars*, [NRAO: Green Bank], p. 48) shows an unusual red star near the position of the pulsar with colors that are inconsistent with emission from a white dwarf, the pulsar itself, or even a normal star. Our carefully calibrated colors for this star are completely consistent with an average star in the middle of its evolution. The earlier measurement may have been confused by the crowded field. Given how crowded the stars are in this field, this object is most likely a chance coincidence with a foreground star, unrelated to the pulsar.

The Multiplicity of T Tauri Stars

Principal Investigator: Andrea Ghez
Division of Physics Mathematics and Astronomy
California Institute of Technology

Coinvestigators: Gerry Neugebauer and Keith Matthews

Subject Heading: Stars

Understanding the formation of stars like the Sun remains one of the unsolved fundamental problems of astrophysics. Much of the work on this topic has been driven by the desire to explain the origins of our solar system and thus has resulted in scenarios for the production of single stars that, at a young age, are surrounded by a disk of gas and dust from which planets may form (see Shu et al. 1987). Yet surveys of nearby stars that are like our Sun have already shown that about 2/3 of the solar-type stars are in multiple star systems (Abt 1983; Duquennoy & Mayor 1991). So the question arises of how and when these multiple star systems form, for they appear to be the norm as opposed to the exception.

Over the last three years we conducted a similar survey of T Tauri stars, a class of young stars that will evolve into stars much like the Sun in roughly a billion years, to understand how and when multiple systems form and what effects a companion star would have on planetary formation. The survey was conducted in the two nearest star forming regions observable from the northern hemisphere, Taurus-Auriga and Ophiuchus-Scorpius, using the high resolution imaging technique of speckle interferometry at infrared wavelengths. With this technique we were sensitive to companion stars that are separated by a distance range that corresponds to the radius of Saturn's orbit to roughly twice the radius of Pluto's orbit.

The principal results of this work are the discovery of an overabundance of T Tauri star companions relative to their older solar-like counterparts. This implies that most, if not all, solar-like stars are formed as members of multiple star systems. Furthermore, at the smallest separations that we were sensitive, i.e., at separations that correspond to the distance from our Sun to the outer planets, we found a higher frequency of companion stars among T Tauri without evidence for a disk than among those with evidence for a disk. This suggests that the companion stars have disrupted the disks. Since the planetary systems are thought to form from such disks, this then implies that the presence of a close companion star suppresses the formation of planetary systems around these young solar-like multiple star systems.

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Herbig-Haro Objects around Herbig Ae/Be Stars

Principal Investigator: Robert W. Goodrich
Division of Physics, Mathematics, and Astronomy
California Institute of Technology
Subject Heading: Stars

The so-called Herbig-Haro (HH) objects are manifestations of the high-velocity outflows occuring around young, newly-formed stars. Most of the known HH objects are associated with stars of near solar mass, the T Tauri stars. Whether this is because these stars are more prone to form HH objects, or because it is harder to find HH objects around the more massive, Herbig Ae and Be stars, is not known. It is of interest to know how the characteristics of HH objects depend on the characteristics of the parent stars, but until recently no one has undertaken a survey looking for HH objects around the more massive stars. After such a survey, follow-up spectroscopy is needed to determine characteristics of the HH outflows, such as velocity, density, and size.

In 1990 and 1991 the 60-inch telescope of Palomar Observatory was used to conduct a systematic search for HH objects around a sample of 40 Herbig Ae/Be stars. Images of the fields containing each star were imaged in the light of ionized sulfur, [S II], in which the HH objects are particularly bright. A second set of images was taken in a nearby wavelength band in which the HH objects do not emit at all. Comparison of the two sets of images then reveals any [S II]-bright knots, which are considered as potential HH objects until a spectrum can confirm the identification. In this way a bright HH object near HK Ori was found, and confirmed with a spectrum from the 200-inch. HH objects around three other stars were confirmed, and faint HH objects around BD+40° 3731 and BD+47° 3471 were found. A jet-like feature was discovered embedded in a photoionized region near AS 343, which is relatively brighter in [S II] than photoionized lines like Hα. The survey has been submitted for publication to the *Astrophysical Journal Supplement Series*, and should provide a basis for continued study of these objects.

SpectroCam-10 Observations of Nova Cygni 1992

Principal Investigator: Thomas L. Hayward
Center for Radiophysics and Space Research
Cornell University

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

Subject Heading: Stars

SpectroCam-10 is an infrared spectrograph/camera built by Cornell University as a facility instrument for the 200-inch telescope. It is the first instrument to be built under a cooperative agreement between Cornell and the California Institute of Technology which gives Cornell astronomers access to the Hale telescope. During 1991-1992, its first full year of operation, SpectroCam was allocated three observing runs. In this report we describe one of our projects this year; reports describing additional scientific results from the instrument may be found elsewhere in this volume.

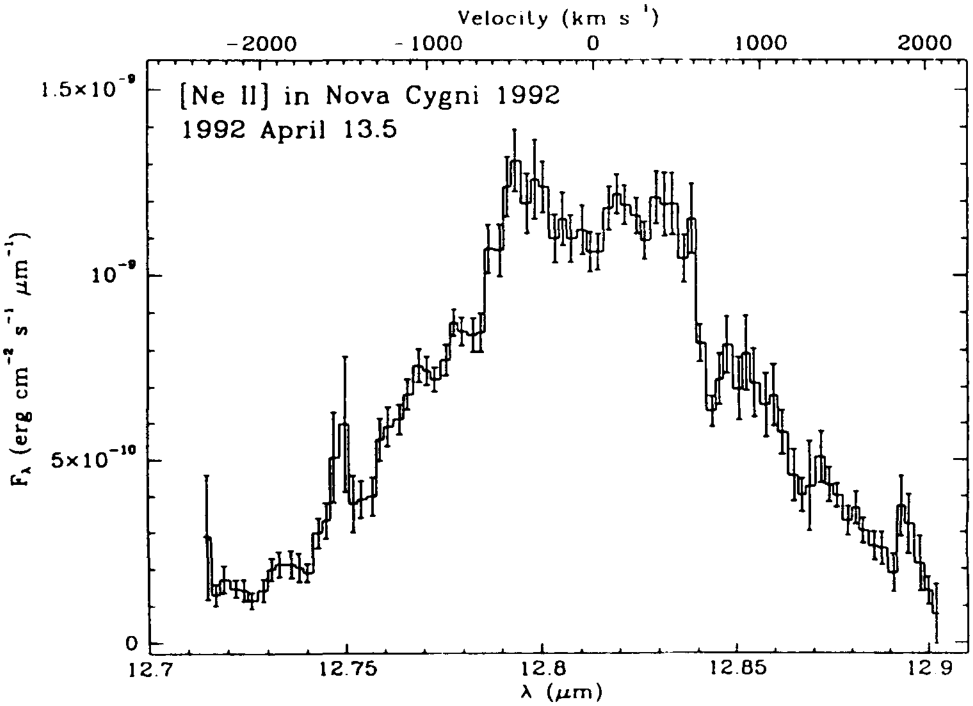
One of the more unexpected events of the year was the eruption of Nova Cygni 1992. Discovered on 19 February 1992 by amateur astronomer Peter Collins, Nova Cygni (in the constellation Cygnus) quickly brightened to naked-eye visibility, then slowly began to fade. Because it was the brightest nova in 17 years, its eruption and subsequent evolution have been the subject of intense study by astronomers around the world. We were lucky to have a scheduled SpectroCam-10 observing run at Palomar in mid-April, allowing us to observe the nova just 53 days after the outburst.

A nova begins as a pair of stars orbiting each other. One star is a very hot, dense white dwarf star, while the other is more typical star similar to our sun. The two stars are so close that the gravitational force of the white dwarf pulls a stream of gas off the surface of its companion. The gas gradually accumulates on the surface of the white dwarf until it is sufficiently hot and dense to detonate in a thermonuclear explosion. The layers of gas are flung off the white dwarf to form a hot, intensely bright gaseous shell that makes the system suddenly visible to us as a nova.

The explosion of a nova is one way that elements such as carbon, nitrogen, and oxygen, which are made by nucleosynthesis reactions in stellar interiors, are recycled back into the interstellar medium. Eventually, this material may become part of a molecular cloud which collapses to form a new generation of stars. Our solar system condensed from such a second generation cloud, and by studying novae we hope to better understand how the elements in the sun and planets may have been formed.

Using SpectroCam-10's low-resolution spectrograph mode, we detected several lines in the 8–13 μm spectrum of Nova Cygni 1992. The brightest feature, at 12.81 microns, was due to emission from singly-ionized neon in the nova shell. The other features, as well as the faint continuum, were due to hydrogen which makes up most of the shell. By comparing the intensity of the neon line to the brightness of the continuum, we calculated that neon is at least four times more abundant relative to hydrogen in Nova Cygni than in our solar system.

The figure below shows a spectrum of the neon line taken in SpectroCam's high-resolution mode. The line is very broad because the near side of the expanding nova shell is coming toward us, and its light is doppler-shifted to the blue (short-wavelength) side of 12.81 microns, while the other side is moving away and its light is shifted to the red. The width of the line indicates an expansion velocity of about 2000 km per second. The line's double-peaked structure implies that the shell is clumpy instead of being perfectly symmetric. While such phenomema are well-known from optical spectra of novae, our infrared spectra are the most detailed of a nova to date, and demonstrate that the neon is well mixed with the rest of the shell material.



Ten-Micron Spectroscopy of T Tauri Stars

Principal Investigator, 1992: Tom Hayward
Cornell University

Principal Investigator, 1993: Jeff Van Cleve
Cornell University

Co-Investigator: Chris Koresko
Cornell University

Co-Investigator: Steve Beckwith
Max-Planck-Institut für Astronomie

Subject Heading: Stars

The detection of dusty disks (Strom et al., 1989; Beckwith et al., 1990) around approximately half of the T Tauri stars in the Taurus-Auriga cloud, and the detection of optically thin rings of debris around main sequence A stars such as Vega or Beta Pictoris, are evidence for planet formation around stars other than the Sun, if we accept certain broad notions of how planets form. In this picture, disks of gas and micron-size dust grains around young stars are a key part of the matter, energy, and angular momentum transport that occurs when a dense cloud many thousands of AU across collapses into a compact object. Our long-term program is to understand this process by examining dust emission in binary systems and developing a minerology of dusty disks from high signal-to-noise, low-resolution spectra of these objects. The 7 to 14 micron spectral range is ideal for this study since it is accessible from the ground, probes the inner region of planet formation, and contains many spectral features of silicate minerals.

Binary stars with separations on the order of the diameter of the Solar System give insight into planet formation in two ways. First, a resolved T Tauri binary is an analogue of a protoplanetary nebula after the first large gas giant has condensed. Although a secondary with half the mass of the primary is a poor substitute for a Jupiter-mass object, it can at least be given a mass and a separation from its primary with available techniques. Second, most stars are in multiple systems, and Simon et al. (1992) show that T Tauris are distributed in binary systems much like main sequence stars. Understanding the degree to which disk accretion is different in close binary T Tauri stars from that around single stars will help us understand whether planets are unlikely in binary systems.

The dust in disks around young stars can have at least two origins. It can be primordial grains from the interstellar medium, or it can be dust from the destruction of larger bodies such as planetesimals or asteroids. The 8-13 μm spectrum of the dust gives some clues in determining which is the case. The first kind of dust, represented by the dust of the Trapezium, gives a broad silicate emission peak without narrow ($< 1\mu$m) features. The second, represented by dust from comet Halley, Elias 1 (Schutte et al., 1990), and possibly Beta Pic, shows narrow emission features similar to that measured for small olivine grains by Mukai and Koiko (1990).

In January 1992, we were able to obtain spectra of several T Tauri stars – GK Tau, GI Tau, V892 Tau, and HN Tau – during a development run of a new instrument built by Cornell for the Observatory, SpectroCam-10. A comparison of the GK Tau and GI Tau spectra show that the 9.7 micron feature reported by Cohen and Witteborn (CW, 1985) for GK Tau is probably a data-reduction artifact caused by the depth of the ozone absorption at this wavelength. V892 Tau and HN Tau, on the other hand, show a significant ($> 3\sigma$) narrow feature near 11.8 μm. A recent upgrade to this instrument enables it to produce diffraction-limited images at 10 microns, enabling the spatial resolution of roughly 30% of the Solar-System scale T Tauri binaries and deriving full benefit from the aperture of the Hale.

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High-Resolution Imaging of Young Stars

Principal Investigator: Chris Koresko
Department of Astronomy
Cornell University

Coinvestigator: Steven Beckwith
Max-Planck-Institut für Astronomie

Coinvestigator: Andrea Ghez
Division of Physics Mathematics and Astronomy
California Institute of Technology

Coinvestigator: Gerry Neugebauer
Division of Physics Mathematics and Astronomy
California Institute of Technology

Coinvestigator: Keith Matthews
Division of Physics Mathematics and Astronomy
California Institute of Technology

Subject Heading: Stars

Stars are born shrouded in remnants of the dusty molecular material from which they form. By the time the star begins to burn hydrogen on the main sequence, this material is almost entirely lost, either dissipated into interstellar space, accreted onto the star, or condensed into macroscopic bodies such as planets, comets, and asteroids. What happens in the intervening period is of considerable interest, because this placental material - usually in the form of a circumstellar disk or torus or a roughly spherical halo - is believed to be the origin of the solar systems which may come into being around the stars. Furthermore, circumstellar matter can significantly influence the course of a star's evolution toward the Main Sequence.

Recent infrared and millimeter surveys (*e.g.*, Strom *et al.* 1989; Beckwith *et al.* 1990) have detected disks of gas and dust surrounding approximately half of the young low-mass stars in the Taurus-Auriga star-forming region. Their sizes and masses are in many cases comparable to the disk from which our own Solar System is believed to have formed. Broadband infrared spectra give evidence of a clearing of the innermost regions of some of these disks at radii like those of the orbits of the Terrestrial planets, suggesting that planet formation may already have begun there.

Ordinary near-infrared imaging involves exposure times longer than the coherence times of the atmosphere, and its resolution is therefore limited by the atmospheric seeing to about 1 arcsecond, too crude for detailed study of solar-system size structures at the distance to the nearest active star-forming clouds. Koresko and Beckwith are using a technique called "speckle interferometry" to overcome this limitation by analyzing a series of many short exposures. Subsequent computer processing of the short-exposure frames produces an image whose resolution is good enough to show details as much as ten time finer than an ordinary image; structures as small as 15 AU in size can be studied surrounding many nearby young stars. This makes speckle interferometry an excellent means for studying the diffuse material which surrounds some of these stars and for detecting cool companion stars whose gravitational influence may play an important role in shaping the evolution of the disk and therefore the formation of planets.

In at least one case, we have found both nebulous material and companion stars within the same protostellar system. A new set of high-resolution infrared images of Monoceros R2 IRS 3, a distant, massive, and very young system, reveal a conical nebula whose small size would have made it very difficult to distinguish using ordinary imaging. This nebula extends south from one of the stars in the system, and it probably represents a dusty remnant of the material from which the system formed. The nebula's conical shape suggests that the starlight which illuminates it may be collimated by a large, dark disk or torus of denser material surrounding the star. These results have been submitted for publication in the *Astronomical Journal.*

Additional interesting results come from images made of three T Tauri stars in the Ophiuchus star-forming region. These stars have been found by Bouvier and Appenzeller (1992) to have "composite" optical spectra, implying that their light cannot come from a single, normal stellar photosphere. It was suggested that this effect might be the product of disk material being accreted onto the stars. An alternative possibility, that the spectra of these stars are complicated by the presence of close companions of different spectral type, could not be ruled out. We have found that at least two of the three composite-spectrum stars do in fact possess companions, significantly weakening the argument for disk accretion in these systems.

As we and other workers collect more high-resolution images of stars in the early stages of their lives, we become better able to address the broader problems pertaining to the formation and evolution of stars and their stellar, and perhaps planetary, companions. Since the limits to the effectiveness of infrared speckle interferometry depend on the size of the aperture, the Hale telescope is an ideal instrument for these studies.

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Adaptive Optics Stellar Coronagraphy

Principal Investigator: Shrinivas R. Kulkarni
Division of Physics Mathematics and Astronomy
California Institute of Technology

Coinvestigators: Tadashi Nakajima, California Institute of Technology
Samuel T. Durrance and David A. Golimowski, Johns Hopkins University

Subject Heading: Stars

Stellar coronagraphy is a technique to image the vicinity of a bright object with sensitivity to faint objects. In technical parlance this is referred to as high dynamic range imaging. This requires considerable care in minimizing light from the bright object scattered by the telescope optics. The technique consists of masking the central star in the image plane and apodizing the pupil with a mask in the pupil plane. The John Hopkins University (JHU) Adaptive Optics Coronograph (AOC) is an innovative instrument that maximizes the efficiency of a coronagraph by the help of an adaptive optics. The system consists of a tip-tilt mirror which corrects for image motion using starlight derived from a reflected spot in the image mask. The adaptive optics allows us to keep the bright star centered, and in addition sharpens the stellar images in the entire field of view of one arcminute. Both these dramatically increase the dynamic range of the image.

In collaboration with the JHU team led by S. T. Durrance we have begun a major AOC program at the Palomar 60-inch telescope, listed below.

- **Circumstellar Disks.** It has been speculated that some stars may have dust disks left as remnants from the formation of planetary systems (or in some cases, material that failed to become a planetary system). Indication of these disks have been given by their far infrared emission over and above the stellar emision. At visual wavelengths, the dust disk shines by reflecting the light from the main star. Since the disk is much fainter than the star, AOC is the technique of choice. The most spectacular example is β Pictoris in the Southern hemisphere. We have begun a systemic search for similar systems in the Northern hemisphere.
- **Brown Dwarfs.** A brown dwarf is a star that is not massive enough to ignite the hydrogen fusion reaction at its core. However it is still luminous mostly in the near infrared, since the slow contraction of the star releases gravitational energy. Brown dwarfs are characterized by low surface temperature ($T < 2000$ K) and low luminosity ($L < 10^{-4} L_{\odot}$). The latter is a more sensitive and definitive discriminant. We have started a search of nearby stars (with known distances) with the hope of detecting companion brown dwarfs. It is expected that a brown dwarf is fainter than a typical nearby star by at least four orders of magnitude at 0.9 μm, the wavelength of our search. On the other hand, the instrument is capable of finding a companion six orders of magnitude fainter than the main star at an angular distance of 4 arcseconds. An example of the capability of the instrument in this regard is shown in Figure 1.
- **Forming Solar Systems.** A T Tauri star is a young sun that is expected to have a forming solar system around it. The nearest T Tauri stars are in the Taurus dark cloud complex that is 140 pc away from the sun. Our spatial resolution and the field of view permit to study the physical scales of 200 to 4000 AU from a T Tauri star. As our first attempt, we observed an active T Tauri star, DG Tauri and found an arc-like feature previously unknown (Figure 2.). The projected length of the arc is about 2000 AU. It is likely to be a reflection nebula that is scattering the light from the star. Rather uniform surface brightness across the arc indicates that the arc may actually be a semi circle viewed nearly edge-on. The arc may also be a proto Kuiper belt, a future reservoir of comets. This discovery is an encouraging start of our T Tauri program.

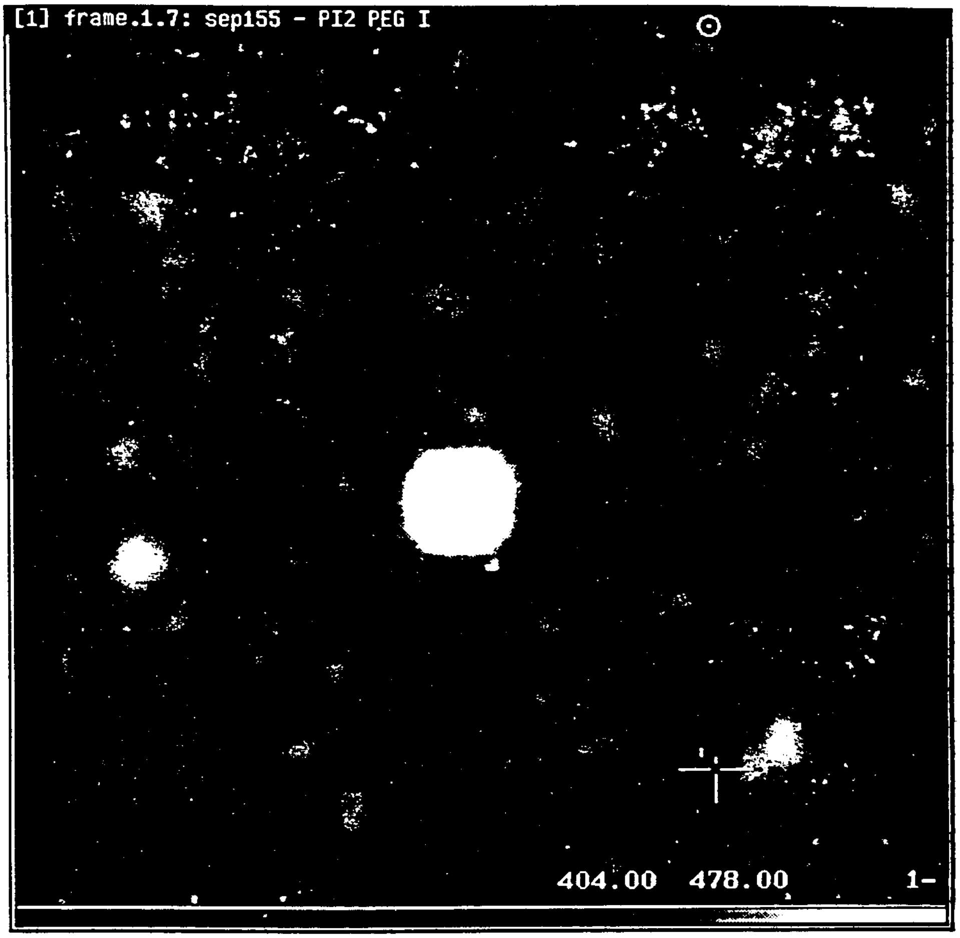

Figure 1. A companion star detected around a bright star. The companion is 1000 times fainter than the main star. The instrument is capable of finding companions more than 10000 times fainter than the main star.

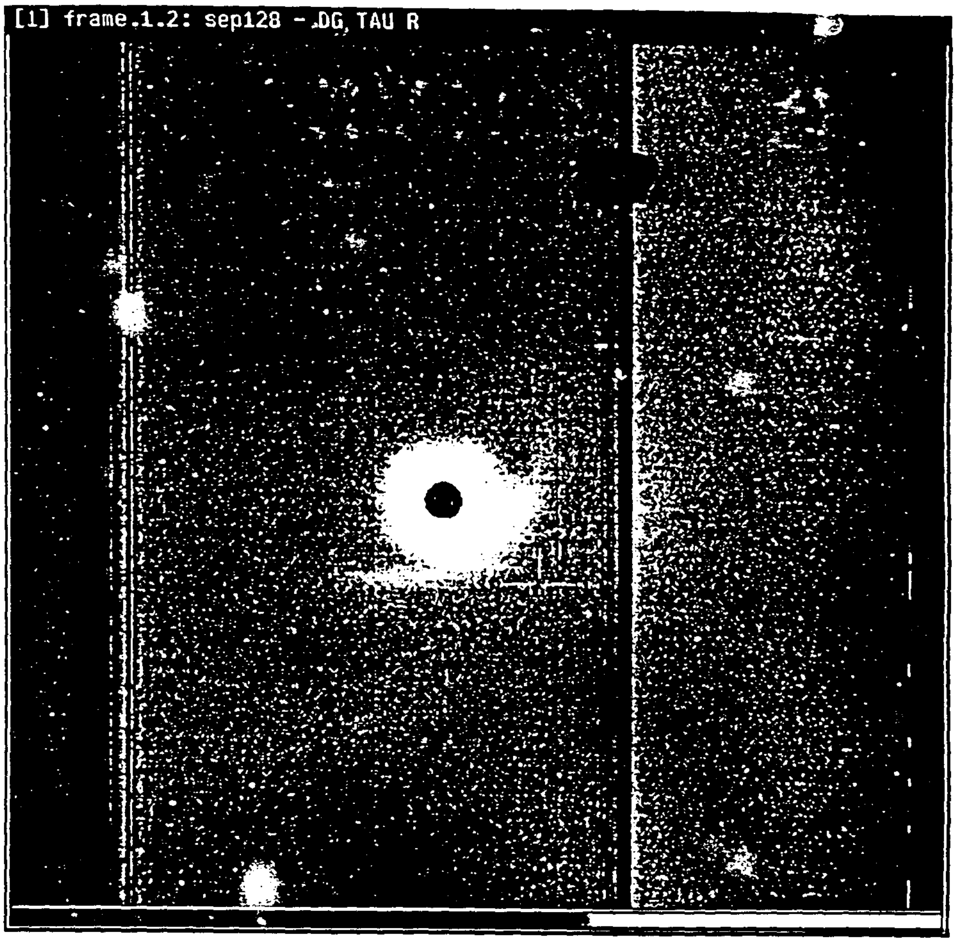

Figure 2. A faint arc-like nebula discovered around a young sun. The nebula may be a future source of comets in this solar system.

The Enigmatic Nebula G70.+1.2: A Be-Pulsar Binary powered bow shock?

Principal Investigator: S. R. Kulkarni
Division of Physics, Mathematics and Astronomy
California Institute of Technology

Subject Headings: Stars and Interstellar Medium

The enigmatic radio and optical nebula G70.7+1.2 has been suggested to be a young supernova remnant, a nova shell, a cometary HII region, and a proto-stellar outflow. The morphology of the nebula (Figure 1; left panel is VLA 8.4 GHz map and right panel is Palomar [OI] image) resembles a bow shock. An infrared (IR) luminous star (marked as "*" in the right panel of Figure 1) appears to be associated with the nebula. It is commonly agreed that mass outflow from the IR star shocks dense interstellar medium and the shocked gas is visible in a variety of emission lines (Hα, [OI] etc) as the optical nebula. The motion of the IR star then explains the bow shock morphology. However, neither this nor the previously listed models can explain the most unique aspect of G70.7+1.2: the non-thermal radio emission. In principle the supernova model can explain the non-thermal emission but the velocities involved are much too small to be consistent with a young remnant.

Last year we undertook a multi-wavelength study of this interesting object. Caltech telescopes at Palomar and OVRO, the Very Large Array and the Arecibo radio telescope were used. We first proved that the radio emission is indeed non-thermal by demonstrating that the radio flux decreased rapidly with increasing radio frequency. We detected linear polarization over much of the source. We carried out Fabry-Perot observations at the 60-inch telescope and found that the nebular velocities were well fitted to a bow shock model with an inferred stellar velocity of 60 km s^{-1}. Spectroscopy of the IR star showed that it is probably a Be star, luminosity class II. Such stars do not typically move at such large velocities.

We propose that both these unique features: the non-thermal emission and the large stellar speed are very nicely explained by a model in which the IR star is hypothesized to have a pulsar companion. The pulsar relativistic wind is shocked at about the same location as the stellar wind shock and gives rise to the non-thermal emission. The large stellar speed is the result of the violent birth of a neutron star in the system. Indeed, it is well known that binary pulsars have large space motions. This model is easily testable: proper motion of the radio nebula and detection of a pulse signal are within reach of radio telescopes. Apart from the novelty of finding a binary pulsar further study of the object is warranted on several grounds. The mixing of stellar wind with relativistic winds is a topic of much interest in plasma astrophysics. Additionally, it appears that a small cloudlet has been overtaken by the bow shock and is currently within the nebula. The cloudlet will be compressed and rapidly ablated during which interval it will radiate copiously in many IR lines. Observations will allow us to study some microphysics of cloud crushing and ablation.

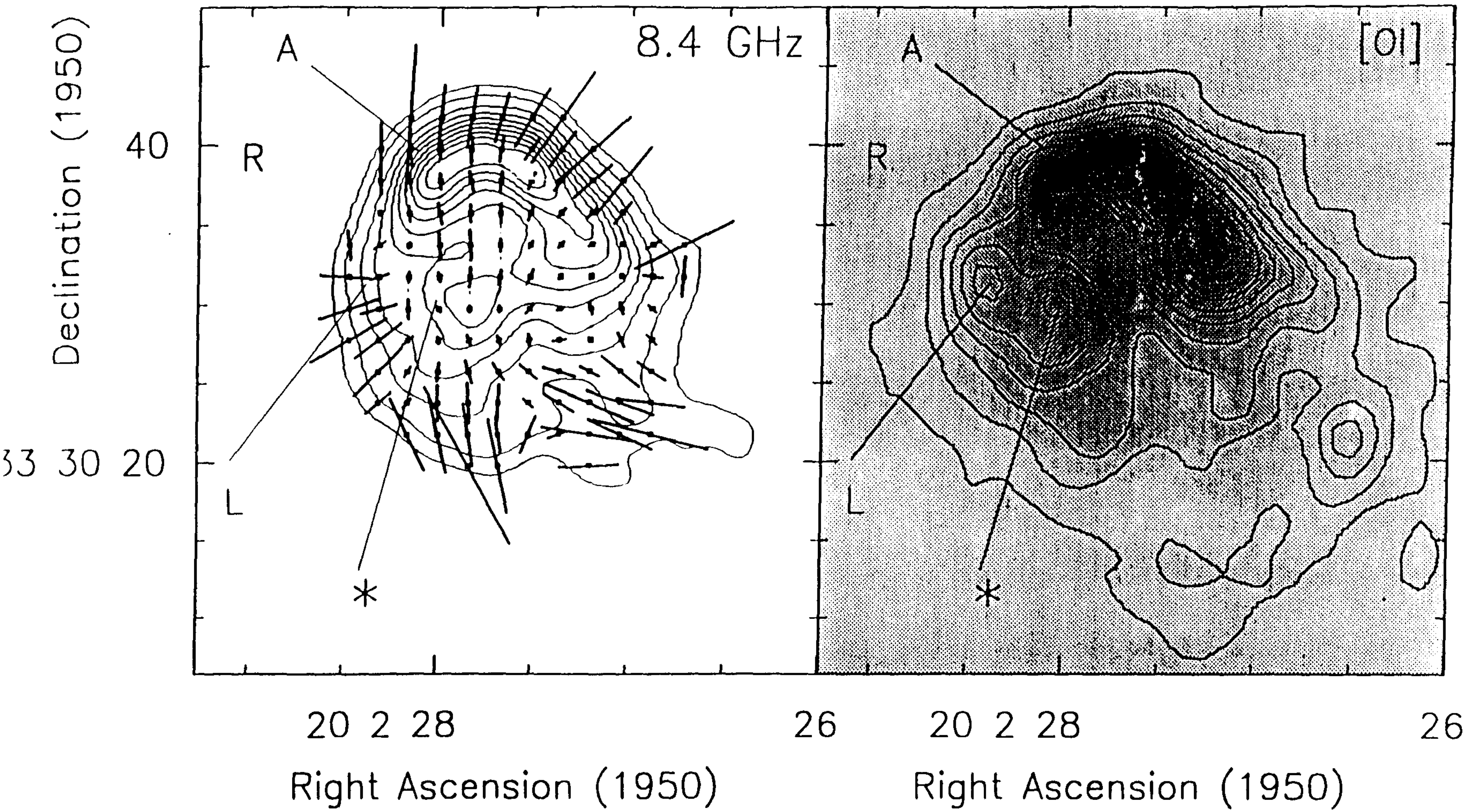

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Figure 2. Kulkarni et al.

Soft X-ray Transients and Millisecond Pulsars

Principal Investigator: S. R. Kulkarni
Division of Physics, Mathematics and Astronomy
California Institute of Technology

Coinvestigators: Y. Tanaka and F. Nagase
The Institute of Space and Astronautical Science, Japan

Subject Headings: Stars and Interstellar Medium

The origin of millisecond pulsars still remains a matter of considerable debate. It is generally agreed that millisecond pulsars are neutron stars that were spun by accretion of matter (and angular momentum) from a companion. During the accretion phase, the binary system becomes visible via its bright X-ray emission, the so-called Low Mass X-ray binaries (LMXB). However, this picture, while attractive in that it links two interesting groups of objects, the millisecond pulsars and LMXBs and provides a simple explanation for the rapid rotation rates, has been steadily challenged by a variety of statistical arguments. The most conclusive proof, the detection of coherent millisecond pulsations at X-ray wavelengths from LMXBs continues to elude us. We present a new approach involving a sub-class of LMXBs, the soft X-ray transients: to search for radio pulsations and to monitor the presence or absence of the accretion disk by optical spectroscopy from Soft X-ray Transients (SXT) during quiescence.

There are two groups of SXTs: soft ($kT \sim 5$ keV) and ultra-soft with a long hard tail (eg. A0620-00 and Cyg X-1). The latter are supposed to be black hole binaries. The former, hereafter SXTs (soft X-ray transients) are supposed to be neutron star binaries, an assertion supported by dynamical studies and detection of type I bursts (attributed to thermonuclear burning instabilities on the surface of a neutron star). It can be proved by using simple but robust arguments based on energetics that energy released during the transient high state must come from gravitational energy released during accretion rather than thermonuclear burning. Since most of the accreted energy comes out in the X-ray window, we can accurately measure the accretion rate, $\dot{M}$. The inferred accretion rates vary from the Eddington limit ($\sim 10^{-8}$ $M_{\odot}$ y^{-1}, in the high or outburst state) to four or more orders smaller.

There are two models for SXTs. In one model, accretion from the secondary is essentially constant but the viscosity of the disk abruptly increases leading to large increase in the accretion rate. In another, heating of the secondary star by X-ray emission from the accretion disk leads to unstable mass loss rate. The details of the mass transfer instability are of little direct concern to us. The changes in $\dot{M}$ are central to our new approach. In addition, along with other authors, we assume that all SXTs are LMXBs with a long history of mass transfer.

Matter close to a rapidly spinning neutron star is subject to two opposing forces: disk -osity which drives it inwards and the neutron star magnetosphere or the pulsar wind -pels it outwards. A critical rate, $\sim 10^{-11} P_3^{-7/2} M_{\odot}$ yr^{-1} can be derived below -creting neutron star will fling off the infalling material; here P_3 is the period of the putative accreting neutron star in units of 3 ms. Presumably it will then start functioning as a millisecond radio pulsar. Another critical rate, $\sim 6 \times 10^{-9} P_3^{-4} M_\odot \text{ yr}^{-1}$ can be derived, above which the radio pulsar will be forced to accrete.

The basis of our new method is that both these accretion rates depend sensitively on P_3. Taking the smaller of the two critical rates we note that when $\dot{M}$, the accretion rate falls below $10^{-12} M_\odot \text{ yr}^{-1}$ we expect the neutron star to function as a pulsar. There are three observational consequences:

1. The pulsar may be detectable in the radio band. Caveat: pulsar may not beamed towards us.
2. There should be no X-ray emission since there is no accretion.
3. The optical emission lines should disappear since the pulsar will clear the accretion disk. [The emission lines (which arise in the accretion disk) can be taken as rough indicators of $\dot{M}$.]

We have started a program to monitor a number of SXTs (Cen X-4, Aql X-1 and 4U2129+47) using the VLA (**1**), Ginga and soon Astro-D (**2**) and Hale 5-m (**3**). So far, we have found that while the emission line strength varies by almost factors of ten, the lines never disappear. Neither have we detected any radio emission during the off state nor do we find suitable cutoff in the X-ray luminosity.

The simplest conclusion we can arrive at is *SXTs do not harbor millisecond pulsars!* This is quite a surprising conclusion and is bound to be controversial. However, with sufficient observational material (so that $\dot{M}$ as measured via the Hα lines or the X-ray emission) we can be quite sure of this conclusion. We are particularly looking forward to the launch of the Japanese satellite Astro-D and nearly simultaneous Palomar observations.

Deep Near–Infrared Imaging of Young, Embedded Clusters

Principle Investigator: S. T. Megeath
Department of Astronomy
Cornell University

Co–Investigator: Terry Herter (Cornell University)

Subject Heading: STARS AND THE INTERSTELLAR TIME

A key issue in the study of star formation is the relationship between high and low mass star formation. Thirty years ago, George Herbig suggested that star formation is bimodal, i.e. high mass and low mass stars form in different locations through different processes (Herbig, 1962). This suggestion was based primarily on a comparison of optical surveys of the Taurus and Orion star forming regions. The Taurus region, which has few stars with masses greater than 2 $M_{\odot}$ ($1 M_{\odot}$ = 1 solar mass), showed an increasing number of stars with decreasing mass. In comparison, the Orion region, which contains several stars with masses greater than 10 $M_{\odot}$, showed a deficiency of stars with masses less than 1 $M_{\odot}$ (Larson, 1982).

The deficiency of low mass stars in the Orion and other high–mass star–forming regions has been an open question since its proposal. Until recently, our information on the low to intermediate mass stellar population of Orion came from optical surveys. These surveys were not sensitive to highly reddened stars embedded in the molecular cores from which they formed. Only in the past several years, with the development of sensitive near–infrared arrays, have we had the ability to survey the embedded stellar population.

We have finished a survey of three high mass star formation complexes in three wavelength bands, 1.25 μm, 1.65 μm and 2.2 μm (1 μm = 10^{-4} cm). This survey was started with the Cassegrain IR camera in 1990; however, in the past observing year we used the Prime Focus Infrared Camera due to its larger spatial coverage. In addition, we supplemented our data with observations from the Univeristy of Hawaii 2.2 meter on Mauna Kea. We selected three regions containing: i.) dense molecular gas capable of forming stars, and ii.) dense ionized gas (HII region), indicating the presence of a young massive star (Mass > 10 $M_{\odot}$). Each of the regions showed signs of recent (< 10^5 years) star formation such as compact HII regions, masers, and bright 10 μm sources. The goals of the survey were threefold:

- To determine whether there is a deficiency of low luminosity objects. Such a deficiency may be the result of a deficiency of low mass stars.
- To search for excesses in 2.2 μm emission. Such excesses are commonly seen in the young stars and protostellar objects found in low–mass star–forming regions.
- To examine the spatial relationship between the high mass stars and low mass stars.

We found dense clusters of intermediate to low mass stars (M < 10 $M_{\odot}$) in each region. At 2.2 μm, the most sensitive wavelength band, we detected 350 to 500 stellar sources. The density of sources ranges from 260 to 1300 per parsec^3. In each case, the cluster is not coincident with most the massive stars in the observed field. In one of the regions, DR 22, no low mass stars are detected near the HII region; the cluster lies almost an arcminute to the southeast.

A comparison of the 1.25, 1.65, and 2.2 μm emission for all three regions did not reveal a population of objects with 2.2 μm excesses. In nearby low–mass star–forming regions, bright excesses have been measured for young intermediate mass stars and deeply embedded protostellar objects. These excesses have been commonly attributed to accretion disks. This suggests that the formation of similar luminous accretion disks does not occur in high–mass regions; however, selection effects may bias us against the detection of stars with such disks.

Finally, an examination of the stellar population shows a deficiency of low luminosity stars for one of our sources, the cluster adjacent to the HII region DR 22. Such a variation may be due to evolutionary processes or may be the result of variations in the initial mass function. The former possibility is supported by an examination of the ratio of the 1.65 μm to 2.2 μm flux. The spread in this ratio is 10 times less for the DR22 cluster than the other two clusters, indicating that the gas density is much lower in the DR 22 cluster. The lack of gas is likely the result of the disruption of the cloud core by stellar winds; implying that the DR22 cluster is older than the other two clusters. This suggests that the appearance of the turnover is a function of age.

The process which produces the turnover is not understood. On possibility is that the lower mass stars are dynamically ejected from the cluster. Another possibility is that the luminosity evolution due to deuterium burning pre-main sequence stars may produce the turnover (Zinnecker, 1992). Currently, we cannot distinguish between these two models.

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Detection of the Companions of Mark III Binaries

Principal Investigator: Xiaopei Pan, Caltech
Co – Investigators : J. Tomkin, U.T. Austin; J. McCarthy, Caltech
I. N. Reid, Caltech; R. M. Rich, Columbia U.

Subject Heading: Stars

The Mark III Stellar Interferometer's ability to resolve the components of binaries has radically increased the overlap between the "visual binary" and "spectroscopic binary" regimes. The recent measurement of αAnd's visual orbit by Pan et al., (*Ap.J.*, **356**, p. 641; 1990 June 20) is a striking example. Previously this star had been known only as a spectroscopic binary.

If the new Mark III visual binaries are to yield their full fruit, however, it is necessary for them to be double-lined spectroscopic binaries. Only if spectroscopic orbits are available for both the primary AND secondary does the combination of visual and spectroscopic results give a complete description of the binary's orbit, the masses and luminosities of its components, and the distance to the binary. Our program of radial velocity observations therefore aims to measure the spectroscopic orbits of secondaries for Mark III binaries in which spectroscopic information about the secondary is skimpy or non-existent.

From our observations of 1991 and 1992 we have made a definite detection of the secondary in θ^2Tau. Figure 1 shows part of a θ^2Tau observation made with the P60 echelle spectrograph in November 1991. The presence of the secondary is evident. So far as we know this is the first direct spectroscopic detection of the secondary. θ^2Tau's membership of the Hyades cluster - it is one of the brightest stars in the cluster - gives it extra interest as a possible means of measuring an accurate distance to the cluster. For the observation in Figure 1 we measure a velocity separation between the primary and secondary spectra of $62 \pm 14 kms^{-1}$, which leads to a preliminary estimate of θ^2Tau's mass ratio of $M_2/M_1 = 0.8 \pm 0.2$.

A preliminary analysis of αAnd also reveals a probable detection of its secondary. It is clear that not only the faintness of the secondaries, but also their large line broadening is a major reason for their spectroscopic elusiveness. In both αAnd and θ^2Tau the secondaries are rapidly rotating A stars - see Figure 1.

In 1993 we plan to:

- Make more observations of our program stars at their ascending or descending nodes when the velocity separations between their primary and secondary spectra are largest. These phases are the most critical for definition of the radial velocity curves' semi-amplitudes.
- Use better matching stars (see Figure 1) so as to remove the primary spectra more completely and obtain cleaner secondary spectra.

- Obtain radial velocity curves and spectroscopic orbits for the secondaries of the program stars.

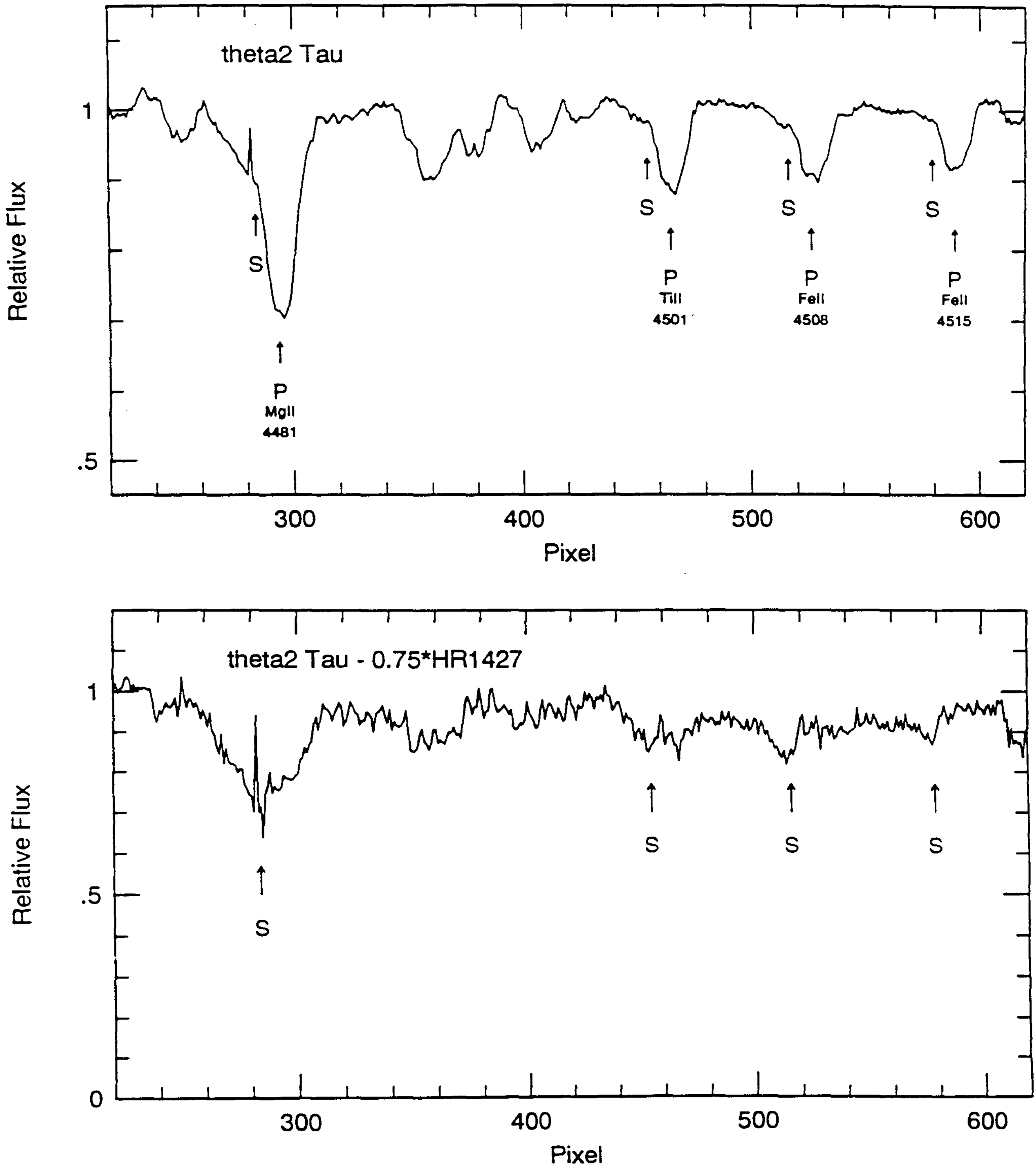


Figure 1. Top panel: A portion of theta2 Tau's spectrum between 4470 and 4520 A. Four of the strongest primary lines are labelled 'P'. The asymmetries in their blue shoulders labelled 'S' are their counterparts in the secondary. Bottom panel: The same portion of theta2 Tau's spectrum after subtraction of a standard star (HR 1427) chosen to match theta2 Tau's primary. The remainder, which has been renormalized to 1.0, is the spectrum of the secondary alone. 'S' marks the broad secondary lines.

Milliarcsecond CCD Based Astrometry

Principal Investigators: Xiaopei Pan and S. R. Kulkarni
Division of Physics Mathematics and Astronomy
California Institute of Technology

Co-investigator: Stuart Shaklan, Mike Shao, and Mark Colavita
Jet Propulsion Laboratory

Subject Heading: Stars

Introduction

Our astronomy program falls into the category of astrometry, the study of the positions and motions of stars. The main purpose for measuring stellar positions is to determine the distances to stars. The technique of parallax measurement, where one observes the change in a star's apparant position as the Earth orbits the Sun, is the only way of directly measuring the distances to stars.

Typically, researchers have been able to measure a star's position with a precision of a few milli-arcseconds (1 milli-arcsecond = 3 x 10^{-7} degrees). The traditional method was to form images on photographic plates and measure the distances between stellar images using high precision machines. In recent years, several stars have been measured with sub-milliarcsecond precision using solid-state CCD imaging devices.

Our long term goals are to demonstrate sub-milliarcsecond measurements using a CCD on the Palomar 60 inch telescope, to perform high precision parallax measurements on interesting sources whose distances are poorly known, to characterize the 60 inch telescope and Palomar mountain as an astrometric site, and to show how larger telescopes (*e.g.* the 200 inch) can improve astrometric precision. To achieve these goals we will carefully calibrate the responsivity and shape of the CCD, observe calibration sources that are known to be stationary for several years, and observe sources that are known to be of scientific interest.

Since beginning observations with our system in March, 1992, we have repeatedly observed several globular clusters and several high parallax stars. We have concentrated our analysis on the globular clusters since they provide many bright, fixed stars against which we can measure the stability of our system. A final analysis of the high parallax stars requires at least a full year of observation.

Summary of Results

Globular cluster M13 was observed on two nights in April, one night in May, June, and August, and two nights in September. Each night we made a set of approximately twenty 30-second exposures. We chose as a reference frame 6 stars in the first April observation that were common to all the observations. A seventh star served as the target star. The 6 reference stars were distributed over one minute of arc.

For each frame we made a flat-field correction then fitted an elliptical Gaussian to each of the 7 stars. A least squares routine was used to fit a linear affine plate constant model to each frame in order to remove shift, rotation, and scale change with respect to the reference frame. Only the 6 reference stars were used to fix the model. The model was then used to the target star centroid from each frame into the (best fit) coordinate system of the frame.

Our result is that the target star centroid standard deviation for the six month period was 1.5 milli-arcseconds in both R.A. and Dec. Figure 1 is a plot of the frame to frame centroid motion. The total observing time for these observations was 70 minutes. We believe that some of the 1.5 milli-arcsecond error is due to the limited total length of the observations. The rest of our error is potentially due to several factors, including: the fitting function; telescope focussing problems (defocussed images show significant astigmatism); and camera q.e., q.e. slope, and pixel position calibration.

In addition to the target star astrometry, we have also analyzed the standard deviation of star separation for all pairs of stars. Figure 2 shows the standard deviation of frame-to-frame motion plotted against star separation. The results indicate: (1) that the motion should average to less than 1 mas per hour; (2) that upper atmospheric conditions at Palomar are comparable to those expected on Mauna Kea; and (3) the linearity of relative star motion as a function of separation means that significant gains are to be expected if a larger telescope is used to collect the same amount of light from a smaller field.

Continued Work

Now that we have finished with our "shakedown," (including both the camera and telescope), improvements to our astrometric program will come from more extensive laboratory calibration of our camera, and the deposition of several neutral density spots on the CCD surface.

Camera calibration involves the imaging of flat fields, a pure sine wave, and sharp, narrow slits onto the surface of the camera. The flat field indicates the product of quantum efficiency and pixel area, while the sine wave is used to determine the pixel position. Sharp slits are used to measure the quantum efficiency slope across each pixel.

To date, we have used this technique to show that groups of 34 rows are shifted by 0.03 pixel, or 7 mas at the telescope. This is due to a known manufacturing defect. Our measurement noise is presently at the 0.003 pixel level, or 0.8 mas. More exposures and analysis are required to improve this calibration.

For the 1993 (and all subsequent) observing cycles, our camera will have 4 neutral density spots deposited directly on its surface. With these spots, we can make long exposures of bright sources that would otherwise saturate the chip.

Figure 1

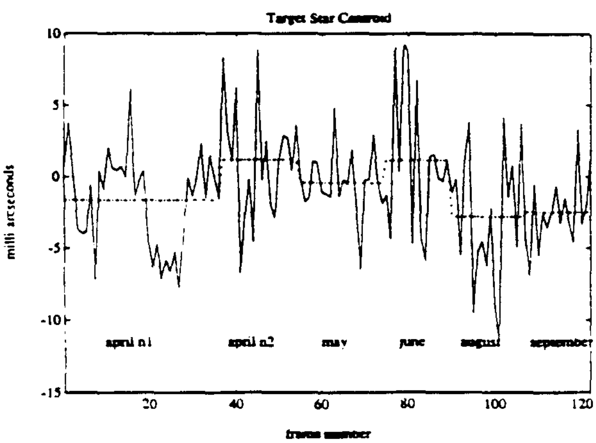
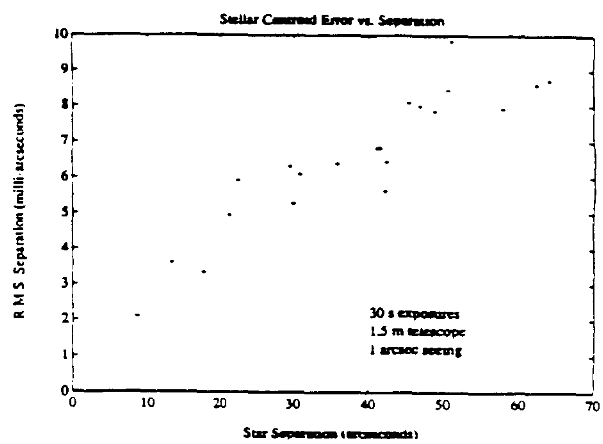


Figure 2



Low luminosity stars in the Hyades cluster

Principal Investigator : I. N. Reid
Palomar Observatory, California Institute of Technology

Subject Heading : Stars

The Hyades, lying at an average distance of 48 parsecs is the nearest open star cluster to the Sun. As a result, it has come to play a pivotal role in many aspects of stellar, Galactic and extragalactic astrophysics. Until recently, the cluster colour-magnitude diagram furnished a reference for determining distances to other open clusters, to globular clusters and to the Magellanic Clouds, although this function has now largely been taken over by the stars of the Pleiades cluster, which are closer to solar abundance than the metal-rich Hyades. However, the nearer Hyades, as a coeval, 3×10^8 years old systems, still provide an excellent means of probing the stellar luminosity function - the number of stars as a function of luminosity - and the fraction of stars that form as part of binary or multiple star systems. Moreover, the radial distribution of stars of different masses shows how dynamical evolution has affected the cluster - the higher mass stars tend to be concentrated towards the cluster core - and, finally, individual stars can be used to study such properties as rotation, chromospheric activity and the decay of the magnetic dynamo as a function of mass.

However, such studies demand a well-defined sample of cluster stars, and the very proximity of the Hyades leads to the cluster covering an area of sky more than 70 degrees in diameter. Hence, while the brighter Hyads have been known since the turn of the century, at faint magnitudes ($V >\sim$ 15 magnitudes) the cluster stars are outnumbered more than 50 to 1 by field stars, and the census is far from complete. The primary method of identifying Hyades stars is to use proper motions - the cluster stars have a distinctive space motion of $\sim 47 kms^{-1}$ which separates them from the bulk of the field stars. But such a study demands good quality, deep, wide-angle plate material, preferably spanning a time baseline of several decades, and until recently the sheer size of the cluster defeated such attempts - the only study to cover the whole cluster, by Luyten using original Palomar Sky Survey (POSS I) plates and plates taken on the Oschin Schmidt in the 1960s, has low accuracy photometry, leading to background star contamination problems.

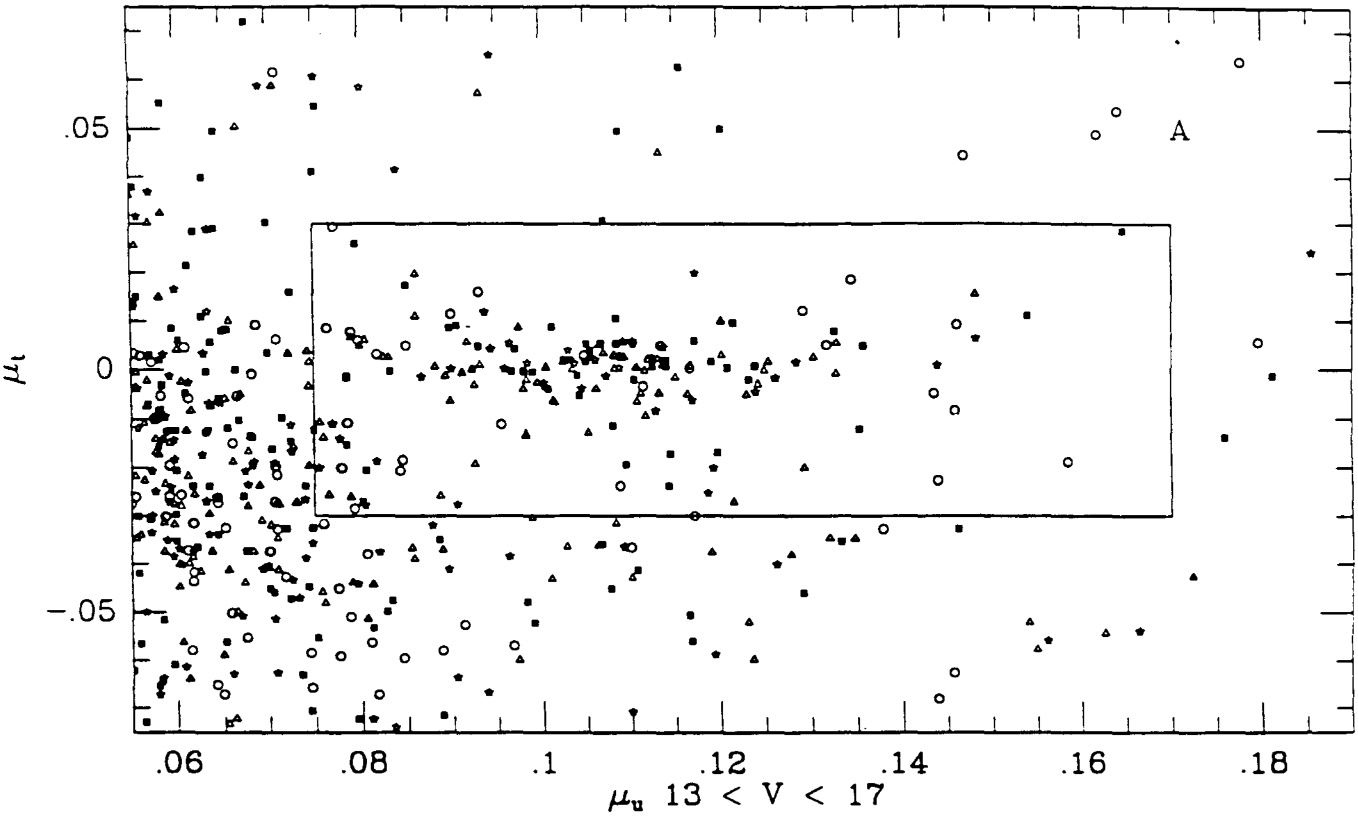
The advent of automated scanning engines such as the Royal Observatory, Edinburgh COSMOS machine, which provides accurate positions and photometry for the $\sim$ 100,000-plus objects on each $6^o \times 6^o$ Oschin Schmidt plate, has revolutionised this area of astronomy. We recently completed a proper motion survey of part of the Hyades region, including four Schmidt fields or $\sim$ 110 square degrees (even this covers only half the cluster) to visual magnitudes of $\sim$ 19.5 - that is, extending coverage to M dwarfs of absolute magnitude 16, or masses of $\sim 0.15 M_{\odot}$. The proper motions, accurate to $\sim 0''.005 yr^{-1}$ or $1 kms^{-1}$ at the Hyades, were derived from comparing measurements of POSS I plates (epoch 1955) with second epoch (1985) plate material from the UK Schmidt. Based on these data, illustrated in figures A and B, we have identified 311 likely cluster members, of which approximately half were previously known.

If we consider the two proper motion diagrams plotted as figures A and B, where we have divided the stars into two magnitude ranges, there are two notable effects. First, amongst the brighter stars (13th to 17th magnitude) there is an obvious tongue of stars centred in the diagram - these are the Hyades members. The extended distribution in one proper motion co-ordinate shows that the cluster has considerable depth along the line of sight - the proper motion (μ) depends on the ratio between the projected stellar velocity and the distance. All of the Hyads have essentially the same space motion (otherwise the cluster would have dissipated over the 300 Myr lifetime), hence the range in μ reflects a depth of ± 10 to 12 parsecs about the cluster core distance.

The second important feature is the *absence* of an obvious concentration of stars with Hyades-like motions amongst the fainter stars in figure B. This might reflect a substantial increase in the uncertainties of our proper motion measurements, although our internal estimates of the uncertainties suggest that this is unlikely. The alternative is a genuine reduction in the number of Hyades stars, with the more uniform distribution in (μ_u, μ_t) reflecting the larger number of field stars at fainter magnitudes. In this latter case we are observing a falloff in number density in the stellar luminosity function at faint magnitudes.

Thus, to obtain a clean sample of the fainter Hyades stars we need to determine whether the candidates have photometric colours that are consistent with the Hyades colour-magnitude diagram. Panel C shows the $(M_v, (B-V))$ diagram for previously known members. The traditional (B-V) colour is not useful for the faintest stars, since it saturates at ~ 1.5 magnitudes for M dwarfs. For this reason we have been using the 60-inch telescope at Palomar to obtain VRI photometry of the candidate cluster members. Of the 311 stars in our sample, 120 already have VRI photometry (by Weis, Hanson, Upgren and collaborators) and, to date, we have obtained photometry of a further 80 stars. Panel D combines these data, where we have plotted the likely members as solid symbols and the field stars - generally more distant (i.e. bluer and intrinsically more luminous) M dwarfs - as crosses. It is clear that most of the fainter stars are *not* Hyads, confirming our suggestion that the scarcity of obvious cluster members in panel B is a real effect. Clearly, the implied decrease in number densities has implications for the expected number of very low-mass stars and brown dwarfs. Our conclusions, however, remain preliminary until we can complete photometry of the sample.

Besides using these stars to probe statistical properties such as the luminosity function, we can also use observations of the individual stars to study stellar astrophysics. In particular, we (Reid, in collaboration with Mateo (OCIW) and Hawley (Lawrence Livermore Lab.) have been obtaining spectroscopy of the fainter Hyades member ($M_v > +9$). These stars have substantial Balmer line emission, arising from chromospheric activity stimulated (though some as yet poorly understood mechanism) by the stellar magnetic field. It is known that the activity declines as a function of time, with, on average, the emission persisting for longer in the lower-mass (highly convective) stars. It is possible that , with calibration, the strength of $H\alpha$ emission might serve as a stellar chronometer. Open clusters - groups of stars of known age - serve as important reference points on this calibration, and considerable data have already been accumulated for the brighter stars in the Hyades and the Pleiades (primarily by J. Stauffer). The result show an upper envelope to the emission that increases with decreasing luminosity, with the younger Pleiades stars having (on average) more emission. Panel E shows an $H\alpha$ spectrum of a confirmed Hyades member with $M_v = +nn$. We are using our new sample to push the coverage to later type M-stars in the Hyades, other clusters and amongst stars in the general field, with the aim of eventually deriving the the recent (up to 1-2 Gyr) star formation history of the Galactic disk.



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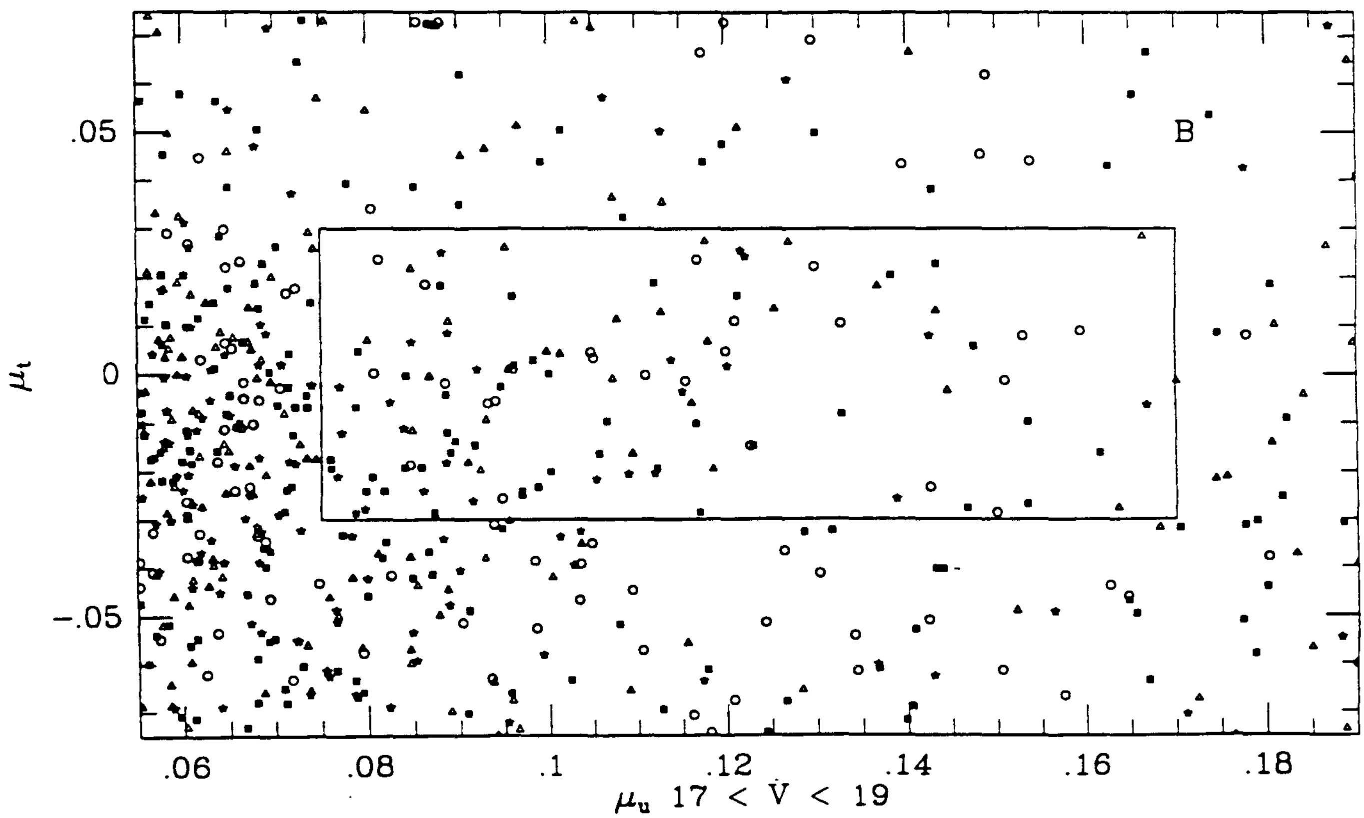

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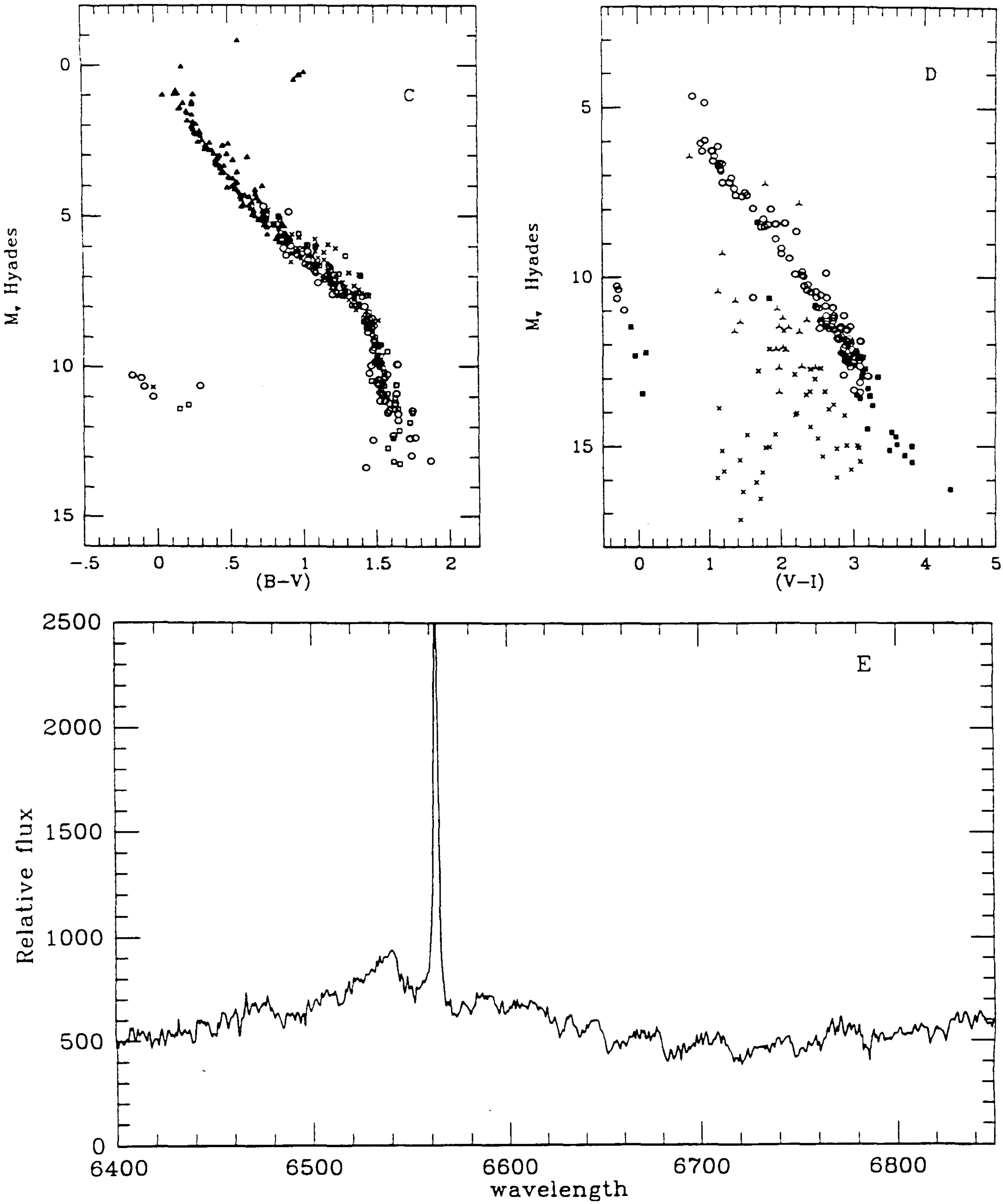
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Relative flux
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Feige 36 - a hot subdwarf binary

Principal Investigator : I. N. Reid
Palomar Observatory, California Institute of Technology

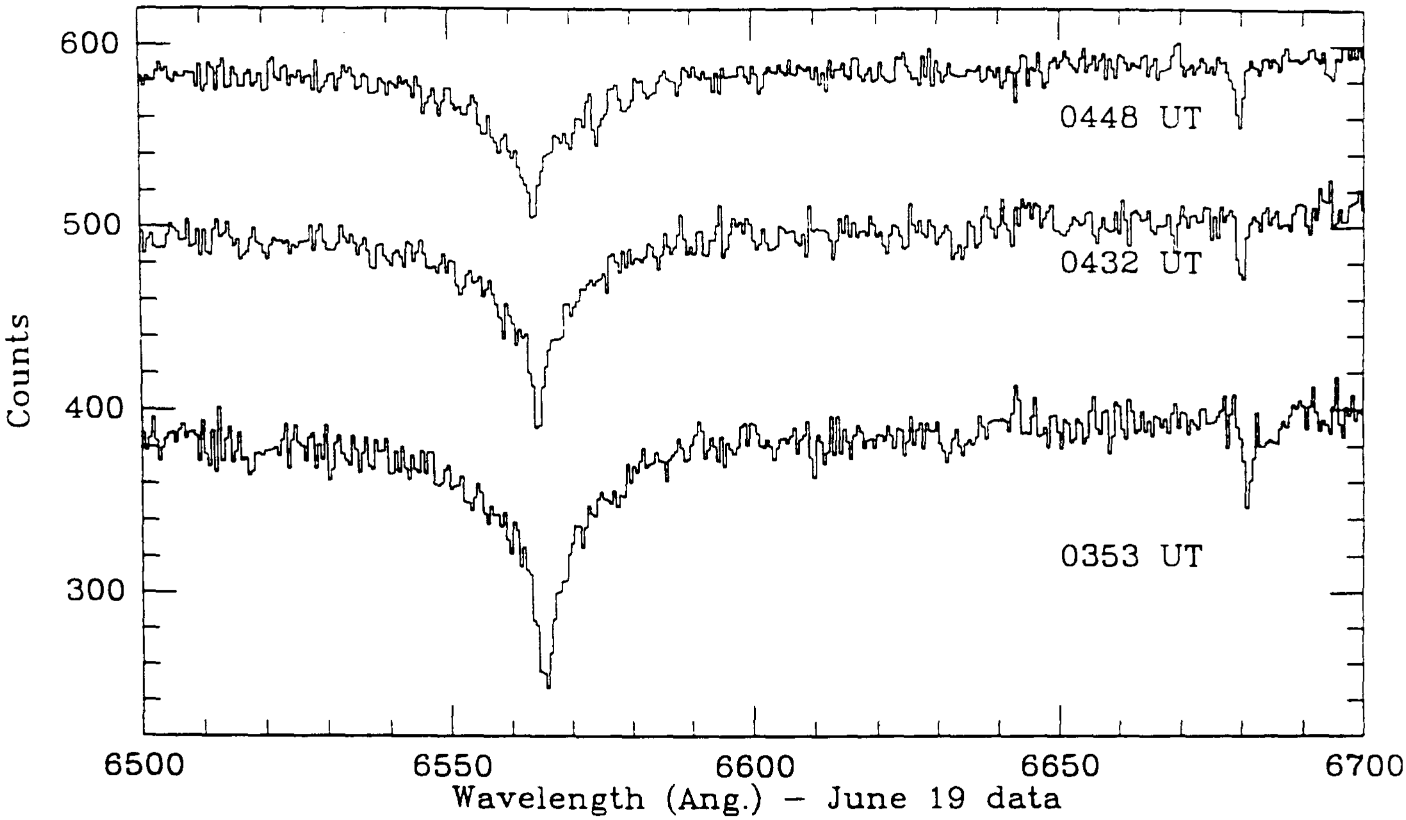
Subject Heading : Stars

Surveys of 'stars' in the local Solar Neighbourhood show that a substantial fraction of them, perhaps as high as 70 %, are actually stellar systems consisting of two or more separate stars. Although binarism is a complication which is often swept under the carpet, it is becoming increasingly apparent that the fact that stars like to be together can have significant implications for their evolution. In the case of white dwarfs or their immediate progenitors, the hot subdwarfs, there are at least three important possible consequences of binarity: first, merging white dwarfs could produce a single object exceeding the Chandrasekhar mass, leading to a type Ia supernovae; second, close binary evolution can lead to the higher mass star dumping mass onto the secondary during giant branch evolution, with the result that the system evolves directly from the horizontal branch to the white dwarf regime, skipping the second, or asymptotic, giant branch and planetary nebula formation; finally, and in many ways a corollary of the second point, Bergeron, Saffer and Liebert (Univ. of Arizona) have identified a number of white dwarfs which appear to have low gravities (log g < 7.5) and hence masses of $\sim 0.3 - 0.4 M_{\odot}$. The lifetime of a single star with such a low core-mass is many Hubble times, so the conclusion that one is forced to draw is that these stars have been helped into retirement by a close companion.

A qualification that must be bourne in mind, however, is that there is something of a scarcity of direct supporting evidence for this picture - although a reasonable number of white dwarf - red dwarf binaries are known, few double degenerate systems have been discovered. Moreover, and of particular importance for the origin of type I supernovae, none of the few systems that have been discovered are in close enough orbits for sufficient loss of energy through gravitational wave radiation to allow for an eventual merger (at least within many Hubble times). Absence of observation is not observations of absence, but supporting evidence is useful to theory. In search of such evidence we have been using the echelle spectrograph on the Palomar 60-inch telescope to monitor candidate binaries - either low-mass white dwarfs or velocity-variable sdB stars - and our observations show the hot subdwarf Feige 36 is, indeed, a binary.

Our echelle observations of Feige 36 showed velocity variations of more than 100 kms^{-1} in a matter of 3 hours - variations too rapid to be monitored with the 60-inch echelle (the star is too faint to permit integrations shorter than ~ 30 minutes). Fortunately, we were able to obtain a few follow-up observations on the 200-inch Hale telescope. The upper panel shows the spectra and the lower panel the resulting velocity curve - even with only 6 observations each night, we have been able to estimate the orbital period since R. Saffer (STScI) has measured the total velocity amplitude as $\pm 100 kms^{-1}$, and we derive a period of approximately 5 hours.

While these results are only very preliminary, it it is clear that Feige 36 is a short-period binary system. Given a mass of 0.5 $M_{\odot}$ for the primary star, the orbital mass function sets a lower limit of 0.22 $M_{\odot}$ for the companion, while the fact that there is no excess radiation (over a standard hot subdwarf) in the near-infrared ($\sim 8500 \AA$) rule out the presence of a main-sequence companion more massive than $\sim 0.5 M_{\odot}$. Longer wavelength observations can set stronger constraints. However, this star is clearly a good candidate for a system that will evolve to become a pair of white dwarfs. If that is the case, then we can also estimate that the system will merge in 2-3 Gyrs - although whether a supernova will result depends on whether the combined masses exceed the Chandrasekhar limit of 1.4 $M_{\odot}$.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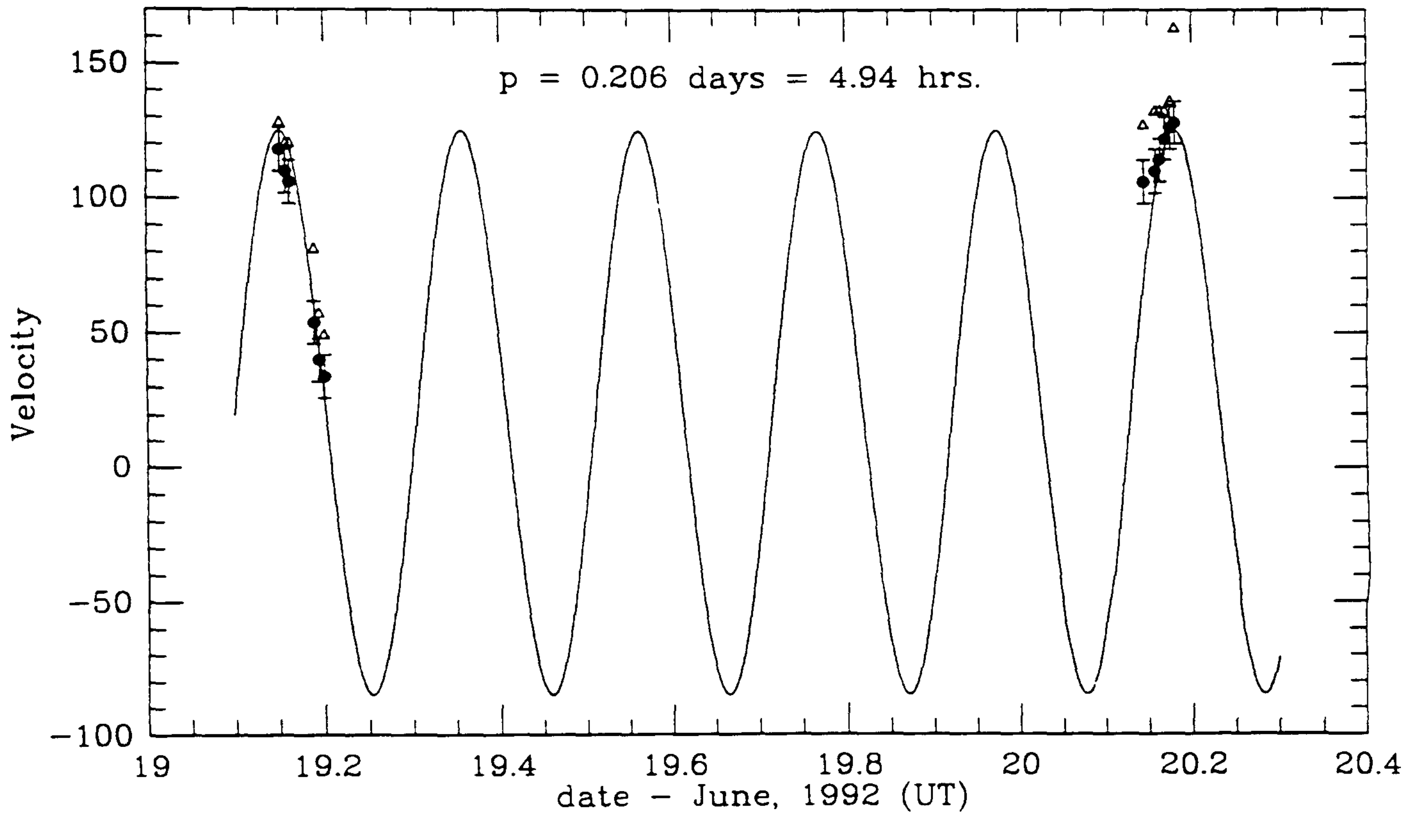
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The Luminosity and Mass Functions for Very Low Mass Stars

Principal Investigator - Chris Tinney
Division of Physics, Maths and Astronomy
California Institute of Technology

Co-Investigators - Jeremy Mould, Neill Reid
Division of Physics, Maths and Astronomy
California Institute of Technology

Subjects Heading - Stars.

One of the greatest dilemnas currently existing in modern astronomy is - where is all the mass hidden in our Galaxy? From observations of the motions of stars inside the Galaxy we can calculate its mass - but when we add up the masses of the stars we see, the amount of luminous matter falls short by a large fraction. The difference, the so-called 'missing mass' has been proposed as being in any number of forms - from brown dwarfs (stars too small burn nuclear fuel, and so almost invisible) to esoteric theoretical constructs like WIMPS (Weakly Interacting Massive Particles).

In this study we have attempted to examine the question - "What is the number density of extremely low mass stars?" That is, what is the shape of the luminosity function (LF) for the very lowest masses? Does it increase so that there are large numbers of small dim stars which escape our attention and are so not counted in estimates of luminous matter? Or does it decrease such that Very Low Mass stars (VLMs - stars less than one tenth of a solar mass) could not make up the missing mass.

This study is based on the selection of objects using photographic plates from the Second Palomar Sky Survey. By scanning the plates and examining the digital photometry automatically, it is possible to sample huge areas of sky (in this survey 270 square degrees) looking for extremely red objects. Follow up observations are then made using both the Palomar 60- and 200-inch telescopes of the selected stars. Infrared observations, in particular, are essential for understanding these stars - since their effective temperatures are so low, they radiate most of their energy between wavelengths of 1 and 2 micrometres.

We have found that the LF does decrease for very faint stars ($M_{Bol} \gtrsim 11$) after reaching a peak at $M_{Bol} \approx 10$. This corresponds to a mass function which peaks at around $0.2M_{\odot}$ and then flattens out, with possible evidence for a further increase below $0.1M_{\odot}$. Because our LF provides the best available normalisation of the density of stars at the H-burning limit for stars, we conclude that brown dwarfs can contribute a significant amount of missing mass *only* if they have a mass function very much steeper than that seen for stars on the main sequence.

VLM stars are also of interest intrinsically. Because they are so faint, very few are known, and their properties are poorly understood. We have therefore carried out (for the first time at Palomar) a program of trigonometric parallaxes on the 60-inch telescope for some the nearest stars in our survey sample. This was done to increase the number of stars tying down the colour-magnitude relations use to estimate absolute magnitudes for the rest of the stars detected in our survey. This is an exciting development not only because of the illumination it provides for VLM studies, but because we have shown (for the first time) that astronomically interesting CCD parallaxes can be obtained on a common-user, non-astrometric telescope.

Fabry-Perot Imaging of the ζ Oph Bow Shock

Principal Investigator: Dave Van Buren
Infrared Processing and Analysis Center
California Institute of Technology *and* Jet Propulsion Laboratory

Co-Investigators: Shrinivas Kulkarni
California Institute of Technology
Stuart Vogel
University of Maryland

Subject Heading: Interstellar Medium

Scientific context

Many of the massive luminous stars are moving supersonically through the interstellar medium. These same stars have powerful winds that rush out in all directions. When the wind reaches large distances it interacts with the surrounding gas and blows a bubble, which elongates into a bow shock, much like the shock around a re-entry vehicle in the earth's atmosphere. We have been investigating these interactions with the Fabry-Perot Camera on the Palomar 60-inch with a view towards understanding the kinematics of the interstellar gas as it flows around the wind cavity.

Long-term program

The stellar wind bow shocks represent ideal laboratories for studying many physical processes and conditions in interstellar space. By constructing mathematical models and comparing observations with the models' predictions we can confidently determine interstellar densities, shock parameters and even the microphysics of energy and mass transport mechanisms. The Fabry-Perot is the ideal instrument to carry out these observations - its wide field matches well the angular sizes of bow shocks and the velocity resolution is adequate to give many samples across the large linewidths expected. Over time, we plan to observe a number of bow shocks in several different emission lines diagnostic of shock conditions. Each line for each object takes two nights, so this is a long process, spanning years.

Short-term program

Last July we observed the ζ Ophiuchus bow shock in the line of doubly ionized oxygen, a line characteristic of strong shocks in the interstellar medium. The figure shows two aspects of our data. First, we show a "photograph" taken by assembling each of our very narrow band images. Near the center of the image is an occulting disk hiding the bright star (it looks like zebra stripes). The star is moving slightly away from us and to the left, its wind racing out ahead to drive the shock we see. In the second frame we show a different "slice" of the data, this time with position along the long direction and velocity the other way. The tadpole shaped region is the O^{++} line emission, which is wider at the bright end and bends subtly, matching well the morphology expected from our models.

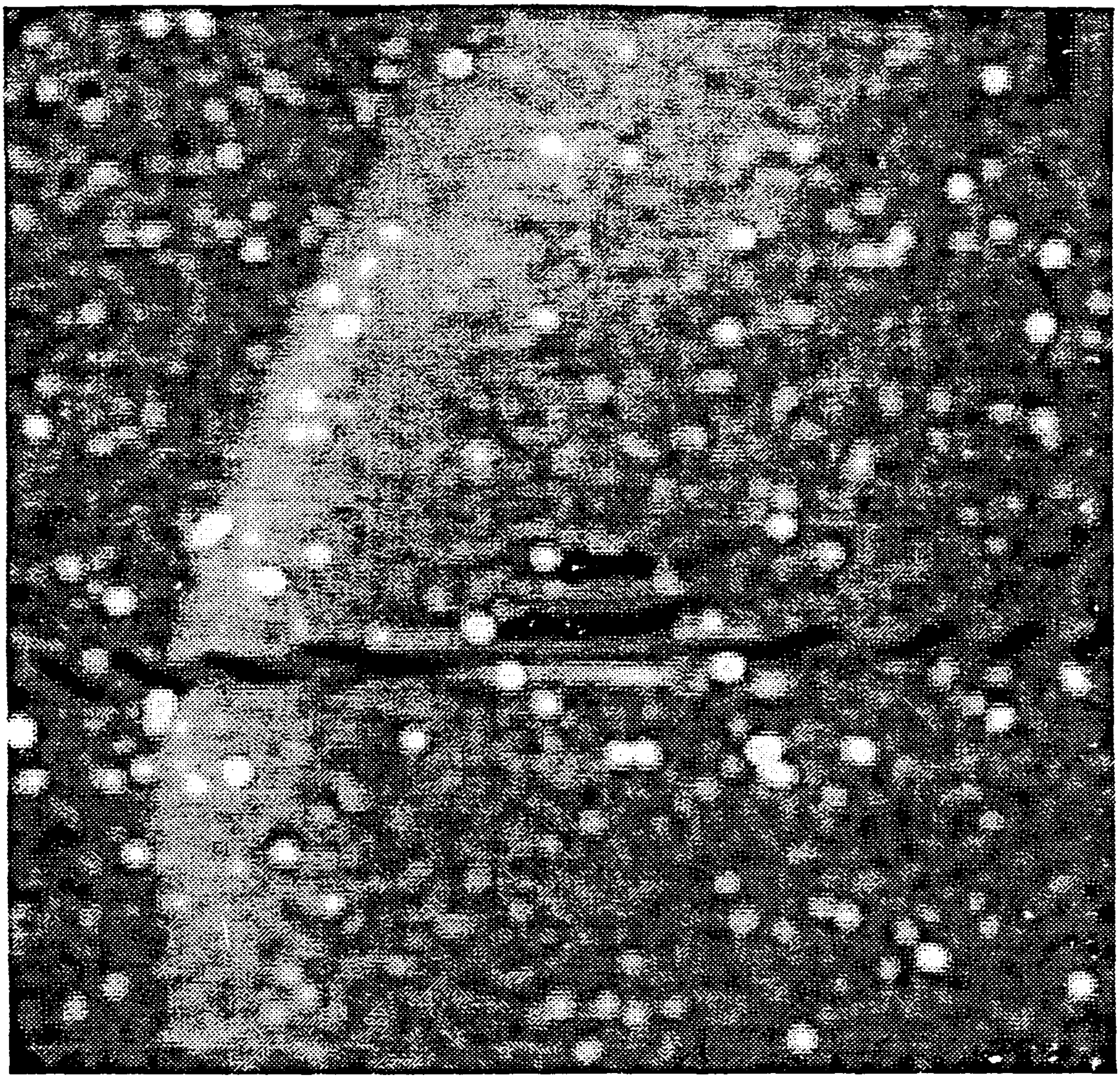
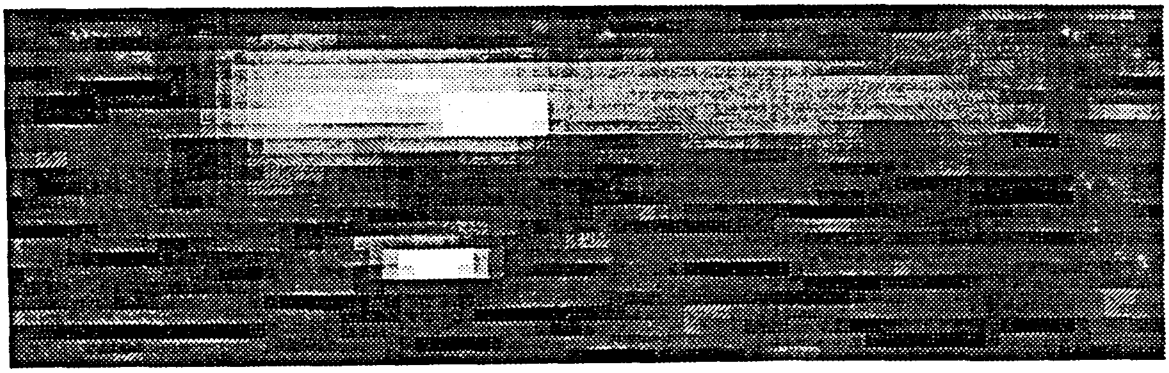


Figure 1. a) top - Fabry-Perot stacked image of the zeta Oph bow shock, binned into 12" pixels. The limb brightened leading edge of the bow shock is to the left. The zebra stripes extend over the region of an occulting mask inserted at a reimaged focal plane to reduce the scattered light from zeta Oph. b) bottom - position-velocity cut through the mid-point of the cube showing the curvature in the line (velocity gradient) and decrease in linewidth downstream (to the right).



The Binary Fraction in Globular Clusters

Principal Investigator: Lin Yan
Coinvestigators: Judy Cohen and Jeremy Mould
Department of Astronomy
California Institute of Technology

Subject heading: stars

It was generally accepted about 10 years ago that globular clusters contained virtually no binary stars, in contrast to the disk star population in which the binary star fraction is about as large as 50%. (Abt 1983) The first discovery of binary stars in globular clusters by Pryor et al (1989) completely changed our view about this subject and dramatically revised our understanding of the dynamical evolution of globular clusters and associated phenomena, such as pulsars, X-ray sources and blue stragglers. The binding energy contained in a binary with two $1M_{\odot}$ stars and $2R_{\odot}$ separation is comparable with that of a whole globular cluster with $10^5\,M_{\odot}$ single stars and $10\,\mathrm{km\ s^{-1}}$ velocity dispersion. During the cluster evolution process, the stellar encounters between single stars and binaries and between binaries and binaries releases kinetic energy from the binary star and alters the dynamical evolution to one quite different from that of a star cluster composed of single stars (as were computed and believed relevent in the 1980s).

Our project is to search for binary stars among giants with magnitude in a range from 15.3 to 18.3 in NGC 5053. It was started with the Norris spectrograph on the 200 inch telescope at Palomar observatory last year. We had two runs, separated by two months, in a total of 5 nights. 3.5 nights were usable. Both runs were quite successful and yielded very encouraging results.

On NGC 5053 fields, we deployed a total 54 fibers. Among these 54 were 4 sky fibers, which were positioned at places we chose carefully to be without stellar contamination, 45 fibers gave usable spectra, 3 were not paired up in both runs, and 2 fibers gave very low signal level spectra. We achieved a median of $2.6\,\mathrm{km\ s^{-1}}$ error for single measurement. Our technique for detecting binaries is to look for velocity changes in stars (relative to the solar system barycenter) between our April and May runs. Among 45 stars, there are 6 stars having spectra with broad H_{β} absorption lines, whose velocities can not be determined accurately by simple cross correlation and which we will treat differently. Some of these broad-line stars are horizontal branch stars(Sandage 1977). For the rest of the 39 spectra, we applied the standard cross correlation with some modification specifically to handle our data. We achieved a median of $2.6\,\mathrm{km\ s^{-1}}$ error for single measurement. Figure 1 shows that 6 stars have velocity changes $\geq 2.5\sigma$ (σ is the respective error in the velocity changes for each star) and are candidates which we hope to confirm as binaries in the coming year. One of the stars, marked p5 in the figure, in which we measured a $16\,\mathrm{km\ s^{-1}}$ velocity change, was also observed by Pryor(1991), who determined a very tentative orbit of $P = 0.8$yrs, $2K = 25\mathrm{km\ s^{-1}}$. To estimate the error of our measurement we adopted the Tonry and Davis (TD 1979) method. For all of our sample stars, we find that systematic errors, such as the residual of the spectrograph flexure correction and the error of wavelength calibration, dominate in a few very high S/N spectra, but the photon statistics error dominates in those spectra with low to median signal level. Hence the TD estimate serves as an adequate error indicator for most spectra except a few high S/N spectra, for which we simply use the dispersion between independent measurements as the final error estimate.

The results provide a very promising start and we are well on our way towards better estimation of the fraction of binary stars in globular clusters. Computer simulation shows that with the two runs we requested in the coming year we can double our binary star detection efficiency, as well as increase the confidence level on the binarity of our existing candidates, especially for those stars with low signal level. Our observations are the first which are sensitive to cluster binaries with orbital periods between weeks and a few months. We conclude that the further Norris spectrograph observations on NGC 5053 will help us to have a better understanding about the binary population in globular clusters, especially in low density clusters.

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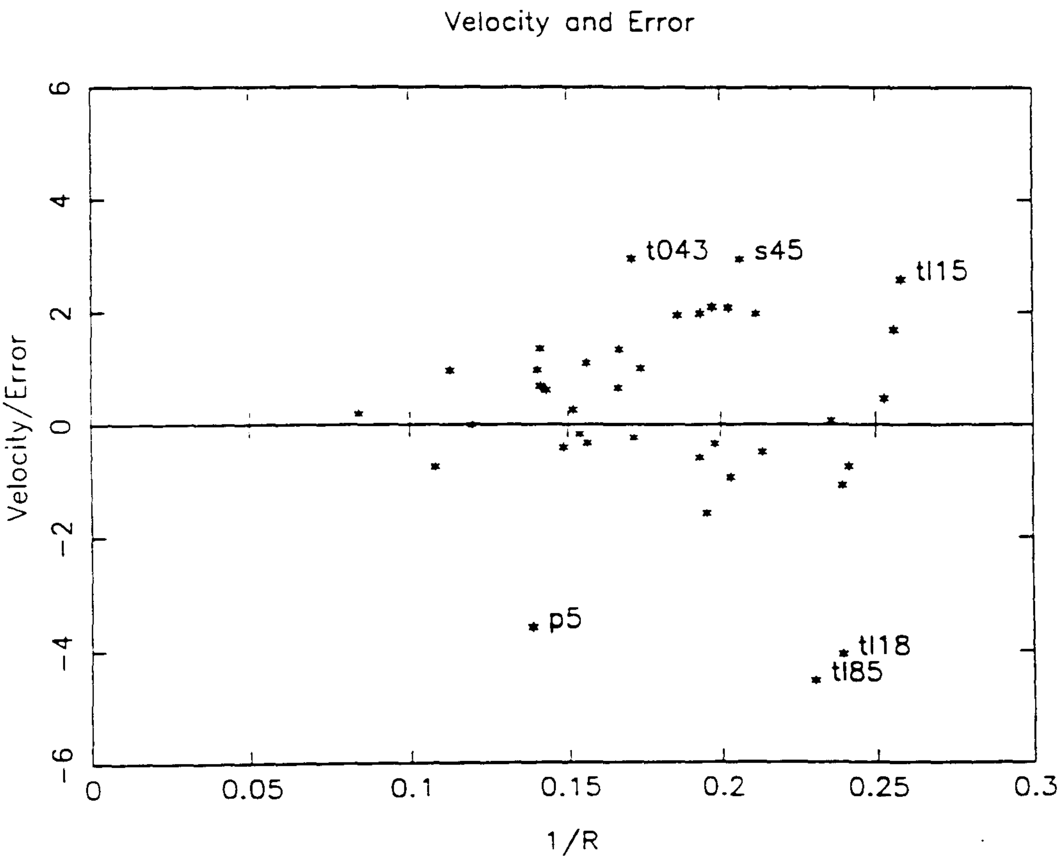

Fig. 1

GALAXIES AND QUASARS

Markarian 273 : An Ultraluminous Far-Infrared Galaxy Unveiled

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

Co-Investigators: B.T. Soifer, J.M. Mazzarella, G. Neugebauer, K. Matthews
California Institute of Technology
and J.R. Graham (University of California, Berkeley)

Subject Heading: Galaxies and Quasars

During the past year, our research efforts have concentrated on near-infrared ground-based observations of the 10 nearest "ultraluminous" infrared galaxies discovered by the IRAS satellite (Sanders et al. 1988). These 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. We have recently analyzed in detail our near-infrared images and spectra of one of these ultraluminous galaxies, Markarian 273 (Armus et al. 1992). Markarian 273 (object #273 in the catalogue of blue galaxies compiled by B.E. Markarian in 1969) has one of the most amazing optical morphologies of any active galaxy. From a disturbed nucleus, a straight, narrow (length:width ~7:1) "tail" extends due south for nearly 35 kiloparsecs, or over 100,000 light years (see Fig. 1). The structure of Markarian 273 is probably the result of a collision between two gas-rich galaxies that occured about 100 million years ago. Markarian 273 is extremely luminous in the far infrared, emitting over one trillion times the energy of the sun. Our near-infrared data obtained with the 200 inch Hale telescope consist of images in the J (1.3 microns (μ)), H (1.6μ), K (2.2μ), and L' (3.7μ) atmospheric windows, as well as H and K-band nuclear spectra. The images show two peaks at 2.2μ separated by about 700 parsecs (~23,000 light years), which are undoubtably the nearly merged nuclei of the parent colliding galaxies (see Fig. 1). The central near-infrared colors of Markarian 273 argue for a pair of very red, possibly quasar-like nuclei, surrounded by what may be a large burst of star formation. A combination of thermal (stars) and non-thermal (black hole) processes may be generating the the great energy in this galaxy. The close nuclei in Markarian 273 are hidden in the optical, and these observations highlight the tremendous power of high resolution near-infrared imaging to penetrate the dusty circum-nuclear environments of these dusty, luminous galaxies and accurately "map-out" their true structures. Radio wave observations made by Ulvestad and Wilson (1984) show a structure extended nearly perpendicularly to the near-infrared nuclei, which may be a "jet" of relativistic particles, emerging from the nucleus, triggered by the galactic collision. Our spectra show strong emission lines of singly ionized iron, ionized hydrogen, and molecular hydrogen (see Fig. 2). The molecular hydrogen and ionized iron may be excited by either x-rays or an outflowing wind emerging from the nucleus. Clearly Markarian 273 is an exceptionally interesting and complicated galaxy and one whose true nature we are beginning to understand through the use of near-infrared observations at Palomar.

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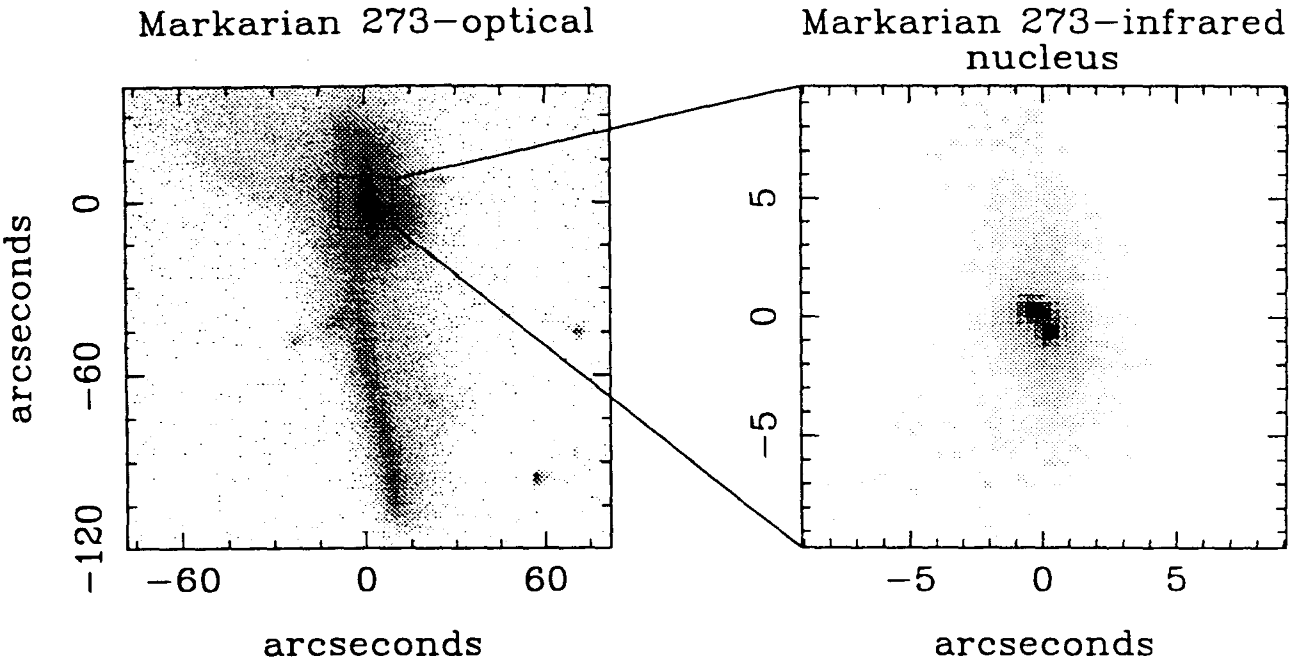
Markarian 273−optical
Markarian 273−infrared nucleus
arcseconds
0
−60
−120
60
arcseconds
−5
0
5

Fig. 1

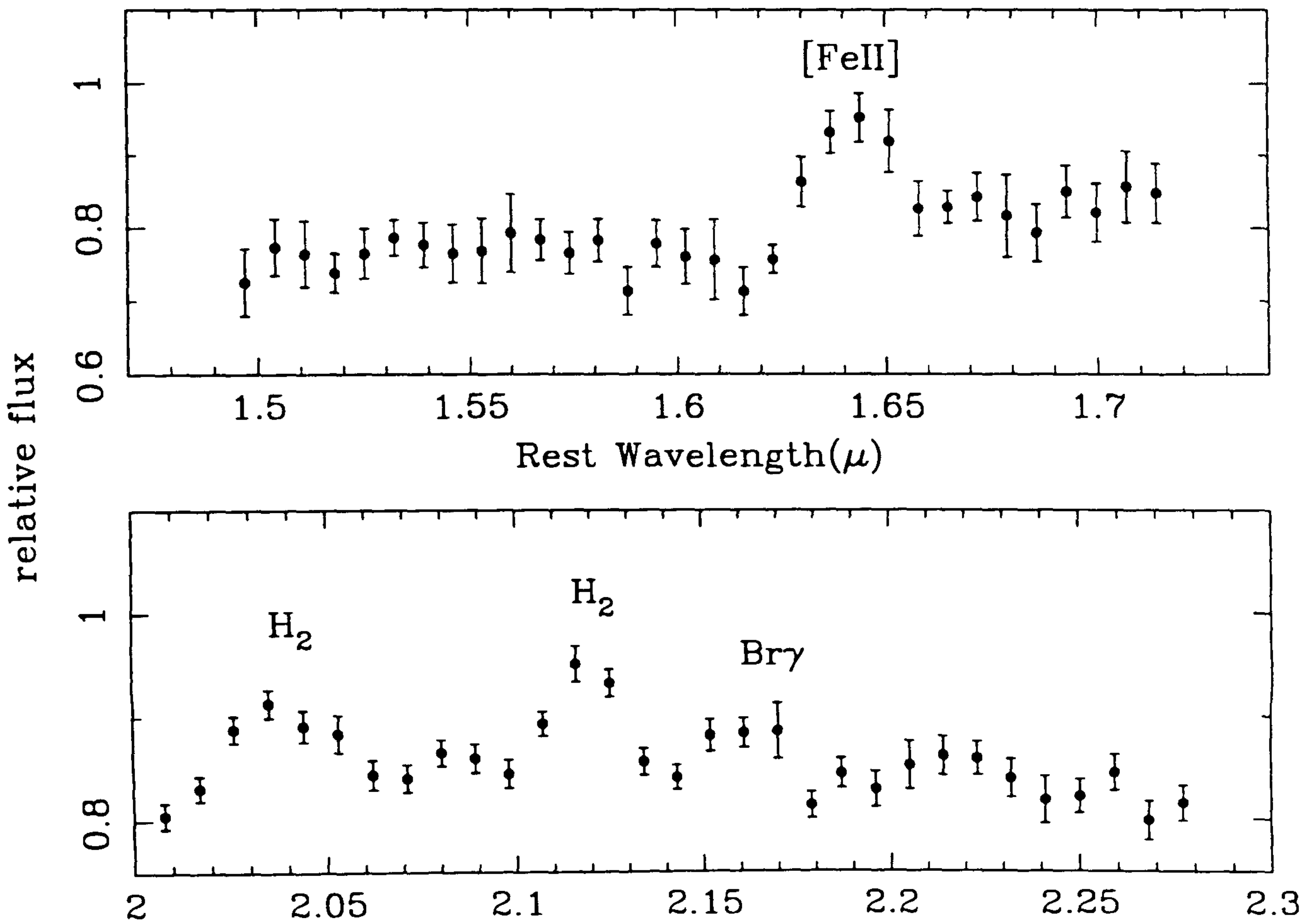
[FeII]
relative flux
Rest Wavelength(μ)
1.5
1.55
1.6
1.65
1.7
0.6
0.8
1
H_2
H_2
Brγ
2
2.05
2.1
2.15
2.2
2.25
2.3

Fig. 2

Deep Infrared Galaxies

Principal Investigator: Matthew Ashby
Department of Astronomy
Cornell University

Co-Investigators: J. R. Houck
Cornell University
P. B. Hacking
Jet Propulsion Laboratory

Subject Heading: Galaxies and Quasars

Scientific Context

One of the most important issues in extragalactic astronomy is galaxy evolution. This is a complex field: Galaxies not only dim or brighten over time (luminosity evolution), they may change appearance (morphological evolution), and chemical changes that accompany star formation will gradually enhance metal abundances. But a systematic study of any of these aspects will provide useful diagostic tools to help understand how galaxies change over time.

We are investigating the type and evolution of the luminosity sources of infrared-bright galaxies. Such galaxies are unusual because they emit up to 95% of their light in the infrared, and are typically very faint optically. Two alternatives are currently proposed: The energy may derive either from very rapid bursts of star formation, or large central black holes surrounded by hot accretion disks. In 1992 we took optical spectra to discriminate between these two alternatives. Correlations of the energy-generation mechanisms with other traits (like morphology or cluster membership) should constrain theories of galaxy evolution.

Long-Term Program

We began our program in 1990 with a complete sample of extremely faint infrared-bright galaxies compiled by P. Hacking from multiple scans of the north ecliptic pole by the Infrared Astronomical Satellite (IRAS). The Hale Telescope's large aperture makes it an ideal facility for observing these infrared-bright, optically-faint objects. We observed this sample twice in 1990 June and 1991 May to obtain redshifts and spectra, and used classification techniques established by Vielleux and Osterbrock (1987) to determine the luminosity sources. The results were surprising: Although 3 sources were found straightforwardly to contain massive black holes and 7 to undergo rapid star formation, 7 of the Hacking galaxies had spectra not explained by either of these alternatives. A write-up of this work has recently appeared in print (Ashby *et al.*, 1992).

This project was extended to brighter infrared galaxies with 1992 May observations of a subset of galaxies from the IRAS Bright Galaxy Survey (Soifer *et al.*, 1987) from Palomar Observatory. These long-slit spectral observations are described below.

Future work will be based on comparisons of the two samples of galaxies. Discrepancies should not only reveal differences between the two populations, they should also indicate the luminosity and redshift dependence of the energy generation mechanisms. Our program will be geared toward measuring the relative contributions of star formation, accretion disk radiation, and shock waves to the energy budget, and we hope ultimately to measure the time evolution of each component. Follow-up observations are planned in 1993 to resolve these issues. In particular, infrared photometry will be used to measure the contribution of shock waves in sources which fail the two-component description.

Short-Term Program

In 1992 May we spent four nights at the 5 meter Hale Telescope observing galaxies from the Bright Galaxy Survey. Our sources were chosen face-on to minimize reddening and permit separation of the disk and nuclear contributions. Unlike the objects from the Hacking survey, these sources were bright and extended. It was therefore possible to obtain spectra along the entire breadth of roughly 20 galaxies, with both high spatial and spectral resolution, so that the energy generation mechanism could be determined as a function of distance from the nucleus. Once again, the large diameter of the primary mirror was crucial in making these observations feasible. Most sources were sufficiently bright that with long exposures their spectra could be classified.

The spectral criteria were established by Baldwin, Phillips, and Terlevich (1981) and later improved by Veilleux and Osterbrock (1987) to distinguish between the relative contributions of star formation and active galactic nuclei to the total optical luminosity. In particular, the ratios [O III] $\lambda5007/H\beta$, [N II] $\lambda6583/H\alpha$, [S II] $(\lambda6716 + \lambda6731)/H\alpha$, and [O I] $\lambda6300/H\alpha$ are used by Veilleux and Osterbrock (1987) in their classification scheme. We chose them for identical reasons: they are prominent in our galaxies, and comparing all line intensities to neutral hydrogen is more reliable than comparing ratios of other elements because the uncertainties in relative abundances become less important. The effects of reddening are minimized because the difference in wavelength is small for any particular line ratio. These factors combine to make these line ratios very convenient from an observational standpoint.

Our preliminary finding is that the energy generation mechanism in galaxies does in fact change with distance to the nucleus: Line intensity ratios vary perceptibly across each of our sample sources. We also learned that a number of the sources are interacting with companion galaxies, or have multiple nuclei. Such information is a useful probe of the internal structure and past history of these galaxies; for example multiple nuclei may indicate the galaxy has undergone a collision with a former companion. We are currently working to properly quantify and interpret our data. However, we tentatively identify 8 AGNs and 17 starburst nuclei in our sample.

More observations from the Hale Telescope are anticipated in 1993 to search for supernovae shock waves. If such shocks are found in abundance they would explain why more than one-third of the Hacking survey sources fail the two-component model.

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Are BL Lac Objects Gravitational Lenses ?

Principal Investigator: Judith Cohen
Division of Physics, Mathematics, and Astronomy
California Institute of Technology

Subject Heading: Galaxies and Quasars

BL Lac objects are extragalactic stellar objects with featureless continuum spectra (at low spectral resolution) that extend from the ultraviolet spectral region through the radio regime. They are often highly variable on short timescales of a day or so. There have been repeated suggestions over the years that some or all BL Lac objects are gravitationally lensed The rapid variability of this class of objects could perhaps be explained by microlensing. Stickel, Fried, and Kuhr (1988a, 1988b, and 1990) discovered that 3 high redshift BL Lac objects in fact consist of a point source at high redshift superposed on a faint relatively nearby galaxy with a redshift of less than 0.3. This provides additional support for the microlensing hypothesis.

There have been many calculations of the expected frequency of multiple images. The predicted fraction of multiply imaged sources is not large. Even though the probability of success is low, we undertook a direct imaging study of the BL Lac objects with known redshifts to look for closely spaced components to check the gravitational lensing hypothesis. A maximum entropy image restoration code was used to improve the spatial resolution of the ground based data.

Images were obtained on the 1.5–m telescope of Palomar Observatory through a red filter of most of the northern BL Lac objects with known redshifts. After image restoration to improve the point spread function, all sources within 20 pixels of the BL Lac object were noted and examined. The image of the central BL Lac object was examined carefully to look for closely spaced components.

There was no evidence for any excess of point sources near the image of a BL Lac object beyond that expected from the statistics of the background field. In addition, there was no evidence for multiple components in the image of the central source. A histogram was constructed for the distribution of galaxy versus point like appearance of the BL Lac object as a function of redshift. As expected, the stellar objects are those at the largest redshift while the BL Lac objects that appear embedded in galaxies are found at small redshift ($z \leq 0.30$). This roughly suggests a continuum of properties between the high and low redshift systems.

Based on this evidence we conclude that the majority of BL Lac objects are not gravitationally lensed. We cannot rule out the hypothesis that a small subset with particular properties are in fact lensed or microlensed.

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An Infrared Search For Protogalaxies

Principal Investigator: S. G. Djorgovski
Division of Physics, Mathematics and Astronomy
California Institute of Technology
Co-Investigators: D. Thompson (CIT), S. Beckwith (Cornell/MPI)

Subject Heading: Galaxies and Quasars

Many of the searches for primeval galaxies to date (including our own at Palomar) are aimed to detect them through their Lyα line emission in the rest-frame UV. However, if forming galaxies were even moderately obscured by dust, this line would be very weak. If that were the case, a better approach would be to use some other strong line with a longer rest-frame wavelength, e.g., hydrogen Balmer lines or nebular oxygen emission lines, which would be less affected by the extinction. Such a line would now be redshifted to the near-IR. For example, in the K-band window, one can search for the [O II] 3727 line in the redshift range 4.42 – 5.51, Hβ in the redshift range 3.16 – 3.99, [O III] 5007 in the redshift range 3.04 – 3.85, or Hα in the redshift range 2.08 – 2.70.

We have started a pilot experiment with the IRA Cass camera at Palomar, to search for emission line objects, ostensibly forming galaxies, at high redshifts, using narrow-band imaging in the near-IR. This is perhaps the first serious search for emission-line protogalaxies in the near-IR, using modern observing technology.

The limiting sensitivity of the Palomar instrument with the continuous variable filter (CVF) in the K-band should correspond to the limiting line flux of $\sim 4 \times 10^{-17}$ erg/cm^2/s, which is in the range expected from young galaxies $z \sim 2-5$. The resolution of the narrow-band filter corresponds to $\sim 4,000$ km/s in the rest-frame, which is well matched to galaxy cluster or supercluster sizes in the redshift space. The field covered at Palomar is about 0.3 arcmin^2 per target (assuming 4 detector fields).

The initial search (in March and July 1992) was targeted towards [O II] 3727 emission line companions near the three known, $z > 4.4$ quasars, in the K-band window. One initially promising candidate was detected, but it was not confirmed by repeat observations; the reason for this is not yet fully understood.

Figure 1 gives the survey limits achieved to date, in comparison with the two previous, continuum surveys. Even in this early stage, the Palomar survey is the most sensitive one so far. Only two other surveys (by Boughn et al. 1986, and by Collins and Joseph 1988) are even remotely comparable, having a larger area covered, but a shallower depth.

It is hoped that the survey will be extended in 1993 at Calar Alto and ESO using a special instrument built for this purpose by Beckwith's group at MPI-Heidelberg, and also continued at the Keck telescope using NIRC instrument built by Soifer et al. at Caltech.

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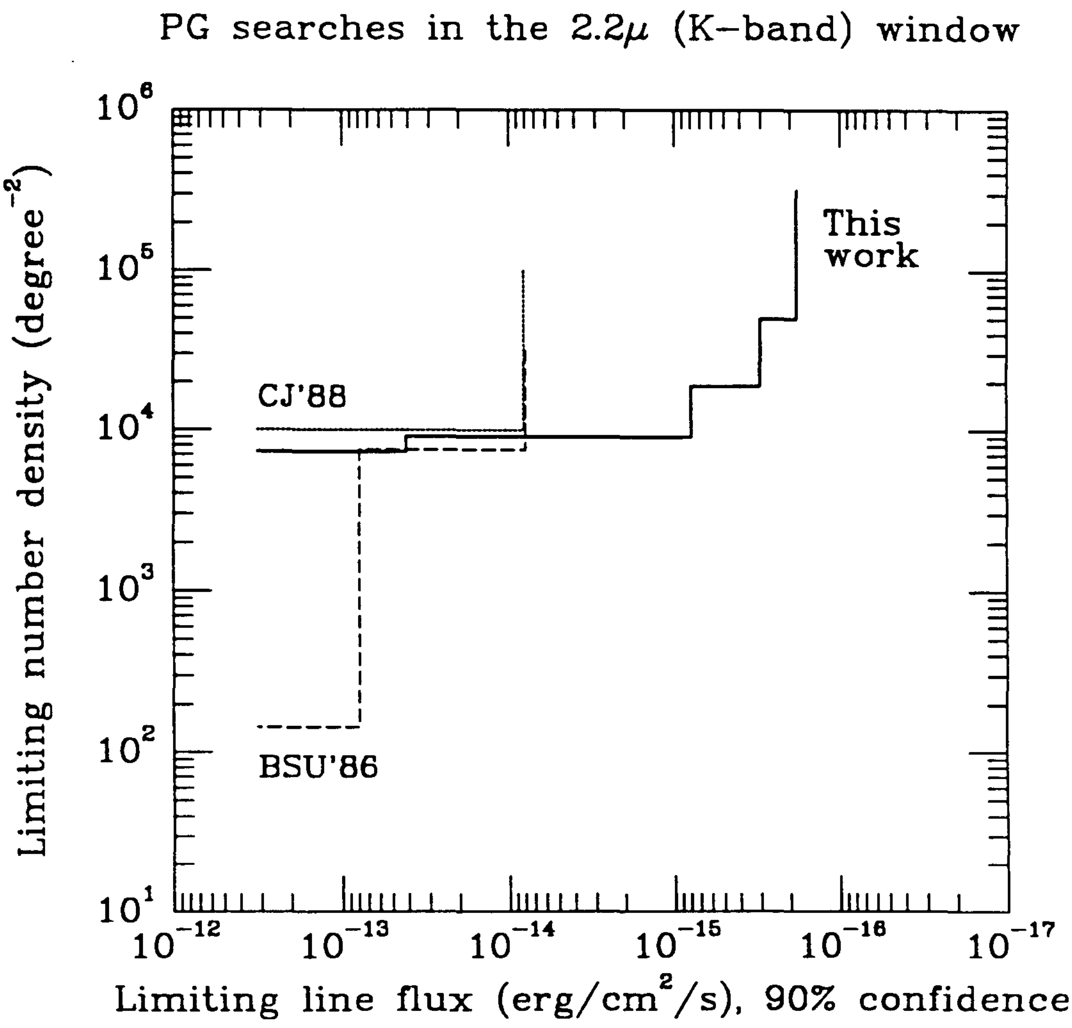

Figure 1. Limits on the surface density of primeval galaxies as a function of the [O II] 3727 emission line flux. The areas to the upper left of the limit lines are excluded. Solid line gives the current limits from the Palomar survey. Dotted and dashed lines represent the limits from the surveys by Collins & Joseph (1988) and Boughn et al. (1986), respectively. Their continuum magnitudes have been converted to line fluxes by assuming that all of the light would be in the emission line.

A Search For Primeval Galaxies

Principal Investigator: S. G. Djorgovski
Division of Physics, Mathematics and Astronomy
California Institute of Technology
Co-Investigators: D. Thompson (CIT Thesis), J. Trauger (JPL)

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 one of the milestones of cosmology, comparable in reach and significance to the discovery of quasars. Cosmological tests, studies of galaxy evolution, and the formation and evolution of large-scale structure all depend on the physics and timing of galaxy formation.

One needs some physical signature of forming galaxies. Lyman α emission is expected from unobscured galaxies powered by star formation, at levels that are detectable with current technology, and is a viable signal on which to base a survey. Thus, we are conducting a search for elliptical galaxies or the bulges of spiral galaxies (i.e. *normal* galaxies), undergoing their first major burst of star formation at high redshift galaxies.

An ideal instrument for this type of experiment is a low-resolution, scanning Fabry-Perot imager, which was designed and built for this project. The experiment consists of deep imaging of selected fields in a series of adjacent narrow bands, with a spectroscopic follow-up of all objects which show a probable line emission excess in one or more bands. A three-dimensional data cube (two spatial dimensions plus radial velocity, or redshift) is built up by successive exposures. The experiment emphasizes spatial information in deep exposures over a range of redshifts. The flexibility of the scanning instrument can be utilized by avoiding the strong emission-line features of the night sky (which determines the redshift intervals: 4 bands with widths $\Delta z \simeq 0.2 - 0.3$, in the range $z \sim 2.8 - 4.9$), thus achieving a better S/N at faint light levels. The field of the instrument is about 5.5 arcmin, and the velocity resolution about 1000 km/s in the restframe for Lyα at any redshift.

We have surveyed 3 fields (0.02 deg^2) in the redshift range 4.42 – 4.61, and 6 fields (0.06 deg^2) in the redshift range 4.74 – 4.90, down to a limit of $AB_\nu \sim 23^m$. This is comparable to the best limits obtained to date in other similar experiments. We have detected some faint emission line objects, and though many or all of them are probably foreground emission-line galaxies, some may actually be primeval galaxies. We are currently working on obtaining follow-up spectroscopy for our faint emission-line candidates.

The experiment is bound to yield many foreground emission-line galaxies, in addition to any possible primeval galaxy candidates. We will also be able to place some constraints on the properties of evolving galaxies at intermediate redshifts, detected through their [O II] line emission. For example, we have already detected a few galaxies at $z \sim 0.4 - 0.9$, with typical Gunn r magnitudes of $22 - 23^m.5$ and relatively blue colors, which may be representative of the faint blue population found in deep field surveys by Tyson, Cowie and others. Our survey would also provide data for studies of the evolution of the luminosity function of high-z Seyfert galaxies at faint levels, complementary to other past or ongoing quasar surveys. The inventory of the resulting data cube would essentially produce a complete sample of faint starburst or active galaxies, at a depth exceeding most or all other surveys. Another exciting possibility is the detection of Lyα forest clouds, appearing in emission (model computations suggest that this is marginally possible).

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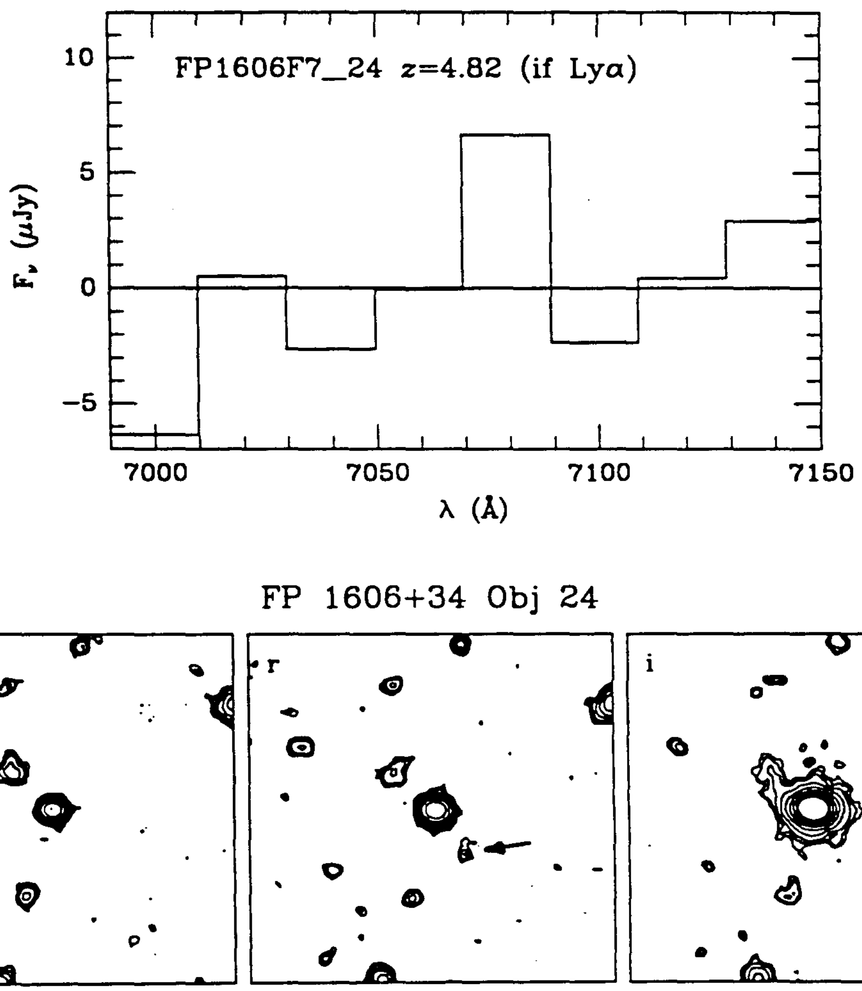

Figure 1. Object 24 in the 1606+34 field. This is one of our more intriguing candidate emission-line objects. Although it is a marginal detection in the Fabry-Perot data, there is a galaxy with very unusual broadband colors at the same location (arrowed). The star in the center of the plots is a red giant, so it appear much brighter on the *i*-band image.

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

Principal Investigator: S. G. Djorgovski
Division of Physics, Mathematics and Astronomy
California Institute of Technology
Co-Investigators: J. Smith, D. Thompson (CIT)

Subject Heading: Galaxies and Quasars

In many hierarchical scenarios for the origins of large scale structure in the universe, the existence of luminous quasars at very high redshifts ($z > 3$ or 4) presents a severe timing problem. At reshifts of $z \approx 4$, the universe is only $\approx$10 percent of its present age and theories of structure formation must account for such luminous objects to form and turn on within the available time. This suggests that these objects form at the very highest peaks of the density field. A generic prediction for practically all scenarios of large-scale structure and galaxy formation is then that the first collapsed objects (which may be identified with the highest known redshift quasars) should be very strongly clustered. We started a search for quasar-marked protoclusters at $z \gtrsim 4$, using multicolor and narrow-band imaging techniques, in the fields of known $z \gtrsim 4$ quasars.

This is an important test for our basic understanding of the formation of galaxies, large-scale structure, and the origin of the first quasars themselves. If this experiment is successful, the scientific payoff would be enormous: the evidence for clustering at large redshifts, and the implications for the primordial density field; possible discovery of primeval galaxies, or at least hints about formation of large scale structure and galaxies, and the origin of quasars; and after the follow-up studies, a valuable probe of the high-z intergalactic and intracluster medium at high redshifts. Even a negative result would place interesting constraints on theoretical models. We should also be able to constrain the early evolution of the luminosity function of faint QSO's and Seyferts, at a luminosity level never probed before at these redshifts.

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.

We have obtained multicolor imaging on 14 of the 15 known $z > 4$ quasars with published coordinates and narrow band imaging on 5 of them. Most of the data has been obtained at Palomar, but some of the southern fields were observed at CTIO. We have selected 49 objects for follow-up spectroscopy using the multicolor technique, with $\approx$ 15 of those being high-priority candidates. So far, we have obtained follow-up spectroscopy on 11 objects. Most of these objects have $z < 1$. However, one object in the PC 0910+5625 field has a tentative redshift of $z = 4.06$ (figure 1). Fifteen candidates have been selected from the narrow-band imaging and spectroscopy has been performed on six. One candidate in the PC 0307+0222 field shows possible Lyα emission at 6560 Å giving it a tentative redshift of $z = 4.39$ (figures 2 and 3) More spectrocopy is needed on these objects to confirm these results.

In the future, we hope to cover several additional fields using both the multicolor and the narrow band techniques. Most of all, we need spectra of the candidates already in hand.

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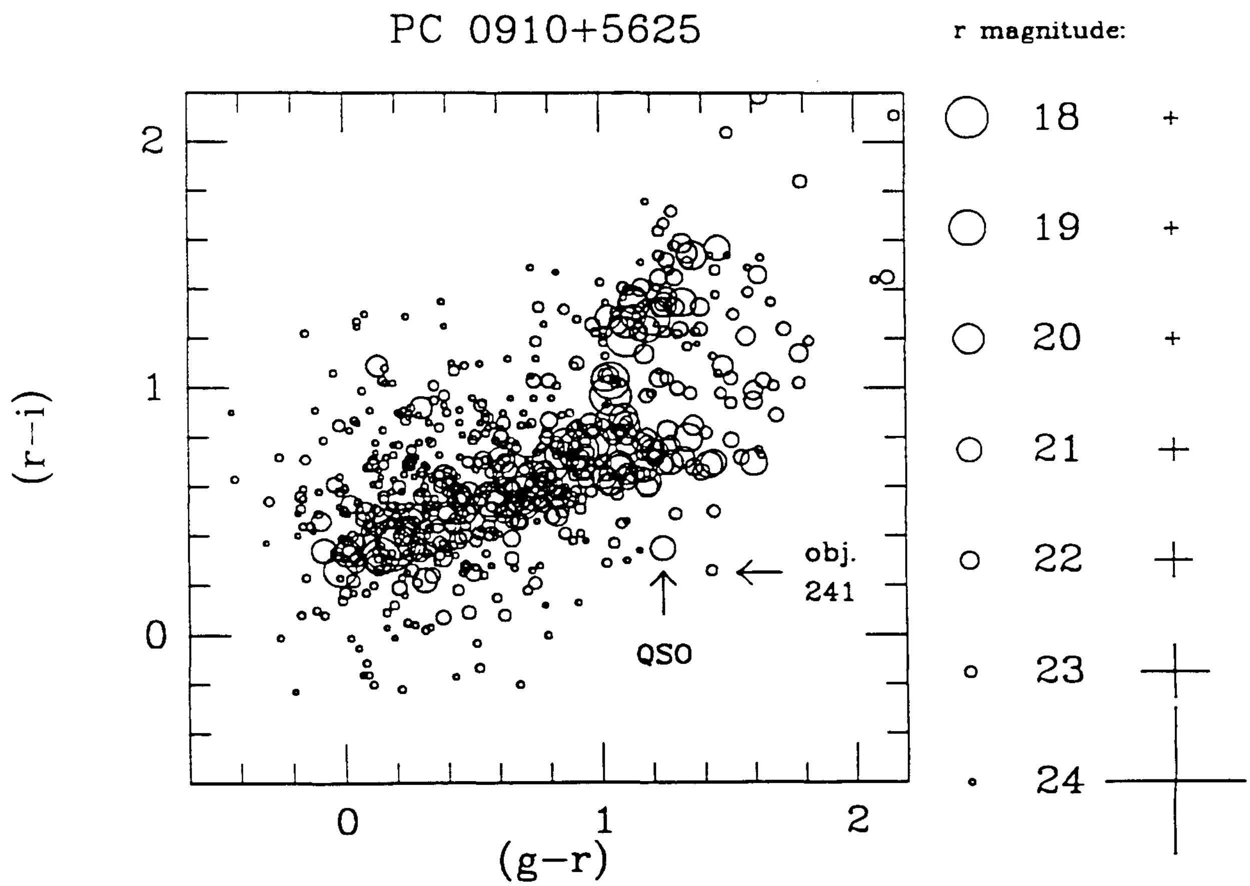

Figure 1. The color-color diagram of all objects ($r < 24^m.5$) in all four CCD's of a 4-shooter frame of the PC 0910+5625 field. Symbol size scales with the r magnitude. The error bars indicate the median error in the $(r - i)$ and $(g - r)$ colors in each magnitude bin. Object 241 is a candidate with a tentative redshift of $z = 4.06$. The quasar has a reshift of $z = 4.035$.

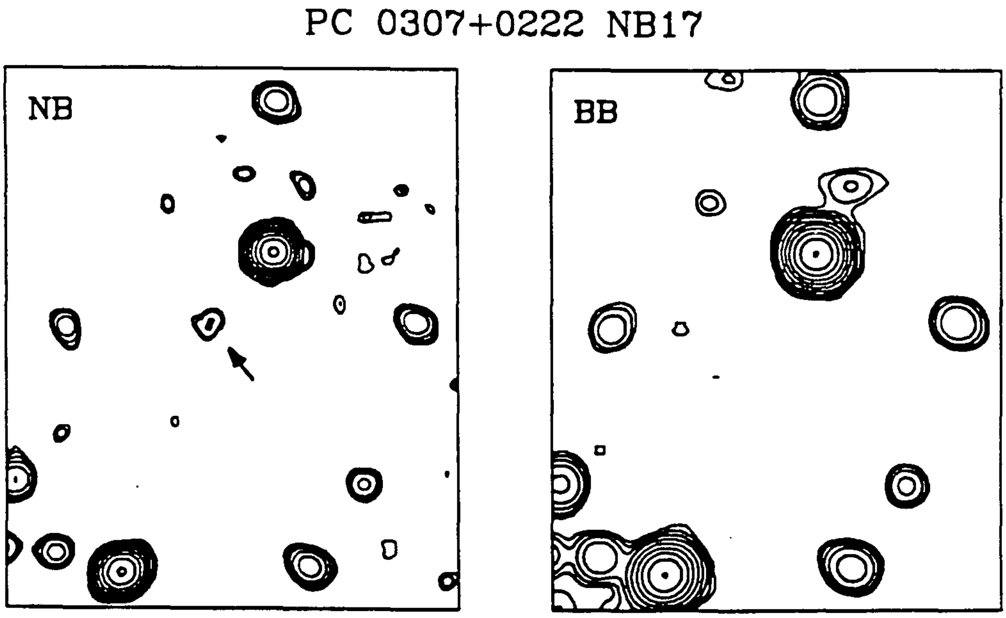

Figure 2. Narrow and broad band images of candidate object 17 in the PC 0307+0222 field. The object is clearly visible in the narrow band frame (left) while it is undetected in the broad band (right).

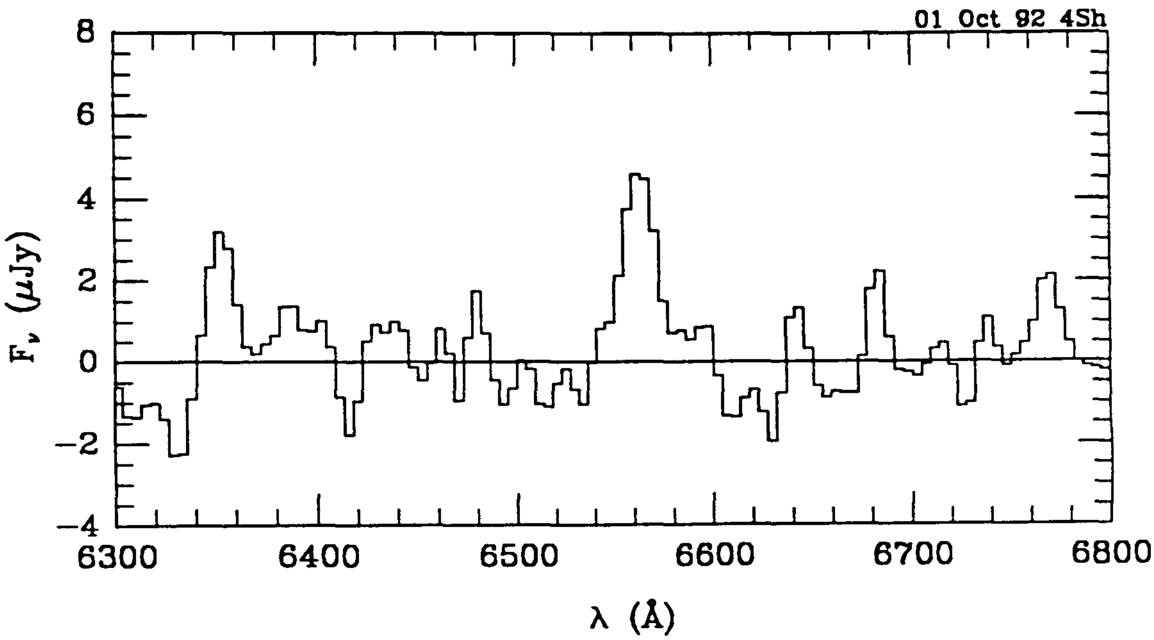

Figure 3. Part of a spectrum of narrow band candidate 17 in the PC 0307+0222 field. The possible Lyα emission at 6560 Å gives this object a tentative redshift of $z = 4.39$. The quasar has a reshift of $z = 4.379$.

Cluster Spectroscopy in the Pisces–Perseus Supercluster

Riccardo Giovanelli and Martha Haynes (Cornell)
Gary Wegner and Shoko Sakai (Dartmouth)

The density perturbations that gave rise to the formation of clusters and allowed their galaxian membership to decouple from the Hubble expansion flow have long growth times, and most clusters have not yet attained dynamical equilibrium. Thus, the understanding of their dynamical state necessitates rich kinematical information, to disentangle substructures and to adequately map local deviations from Hubble flow.

The two main methods for the determination of redshift–independent distances of galaxies beyond the Virgo cluster rely on the combination of a photometric and a kinematic parameter. The Tully–Fisher (TF) method, for spiral galaxies, and the Faber–Jackson (FJ; or its variant, $D - \sigma$) method for elliptical and lenticular galaxies, have been extensively applied in recent years to the determination of deviations from Hubble flow in the local universe. Because the application of these techniques has the potential to trace the *overall* mass distribution (instead of just the *luminous* component), they have become one of the main foci of attention in observational Cosmology. Both methods are however plagued by uncertainties in their application, some instrumental, others associated with the intrinsic properties of the galaxian population. At best, they yield estimates of the distance of a single galaxy with an error of about 15%. In order to extend their application to distances ofcosmological interest, volume averaging is necessary over scales on the order of (tens of Mpc)^3 or over whole clusters or groups. Hence, a reliable determination of peculiar velocity flows requires large galaxy samples.

We have conducted an extensive HI survey of the Pisces–Perseus supercluster (PPS) over the last several years, using the Arecibo 305m telescope. The main ridge of the PPS is dominated by the clusters A426, A262, the Pisces cluster around N507, A2666 and A2634. The PPS survey is virtually complete to $m_{cgcg} = 15.7$. We have initiated a spectroscopic survey of fainter galaxies in and around those clusters, to (a) obtain a more detailed kinematic picture of the velocity field and (b) to trace the density field in the vicinity of the PPS, using the Tully–Fisher and $D - \sigma$ relations to estimate redshift–independent distances. The 5m telescope is being used to carry out a quick redshift survey of faint PPS members and to obtain velocity dispersions of elliptical and lenticular galaxies in the cluster cores and their peripheries, for which CCD photometry is being obtained elsewhere. These will be combined with 21cm widths and I–band images of spirals to obtain a detailed picture of the velocity and density fields in the neighborhood of the PPS.

In the first year of this program, we have obtained low dispersion spectra of approximately 400 galaxies and high resolution spectra — adequate for velocity dispersion measurements — in 30 galaxies in one cluster. A first paper which presents the low dispersion measurements is currently in preparation (Sakai, Giovanelli and Wegner 1992).

SPECTROSCOPIC STUDIES OF THE GLOBULAR CLUSTERS of the ANDROMEDA GALAXY M31

Principal Investigator: Donald Hamilton
California Institute of Technology
Co-Investigator: W. L. W. Sargent, California Institute of Technology
Co-Investigator: P. O. Seitzer, University of Michigan

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 700,000 pc 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 10 km/sec, and accurate estimates of the chemical composition. The just recently acquired data are still being analyzed so no results are as yet forthcoming. The main conclusion that one can make form from the reduced data is that the Norris Spectrograph is a very powerful instrument for multi-object projects.

Metal Abundances in Low Metallicity Galaxies

Principal Investigator: Martha P. Haynes
Department of Astronomy, Cornell University

Co–Investigators: Riccardo Giovanelli and Liese E. van Zee
Department of Astronomy, Cornell University

Subject Heading: Galaxies and Quasars

Over the last decade, a number of galaxies have been identified that may be undergoing bursts of star formation for the first time. The notion that such objects may be "young" or even "protogalaxies" is a matter of debate and perhaps semantics. While many of them are too small and of too low mass to be the precursors of normal spirals and ellipticals, the HI–rich, low luminosity dwarfs may be the best candidates for objects just above the density perturbation threshold required for a coherent isolated gas cloud to separate from its surroundings, collapse, and eventually form a bona fide galaxy.

Our current project centers around the study of objects with very high ratios of hydrogen mass to blue luminosity M_H/L_B. The reasoning is as follows: galaxies must form out of large clouds of hydrogen gas, so young galaxies should still be surrounded by their nascent material; spectroscopic studies will enable us to correlate the ambient hydrogen mass with the age of the galaxy as determined from metal abundances. For instance, object 1225+01, discovered serendipitously at Arecibo (Giovanelli and Haynes 1989), visually appears to be a normal dwarf irregular galaxy, but its extreme blue colors imply that most of the light is produced by young stars (Salzer *et al* 1991). The H I counterpart to the dwarf irregular galaxy has a dynamical time comparable to the Hubble time (Giovanelli *et al* 1991) which leads us to hypothesize that star formation may have been delayed until the present epoch. If star formation has not yet occurred, most of the mass in the galaxy is gaseous, not stellar, so the neutral hydrogen distribution should accurately trace the mass distribution.

Long slit observations across the optical counterparts allow us to determine metal abundances as well as the electron temperature and electron density of several H II regions with a single integration. Electron temperatures can be determined from the ratio of [O III] lines (λ4959 + λ5007)/ λ4363 and the ratio of [N II] lines (λ6548 + λ6583) / λ5755 (Osterbrock 1989). One major problem with previous observations has been the difficulty of detecting the [O III] λ4363 line; it has become common practice to use empirical relationships determined from H II regions where the temperature has been measured, including H II regions in other galaxies if necessary. However, with the additional light gathering power of the 5 meter telescope at Palomar, we have been able to detect the faint lines with a reasonable integration time, so we do not have to rely on this uncertain practice. The electron density can be determined from ratioed intensities of the [S II] $\lambda\lambda$ 6716 and 6731 transitions in a similar manner. Measurements of the electron temperature and density will allow us to directly compute the ionic abundances from the observed spectral line intensities and therefore infer the age of stellar population within the optical galaxy (Salzer *et al* 1991).

Long slit spectra along the major axis of eight such galaxies were acquired during February 1992, with the double spectrograph on the 5 m telescope at Palomar. Separate spectra taken with the red and blue cameras were overlapped on the λ4959 and λ5007 [O III] lines. Using standard data reduction procedures within the IRAF package, we repaired bad columns, flat-fielded the spectra, and removed cosmic ray hits. We used both He-Ne-Ar lamp spectra and the intrinsic night sky lines to straighten the spectra in the dispersion direction and spectra of standard stars to straighten in the spatial direction. Representative red and blue spectra of UM 439 are shown in Figure 1. Further work will focus on the candidate objects found during 1992 HI mapping observations at Arecibo in a comprehensive study of the class of very high M_H/L_B objects.

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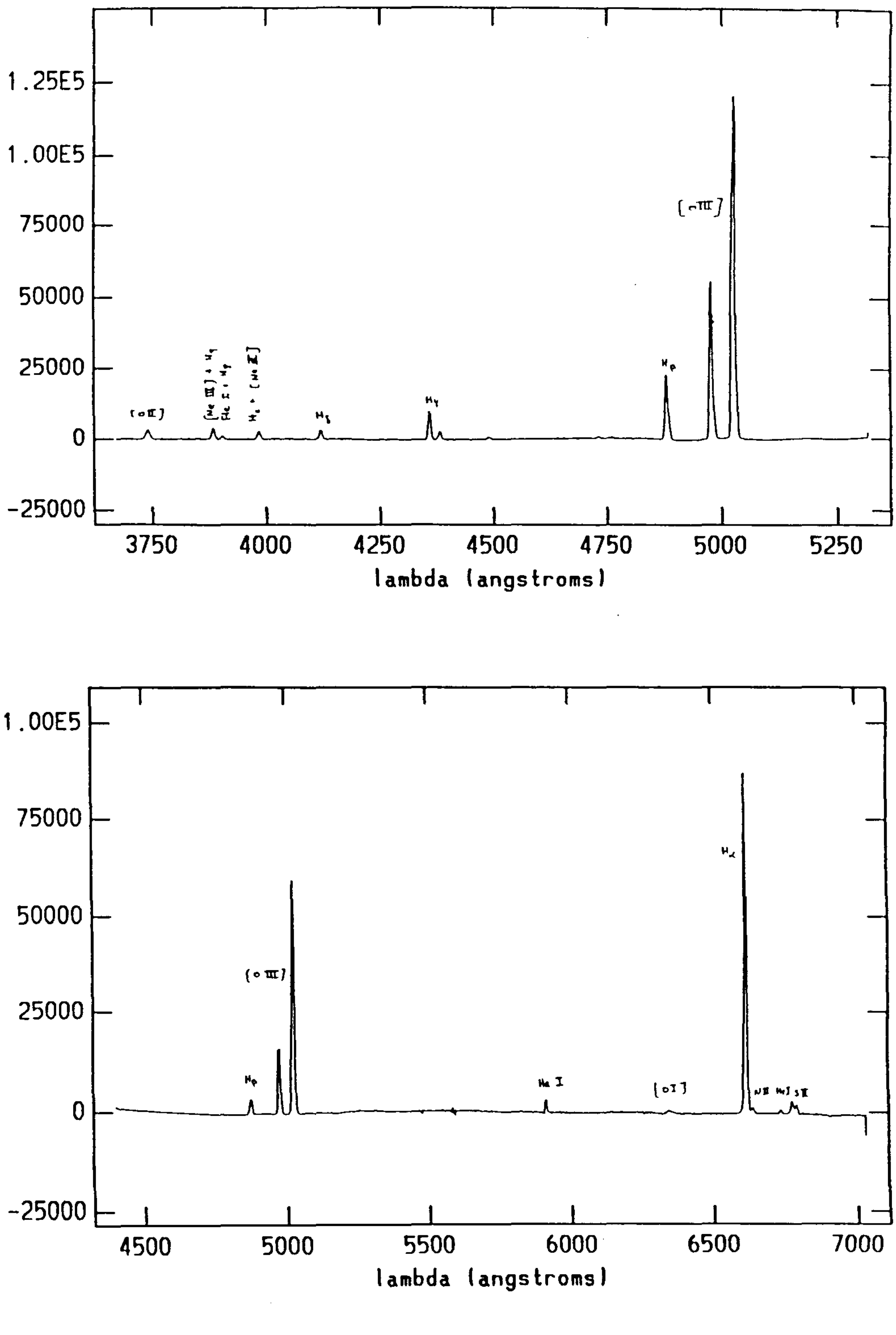

Figure 1: Blue and Red spectra of UM 439 taken with the Double Spectrograph on the Palomar 5 m telescope in 1992.

Rotation Curves of Spiral Galaxies in Clusters

Principal Investigator: Terry Herter
Department of Astronomy
Cornell University

Co–Investigators: Martha Haynes (Cornell University)
Nicole Vogt (Cornell University)
Riccardo Giovanelli (Cornell University)
Wolfram Freudling (ESO)
John Salzer (Wesleyan)

Subject Heading: GALAXIES

One of the most promising global secondary distance indicators is the Tully-Fisher (T-F) relation whereby the distance to a galaxy is derived from observations of its optical brightness and its rotational velocity as derived, in the usual instance, from the 21 cm line emission profile (Aaronson and Mould 1986). A simple physical explanation for the correlation between luminosity and profile width may be found in the expected dependence of both luminosity and disk rotational velocity on galaxy mass.

The application of the T-F relation constitutes one of the most useful methods of determining the local peculiar motion to relatively large distances. An accurate measure of the distance to a cluster can be derived using the distance data for many galaxies in the cluster. In principle, the 21 cm HI line width should be adequate for T-F applications and is being extensively used by us. However, HI widths at the larger distances ($z > 0.02$) can only be measured (today) with the Arecibo telescope, and unfortunately, 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 reduced if we use only clusters visible from Arecibo. 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 regions of highest density are the cores of rich clusters. In such environments, a variety of mechanisms are likely to affect galaxy evolution at both early and late epochs. For spiral galaxies, a key sign of recent evolution is the observed HI deficiency (e.g. Haynes et al. 1984) seen to be prevalent among spirals that pass within the cores of rich clusters with moderate X-ray luminosity. The HI-poor spirals are prime candidates for the investigation of environmental effects, and since in clusters more distant than Virgo they are generally not detected in HI even at Arecibo, the consequences of the cluster core location on their mass distribution must be investigated by optical means.

To date, only a few studies 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. We have undertaken a program to obtain the optical rotation curves of spiral galaxies in a significant number nearby clusters of galaxies. This is part of a larger project to also conduct optical CCD imaging at I-band and HI line emission observations of 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 274 spiral galaxies located in 12 different clusters. All of this data has been reduced and rotation curves extracted. Optical imaging of these galaxies has been performed or is planned 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. Programs have also been developed to analyze optical images via a decomposition technique which separates the contributions of the bulge and disk components of the galaxies.

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. 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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Halo Dynamics and Masses in Virgo Ellipticals

Principal Investigator: Xiaohui Hui
Division of Physics, Mathematics and Astronomy
California Institute of Technology

Co-Investigators: J. Mould (CIT)

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 severly 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. Our last year's program consisted of two parts. First, we planed to survey planetary nebulae in four Virgo galaxies out to a galactic distance of 20 kpc. Unfortunately, the observation was completely weathered out due to a combination of bad seeing ($> 2''$) and overcast. The second part involved using the Norris Spectrograph to take spectra of known PNe in several Virgo ellipticals for velocity measurement. The data taken in the limited time available (about half night, other times were either used to setup the instrument or weathered out) are being analyzed. It appears to be difficult to reach the Virgo PNe with the Norris at the present time. However, the spectra of these planetary nebulae can be obtained easily with the LRIS, which is expected to be on-line next spring on the Keck telescope. We can carry out the observation with a simply drilled aperture plate before the LRIS custom mask punching machine becomes available.

INFRARED IMAGING OF GRAVITATIONAL LENS SYSTEMS

Principal Investigator: C. R. LAWRENCE
Division of Physics, Mathematics, and Astronomy
California Institute of Technology
Co-Investigators: G. NEUGEBAUER, AND K. MATTHEWS (Caltech)

Subject Heading: Galaxies and Quasars

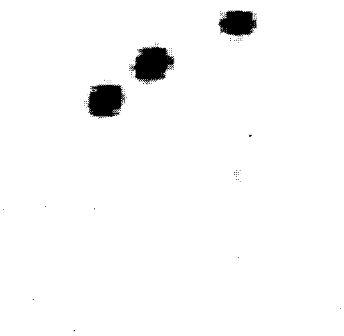
Observations of gravitational lens systems, in which light from a distant object is deflected on its way to us by the gravitational field of intervening matter, are a powerful tool for determining the distribution of mass in galaxies and clusters of galaxies, and possibly values of cosmological parameters. The most important weakness of existing observations is that the lens itself is often undetected. Imaging in the infrared offers two advantages over optical imaging in the hunt for the lensing mass. First, atmospheric seeing is significantly better in the infrared than at shorter wavelengths, sometimes getting below 0.″5 at Palomar. This is a critical advantage in single-galaxy lensing, where separations are typically less than 2″. Second, galaxies at redshifts suitable for lensing are often much brighter relative to typical quasar images than they are at visible wavelengths, and are therefore significantly easier to detect.

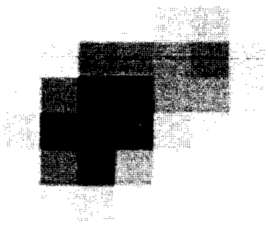
These two advantages of infrared observations of lens systems are demonstrated in the 2.2 μm image of 2016+112 given in Lawrence, Neugebauer, and Matthews (1992, *A. J.*, in press reproduced in Figure ?). From previous optical images it was known that there were two galaxies in this system, the first at $z = 1.01$, the other at an unknown redshift. The infrared image extended our knowledge in two important ways. First, a position angle for the ellipticity of the first galaxy was determined, giving an important constraint on the lensing potential. Second, the colors of the second galaxy show that it is almost certainly at much higher redshift than the first galaxy. 2016+112 is thus the only system known in which two lenses at different redshifts are required.

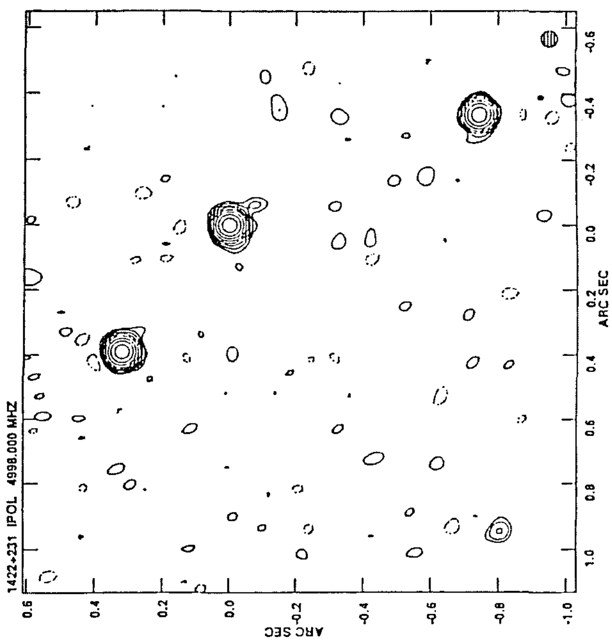
An even more dramatic demonstration of the advantages of good seeing in the infrared is given by a 2.2 μm image of 1422+231 obtained in March 1992 (Lawrence *et al.* 1992, *M.N.R.A.S.*, in press), shown in Figure ?. A radio image with 0.″05 resolution shows four unresolved components with flux density ratios 1:1:0.5:0.02 forming roughly an equilateral triangle 1.″3 on a side. A single infrared exposure in 0.″6 seeing (left panel) clearly resolves the source, and is consistent with unresolved emission coincident with the three brightest radio components. When eight exposures are combined (middle panel) faint emission possibly coincident with the faintest radio component can also be seen. When the effects of atmospheric seeing are partially removed using a powerful image processing technique called maximum entropy deconvolution (right panel), the result is so similar to the radio image that there can be little doubt that the four components are all images of a single quasar.

FIG 1.—Composite of ten 2.2 μm images of 2016+112. The total integration time was 6120 seconds. Pixels in this composite are 0.″0314 square. Pixels in the individual exposures were 0.″314. North is at the top, east is to the left.

FIG 2.—**Left:** Single 60 second 2.2 μm image of 1422+231. Pixels are 0.″314. North is at the top, east to the left. **Middle:** Composite of eight 60 second images. Pixels are 0.″0314 square. **Right:** Maximum Entropy Method deconvolution of the seeing disk.







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INTRINSIC DIFFERENCES AND ORIENTATION EFFECTS IN EXTRAGALACTIC RADIO SOURCES

Principal Investigator: C. R. LAWRENCE
Division of Physics, Mathematics, and Astronomy
California Institute of Technology

Co-Investigators: G. NEUGEBAUER, T. J. PEARSON, AND K. MATTHEWS (Caltech)
P. J. McCARTHY (OCIW)

Subject Heading: Galaxies and Quasars

There is persuasive evidence for both anisotropic emission and anisotropic obscuration of radiation in at least some powerful radio sources. Thus the appearance of two physically identical objects may be dramatically different depending on the direction from which they are viewed. There is equally persuasive evidence for a wide range of physical differences among radio sources. One of the outstanding problems in the study of galaxies and quasars is disentangling intrinsic differences from orientation effects.

Lawrence and collaborators continued 10 μm extended-emission-line observations of 50 radio galaxies and quasars with redshifts between 0.5 and 1. These observations provide a key test of the hypothesis that the most powerful radio galaxies and quasars are physically the same, but appear to be different simply because they are seen from different directions. According to this hypothesis, the radio jets in the quasars are aimed at us, while those in the galaxies are not. The difference in optical appearance is then explained by a combination of anisotropic emission and obscuration of various radiation components. The 10 μm emission, however, and the extended (i.e., non-nuclear) line emission should be isotropic. If radio galaxies and quasars are physically the same, we should detect both galaxies and quasars at the same level.

Eighteen objects have now been observed at 10 μm, and two in narrow emission lines. The most significant results so far are the detection of a galaxy at a level comparable to the quasars at 10 μm, and detection of extinded line emission around a quasar comparable to that typically seen around galaxies. If such detections continue, the unification hypothesis will be strongly supported.

Infrared Emission Lines in Active Galactic Nuclei

Principal Investigator: John W. Miles
Center for Radiophysics and Space Research
Cornell University

Coinvestigators:
Thomas L. Hayward
James R. Houck
Cornell University

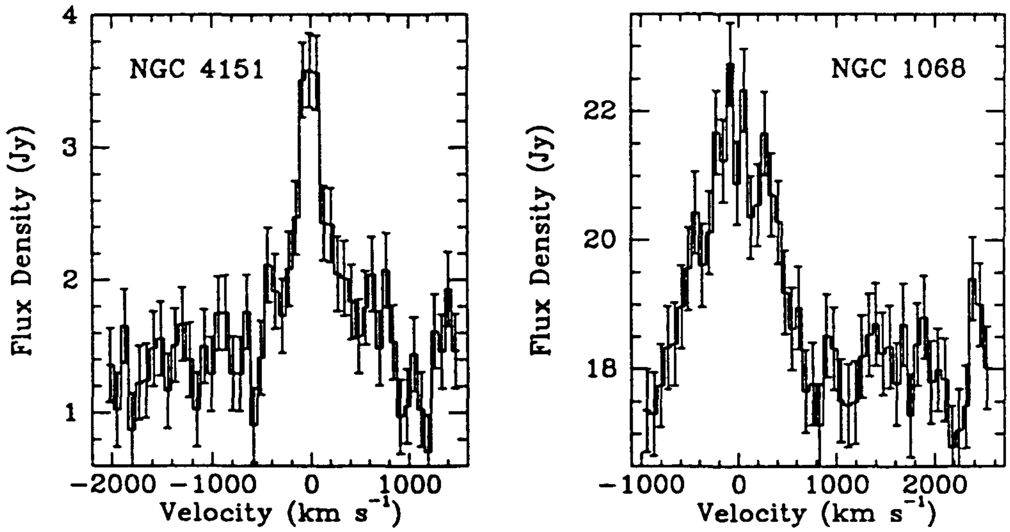
Subject Heading: Galaxies and Quasars

Certain galaxies have extremely powerful cores generating a vast luminosity within a very small region. These sources are called Active Galactic Nuclei (AGN). A great deal of research effort has been spent to determine the source of their energy. A supermassive black hole in the core may be the explanation, where a swirling disk of matter forms as it is drawn into the black hole. This disk becomes extremely hot, generating intense luminosity. Another explanation is massive star formation concentrated in a very small 'starburst' region in the nucleus of the galaxy. The newly born hot stars, if they are numerous enough, can account for the luminosity.

We have used the new instrument SpectroCam-10 on the Hale telescope to do high resolution spectroscopy of two AGNs. We observed an emission line of triply-ionized sulphur at $\lambda = 10.5\mu m$ in the galaxies NGC 4151 and NGC 1068. The data were taken on 25 January 1992 and appear in the figure on the following page.

If one can observe lines of different elements and different ionization states in a source, their relative strengths can give us information regarding the temperature, density and abundances of the elements present, as well as the nature of the ionizing source. They can also tell us something about the nature of the ionizing source, since the stronger the higher ionization line, the 'harder' the ionizing flux must be. A central black hole would have a 'hard' ionizing flux whereas a starburst would have a relatively 'soft' ionizing flux. We therefore plan to follow up these observations by looking at two lower ionization lines accessible by SpectroCam-10: doubly-ionized argon ($\lambda = 9.0\mu m$) and singly-ionized neon ($\lambda = 12.8\mu m$).

This work will be extended to a class of AGNs that emit the vast majority of their energy in the infrared. These ultraluminous infrared galaxies are thought to be ordinary optical AGNs surrounded by thick dust shells. The optical energy of the AGN is absorbed by the dust, thereby heating the dust and causing it to reradiate in the infrared. Optical line emission will be obscured by the dust while infrared line emission can penetrate the dust. Therefore infrared emission line observations provide a unique method for determining the physics in the cores of these objects, and whether or not they are similar to their optical counterparts.



Triply-ionized sulphur 10.5μm line detections in NGC 4151 and NGC 1068.

The Cosmic Distance Scale

Principal Investigator: Jeremy Mould
Co-Investigators: Shaun Hughes, Rachel Akeson, and Joshua Roth
Division of Physics, Mathematics and Astronomy
California Institute of Technology

At a colloquium in March 1992 sponsored by the National Academy at its new Irvine facility, one of the speakers on Physical Cosmology, Richard Gott of Princeton University, opened with the capricious remark: "I have just returned from the future, and we still don't know the Hubble Constant." He summed up the prevailing pessimism of both observers and theorists about the problems of measuring this fundamental property of the Universe. Observers were set back by the delay to the H_0 Key Project, caused by spherical aberration in the Hubble Space Telescope primary mirror. Theorists at Princeton have reached a similar state of mind by analyzing n-body simulations of the galaxy distribution in a critical density Universe and noting that galaxy peculiar velocities are a significant fraction of their recession velocities out to considerable distances (Turner et al. 1992).

Work at Palomar Observatory this year strikes a more optimistic note. The accompanying figure from Mould et al. (1992) shows that clusters of galaxies follow a redshift-distance relation which is much better defined than the simulated velocity field of individual galaxies. These observations result from photometry of spiral galaxies in clusters at the Palomar 60 inch telescope and neutral hydrogen profiles of the same galaxies from Arecibo Observatory. The Tully-Fisher relation then yields a quantity proportional to the cluster distances.

Evaluating the proportionality constant is, of course, the hard part, and HST is required to reliably calibrate the Tully-Fisher relation and other similar 'secondary distance indicators'. This work is, nevertheless, beginning, and it is noteworthy that both Sandage et al. (1992) and Mould (1992) used the new COSMIC instrument at the prime focus of the 200 inch telescope to provide the photometric calibration for their HST data on IC4182 and M81 respectively. The full thrust of the H_0 Key Project will begin with the installation of a new, aberration correcting, wide field camera on the Hubble Space Telescope next year.

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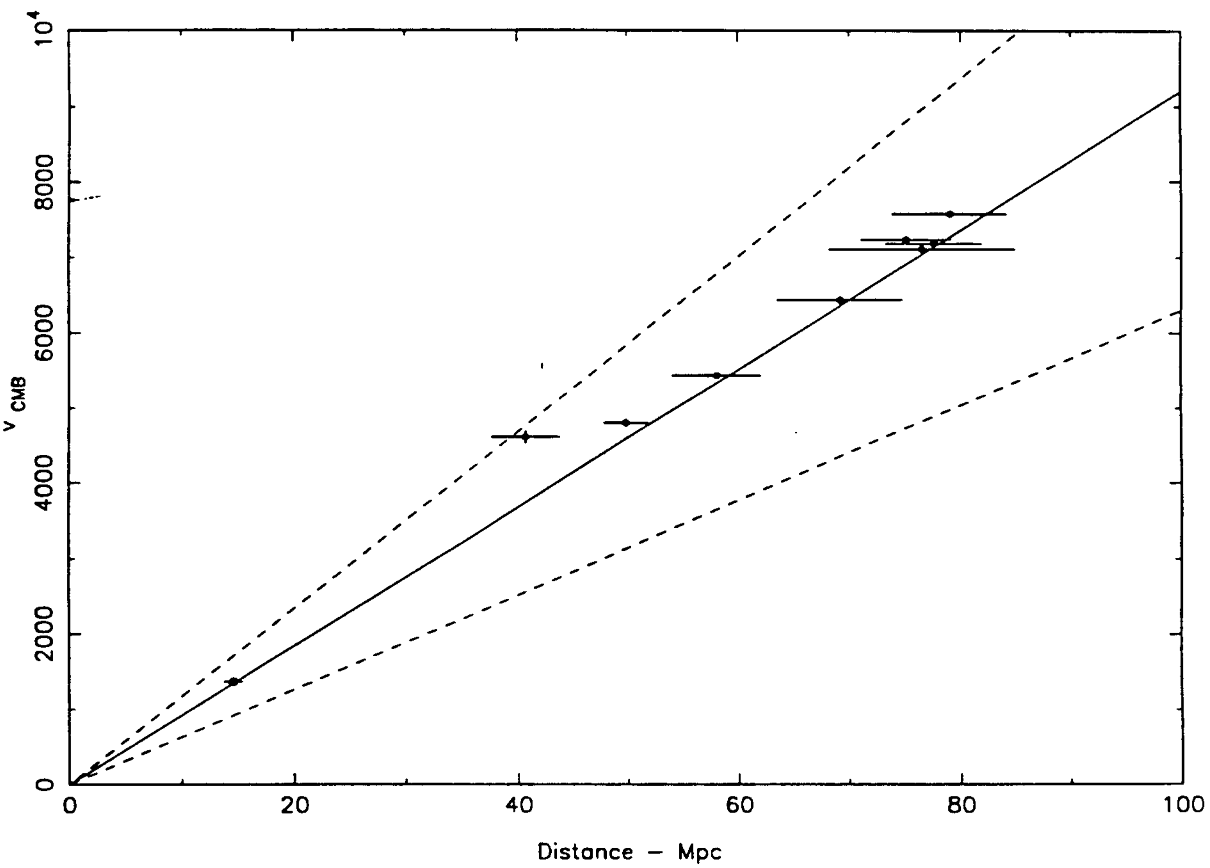


Cluster redshift referred to the rest frame of the cosmic background radiation is plotted against cluster distance from the Tully-Fisher relation using a provisional calibration. The solid line is the relation for $H_0 = 92$ km/sec/Mpc. Dashed lines are the 95% confidence limits on the Hubble Constant that Turner et al. (1992) measure for a complete sample of galaxies within 3000 km/s in a cold dark matter simulation with a global $H_0 = 80$ km/sec/Mpc.

The DEEP Survey

Principal Investigator: Jeremy Mould
Division of Physics, Mathematics and Astronomy
California Institute of Technology

Co-Investigators: Garth Illingworth, David Koo, and Sandra Faber
University of California at Santa Cruz
and John Kormendy
University of Hawaii

The Deep Extragalactic Evolutionary Probe is a new survey, applying the light gathering power of the Keck telescope to learn about the geometry of the Universe from galaxy counts as a function of redshift. Recent results in this field and the problems posed by them were discussed at the Neugebauer symposium by R. Ellis and L. Cowie. In brief, we have learned on the one hand that there are large numbers of faint blue galaxies. Redshifts are needed to distinguish between three possible explanations of the blue galaxy excess: luminosity evolution, density evolution, and volume evolution. On the other hand, redshifts for the faintest galaxies that have been observed with 4 meter telescopes exhibit a distribution that would be expected if luminosity evolution did not occur. The interpretation of K band galaxy counts by Cowie and collaborators favors density evolution or non-conservation of galaxies in the studied volumes. This means galaxies merge between $z = 0.5$ and $z = 0$ or fade to such an extent that they are missing from current epoch samples.

DEEP is a collaboration with an observational core group identified above. There is an associated group of theorists to help plan the observing strategy and interpret results, an instrument development group, and a science working group to broaden the involvement.

The goals of the DEEP project run parallel to the three identifiable sources of the blue galaxy excess. First, we aim to explore galaxy evolution. By measuring geometry independent parameters, such as surface brightness, color, and internal velocities, we plan to trace the time evolution of luminosity, number, color, size, morphology, mass-to-light ratio, star formation rate, and metallicity. Second, we intend to explore clustering evolution. The slope and amplitude of small scale clustering will be studied, along with the number, masses, structure, and sizes of groups, clusters, superclusters, walls, and voids. Third, we wish to learn about the geometry of the Universe through the application of the classical galaxy volume density test. Satisfactory understanding of the first two problems is a prerequisite for the third.

These three goals influence the design of the survey in three parallel ways. First, we intend to conduct the survey at moderate spectral resolution. The DEEP project proposes the construction of a second generation instrument for the Keck telescope (the MBSS. or multi- barrelled super spectrograph) with four times the field of the first generation Low Resolution Imaging Spectrograph and a resolution of 1.5 A/pixel. This will yield velocity dispersion or line width information for velocity dispersion larger than 100 km/sec.

Second, we have devised a sampling strategy in which our eight fields spread around the high latitude sky are sparse sampled, with satellite pointings extending over an area corresponding to 10,000 km/sec in redshift at the mean redshift of the survey. In this way we hope to learn whether the structure that we see in the galaxy distribution today is a relatively recent development. We plan to conduct the survey so that 70% of the area is part of a medium-deep redshift survey with 3 hour exposures per galaxy; the remaining 30% of the area is divided between very-deep and ultra-deep sub-samples with 6 and 24 hour exposures respectively. The limiting magnitude of the ultra-deep survey is B = 25.4.

The extent of the survey is governed by the third goal of DEEP: to learn about the volume evolution of the Universe. At $z = 0.3$ the difference between an open empty Universe and a closed flat Universe is just 25% in volume. To obtain a 5 sigma measurement of that density difference requires counting 400 galaxies. If we conduct the experiment at 3 redshifts, divide the sample into 4 mass ranges, and choose galaxies from three different clustering environments, we need a total of approximately 15,000 galaxy redshifts.

We are ready to begin this survey when the Keck telescope starts acquiring spectra early in 1993. The Low Resolution Imaging Spectrograph (LRIS), currently being completed at Caltech under the supervision of J. B. Oke and J. G. Cohen, has an 8 $\times$ 6 arcmin field offset from the optical axis of the telescope. It will acquire spectra of 40 galaxies per telescope pointing on slit masks which are held in a juke-box and inserted into the Cassegrain focal plane. The proposed second generation instrument, MBSS, replicates this optical train four times to make use of a much larger fraction of the available Keck focal plane. The MBSS will make the DEEP survey feasible within the time frame 1993-1999.

In 1992 the prerequisite imaging was commenced at the Palomar 5-m with the new COSMIC instrument. Twelve fields of 9 arcmin were imaged to $r = 26$ on five nights. This is sufficient to permit DEEP to begin when LRIS becomes operational. It is proposed to continue imaging at Palomar in 1993.

The Stellar Population and Luminosity Function in M31 Bulge and Inner Disk Fields

Principal Investigator: Jeremy Mould
Division of Physics, Mathematics and Astronomy
California Institute of Technology

Co-Investigators: R. Michael Rich
Columbia University
and James Graham
Caltech and University of California, Berkeley

In their program to understand the stellar content of the bulge of M31 Mould and R. Michael Rich (Columbia University) were joined this year by James Graham (now at UC Berkeley). Graham's expertise with the Cassegrain infrared camera enabled them to synthesize one arcmin square images of strategically located fields at wavelengths of 1.2 μm and 2.2 μm .

The first indication that stars in the M31 bulge might not be as simple a stellar population as stars in the globular clusters of the Galaxy was reported by Mould six years ago in the first Space Telescope Science Institute Symposium. That report shows 4SHOOTER images of stars in the bulge of M31 apparently one or two magnitudes brighter than the brightest stars in a cluster such as 47 Tucanae. These stars appeared more centrally concentrated towards the nucleus of M31 than the unresolved visible light of the galaxy. Since these stars are in their final evolutionary phase as red giants (they are called AGB or asymptotic giant branch stars), they stand out even more clearly from the background in near infrared light (1–2 μm).

Following this initial work, Rich and Mould were able to show spectroscopically that ten of the brightest giants in the M31 bulge ($4'$= 500 pc SE of the nucleus on the minor axis) are indeed cool (M type) giants. In 1989 a pilot program at Palomar to image the luminous stars in the infrared found that stars in this bulge field are indeed one bolometric magnitude brighter than the brightest stars in the Galactic bulge. Rich and Mould drew attention to the possibility that these luminous stars are younger than comparable stars in the Galaxy. This notion contrasts with the more commonly held view that the dense central bulges of galaxies are among the first parts to form.

The new mosaic images are the best resolved pictures of the bulge of an external galaxy yet obtained (see Figure 1). Photometry of these images confirmed the presence of luminous AGB stars. These results have been submitted to the *Astronomical Journal.*

In the interpreation of these data the first question that had to be settled was whether these stars belong to the bulge population or are merely projected on to the field from the disk of M31. We addressed that question by examining a field on the minor axis of M31, which, according to a careful study with modern surface photometry is a >80% pure sample of the disk population. Scaling up the luminosity function of that disk field to the surface brightness of our bulge field (centered $2'$ on the SW major axis) *we found* that disk contamination can account for less than 25% of the stars in the bulge field with luminosity exceeding 10^4 $L_\odot$.

Second, we asked: is this extension of the AGB a property of the whole, primarily old, stellar population, or is it a 'straggler phenomenon' ? To be more explicit, we wondered if close binaries which are reluctant to leave the main sequence, because they are able to trade hydrogen fuel, might also, after some restructuring, survive longer on the AGB. Such stars are commonly known as 'blue stragglers'. Since we know the lifetimes of stars on the AGB, we were able to convince ourselves that a significant fraction of the stellar population was involved in this extended AGB evolution, rather than a trace component.

Many other questions are raised by these results. If it isn't disk stars or blue stragglers, what is it ? Are we seeing super metal rich stars climbing the AGB in this way ? Or are these young stars in the bulge of M31 ? What is the effect of long period variability, which stars in this evolutionary phase are known to exhibit ? Are these stars carbon rich or oxygen rich ? Do we see this phenomenon in all galaxies equally ? The latter question is receiving some attention. Freedman (Carnegie Observatories) has been studying the brightest red giants in the dwarf elliptical M32. A similar, but not quite so extended, AGB is seen. The bulge of our own Galaxy has been studied by Frogel (Ohio State University) and collaborators. The Milky Way has a much less extended AGB. But why ? There are many questions to be addressed in further infrared studies of these nearby galaxies.

Observations of the Most Luminous Galaxy in the Universe

G. Neugebauer, B.T. Soifer, K. Matthews,

C. Lawrence, and J. Mazzarella

Palomar Observatory, California Institute of Technology

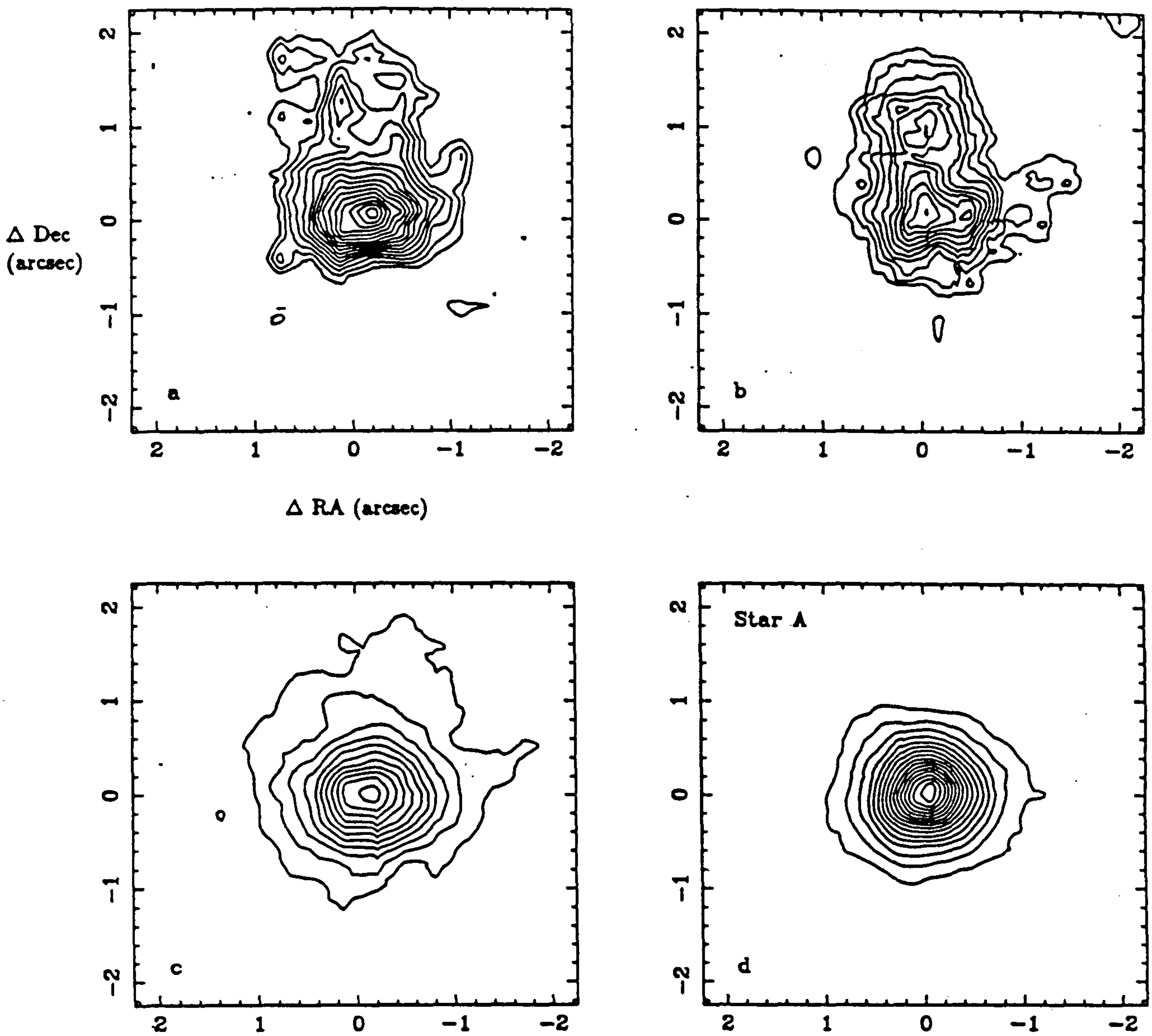
The faint IRAS source FSC10214+4724 has been identified with an optical galaxy at a redshift of z = 2.286 (Rowan-Robinson, et al. 1991, *Nature*, **351**, 719) and has been measured to be the most luminous object known in the Universe. Its luminosity integrated over the entire wavelength spectrum is $\sim 5 \times 10^{14}\, L_\odot$, a factor of two greater than the most luminous known quasar. The molecular gas content is $\sim 6 \times 10^{11}\, M_\odot$, exceeding by an order of magnitude that of the most massive known molecular gas rich galaxy.

The nature of the central source in ultraluminous galaxies like FSC10214+4724 is not certain, but it is clearly important to understand the origin of the prodigious luminosity. Some ultraluminous infrared galaxies are thought to be going through extreme episodes of star formation which provide their power. The ratio of infrared luminosity to gas mass in FSC10214+4724 is, however, an order of magnitude larger than that found in active star forming galaxies in the local Universe. Alternatively, some ultraluminous infrared galaxies are thought to be powered by active galactic nuclei (AGNs), like quasars. The infrared excesses in these galaxies are attributed to reradiation from dust heated by the central source in the galaxy. The large infrared luminosity of FSC10214+4724, if produced via thermal emission from dust, requires $> 108.5\, M_\odot$ of dust.

Near infrared spectral observations made shortly after its discovery showed that the visual emission from FSC10214+4724 was dominated by a very strong emission line of Hα which was red-shifted into the 2.2 μm atmospheric "window". This last year, the Caltech infrared group therefore obtained a series of high spatial resolution images of FSC10214+4724 in the light of the red-shifted Hα line and in the nearby continuum. The results are shown in the figure along with an image of a star (bottom right) to show the point spread function of the infrared camera at the time of the observation.

The images illustrate two features. First, in the light of the emission line, the source appears unresolved (bottom left). A straight forward interpretation is that the Hα radiation originates in the narrow line region of a central quasar which is powering the galaxy; model calculations are consistent with the Hα emission from such a system being unresolved at the distance of FSC10214+4724. The quasar is, however, obscured by an extended surrounding dust cloud.

Second, the images in the top two panels of the figure show that, as seen in the light of the galaxy outside of the line emission (the continuum), the galaxy breaks up into two, and possibly three, separate nuclei. This is taken as evidence that the galaxy was created out of the interaction resulting from a merger of two or more extremely gas rich galaxies, a scenario that is much in vogue in explaining the formation of high infrared luminosity galaxies. The high luminosities of the separate nuclei argue that the individual galaxies are each in an early stage of evolution.



Contour plots of the high redshift (z = 2.28) IRAS source FSC10214+4724 in (a) broadband J continuum (rest wavelength 0.386 μm), (b) narrow-band continuum at 2.124 μm and 2.190 μm (rest wavelengths 0.646 μm + 0.666 μm) bracketing Hα in the rest frame, and (c) narrow-band at 2.156 μm (Hα in the rest frame) of FSC10214+4724. Panel (d) represents the narrowband continuum image for a reference star in the same frames. The Hα source (panel c) appears unresolved compared to a stellar image, while the continuum source (panel b) is resolved into two or possibly three sources.

Emission Lines in Active Galactic Nuclei

Principal Investigator: Wallace L. W. Sargent

Palomar Observatory

California Institute of Technology

Subject Heading: Galaxies and Quasars

The broad emission lines in the spectra of quasars are thought to originate in a relatively small dense region of hot gas, probably a light year or so in diameter, surrounding the much more compact "central engine" which is in turn thought to be a supermassive black hole. Smaller emission regions, perhaps only 0.01 light years in size appear to surround the nuclei of Seyfert Galaxies, which are much less luminous than quasars although their fundamental physical origins seem to be the same. Largely through the work of Maarten Schmidt, it is known that most galaxies more luminous than our own contained quasars in the remote past. Thus it is widely believed that most luminous galaxies currently contain supermassive black holes which are largely inactive, presumably because they are no longer being "fed" by infalling stars or gas. Only a few percent of all nearby galaxies have spectra indicating weak activity of the type characteristic of the gas around a central supermassive black hole. Over the past few years Sargent and his former graduate student A. V. Filippenko (now a Professor at U.C. Berkeley) have made a systematic study of the spectra of the centers of the 501 brightest galaxies in the northern sky visible from Palomar in order to assess the frequency of "dead" (or barely alive) quasars. They have concluded that, as expected from Schmidt's work, such objects are quite common; as many as 20 percent of nearby galaxies have emission spectra which indicate that the gas is being illuminated by very high energy radiation which could not be produced by stars. In the last year Sargent and his associates have completed two pieces of work related to this overall question.

a) Variability in Quasar Emission Lines

Steidel & Sargent (1991) carefully examined very good spectra of the QSO pairs Q1634+267A,B and Q2345+007A,B, both of which are thought to result from gravitational lensing, although the intervening galaxy lens has not been observed in either case. A major criterion for deciding whether two quasars with small separations on the sky are two objects or the result of graviational lensing of a single quasar is how closely their spectra match in detail. Steidel and Sargent found in both cases that the redshifts of the components of the pairs were identical, but that subtle features of their emission line spectra were different. It is well known that different emission lines in the spectrum of a given quasar yield different redshifts by as much as 2000 km s^{-1}- an effect which is attributed to the existence of outflows in the gas surrounding the central black hole. They thus concluded that both pairs were indeed lensed systems and proposed that the spectral differences result from the different light-travel times from the quasar to the observer in the two light paths which pass on either side of the lensing galaxy. According to this hypothesis, a single quasar should exhibit spectral variations, including changes in the apparent redshifts given by some of the emission lines, on time-scales of about one year. Variations in the emision spectra of Seyfert nuclei are well known to occur on time scales as short as days or weeks. However, the central emission regions of quasars are much larger and hence the associated variability time scales are expected to be much longer. Since intrinsically luminous quasars are faint objects, little work has been done to test the possibilty that their spectra might vary, although it is known that they are variable in overall luminosity.

In order to test whether such spectral variations occur, Sargent and graduate student T. Small reobserved 30 quasars which had been studied in a survey of Mg II *absorption* carried out by Steidel & Sargent (1992). We chose bright quasars with $z \sim 1$. Roughly half of the observed quasars are radio-loud. There is typically a two-year baseline between the observations reported by Steidel & Sargent (1992) and our observations this year. We have reduced and cursorily analysed 18 of the quasars. So far, we have detected no variations whatsoever. In fact, the agreement between the spectra taken at two different epochs—and reduced by two different people using different software packages—is striking.

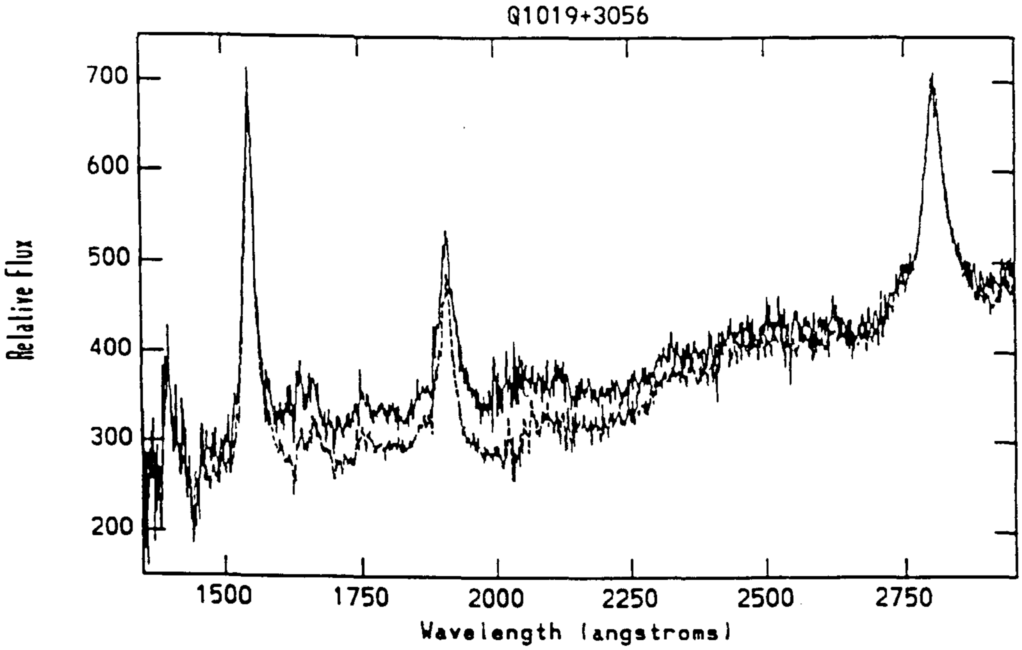


Figure 1. Spectra of Q1019+3056 recorded on 1990 January 22 (dotted line) and on 1992 January 31 (solid line). No scaling or offset has been applied, but the wavelength scale has been transformed to the QSO rest frame ($z = 1.316$).

If we detect no velocity shifts in our remaining 12 spectra, then it will raise serious questions about the natures of Q1634+267A,B and Q2345+007A,B as lensed systems. Already they present problems because of the failure to detect the lensing galaxies. (It has even been proposed that the double images result from lensing by galactic-sized aggregates of "dark matter" whose existence has been hypothesized on other grounds.) Moreover, limits on the sizes and distributions of intervening Lyman α clouds derived from the assumption that these two systems are lensed will likely have to be revised.

Black Holes or Massive Star Clusters?

Over the past few years support has been gaining ground for the idea that some of the anomalies observed in the emission-line spectra of the centers of nearby galaxies could be due to the intense radiation fields of very large clusters of very hot, young stars. Sargent, Filippenko, and Berkeley graduate student L. Ho have completed a study of the spectra of 14 galaxies exhibiting such anomalies using observations made on the 200-inch telescope in 1990. We found that, on close inspection, about half of the anomalous spectra appear to be excited by hot stars while the remaining half are almost certainly excited by non-thermal radition presumed to be radiated in the vicinity of a supermasive black hole. Criteria involving the relative strengths of emission lines produced by various ions of different elements were developed in order to enable the relatively subtle distinctions between the predictions of the two hypotheses to be made.

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High Redshift Quasar Surveys

Principal Investigator: Maarten Schmidt
Division of Physics, Mathematics and Astronomy
California Institute of Technology

Co-Investigators: Donald P. Schneider
Institute of Advanced Study
Princeton

James E. Gunn
Department of Astronomy
Princeton University

Subject Heading: Galaxies and Quasars

Quasars were discovered some 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.

Finding quasars among the millions of stars in the sky, that make up our own Milky Way galaxy, is not easy. Quasars of moderate redshifts exhibit blue colors, which help in their selection among the galactic stars which are mostly red. 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 in our neighborhood, at redshift zero.

Schmidt, Schneider (Institute for Advanced Study, Princeton), and Gunn (Princeton University) have been engaged for almost 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.* have now started a new 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 – 5.6. Spectroscopic observations of the candidate objects are required to determine whether or not they are high redshift quasars. Last year this program produced 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.

ROSAT Deep Survey X-Ray Sources

Principal Investigator: Maarten Schmidt
Division of Physics, Mathematics and Astronomy
California Institute of Technology

Co-Investigators: G. R. Hasinger
Max Planck Institute for Extraterrestrial Physics
Garching

D. P. Schneider
Institute for Advanced Study
Princeton

R. Burg
Space Telescope Science Institute
Baltimore

J. E. Gunn
Princeton University
Princeton

Subject Heading: Galaxies and Quasars

Quasars and the nuclei of Seyfert galaxies appear to be closely related, the main distinction being the ratio of the quasar-like nuclear luminosity to that of the galaxy starlight. The evolution of quasars is becoming well documented through extensive optical surveys. In contrast, little is known about the evolution of Seyferts. This is because collecting complete samples to well defined completeness limits for objects having a blue nucleus and a red envelope is much more difficult than for point-like quasars.

In contrast to the optical band where the majority of objects are stars and galaxies, most of the sources observed at x-ray energies are quasars and Seyferts (and at high fluxes, clusters of galaxies). The German ROSAT satellite, managed by the Max Planck Institute for Extraterrestrial Physics (MPE) in Garching, launched on June 1, 1991, allows imaging at moderate energy resolution in the energy range 0.1 to 2.0 keV. A team consisting of Schmidt, Hasinger (MPE), Truemper (MPE), Giacconi (STScI), Burg (STScI) and Zamorani (Bologna) is conducting the Deep X-Ray Survey with ROSAT.

X-ray exposures totaling about 150,000 seconds have yielded 86 sources in a field within a radius of 16 arcminutes. Among these, 66 sources have an optical candidate brighter than

R = 22 mag within 15 arcsec, and 11 have a candidate with R = 22 – 23 mag. In the past year, 28 of the brightest optical candidates were observed. In 12 cases, the spectral properties (usually the presence of strong emission) confirmed the optical identification. Spectroscopic work on the remaining candidates is continuing.

Infrared Imaging of Starburst Galaxies

Principal Investigator: Denise S. Smith
Department of Astronomy
Cornell University

Coinvestigators: Terry Herter and Martha Haynes
Department of Astronomy
Cornell University

Subject Heading: Galaxies and Quasars

Starburst galaxies define a class of objects having properties consistent with a large population of hot young stars, unusually high star formation rates and significant dust obscuration. The mechanism responsible for triggering such rapid star-formation is currently not well understood. In the case of M82, the prototypical starburst galaxy, recent 2.2 μm images have uncovered the presence of a 1 kiloparsec stellar bar that may have resulted from interactions with M81 (Telesco et al., 1991). Interactions between the bar and interstellar gas may have then triggered the massive star-formation observed in this system. Since interactions are present in many starburst systems, our program is studying star formation properties as a function of the strength and duration of the interaction.

The star formation properties of starburst galaxies are also a subject of current debate. Numerical starburst models applied to M82 suggest that the observed 2.2μm luminosity can only be produced if stars with masses lower than 3 $M_\odot$ do not form (Rieke *et al.*, 1980). This is a controversial result and needs confirmation in other starburst systems. Our study of a sample of interacting starburst systems will determine the lower mass cutoff for star formation.

We have defined a sample of twenty nearby starburst galaxies for study in the infrared. In the radio, 6 cm emission arises from thermal emission in star forming regions and therefore directly traces starburst activity. Condon *et al.* (1991) have classified UGC radio sources with extended 6 cm emission as starburst galaxies. From this group, we have selected the twenty starburst objects with the highest 6 cm luminosities. We are imaging these galaxies at 1.25, 1.65 and 2.2 μms with the Prime Focus Infrared Camera. The 0.5$''$ pixels and large format provide good spatial resolution and field of view for galaxies typically 2 arcminutes in diameter, allowing us to quickly obtain detailed maps of the entire source. The 2.2 μm images are being examined for the presence of multiple nuclei, bars, and other morphological features obscured at optical wavelengths. Since the primary contribution to the 2 μm continuum emission arises from old giants and supergiants, the images 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 needed for reddening corrections.

This program will allow us to constrain the conditions required for the high star-formation rates characteristic of starburst galaxies. The timescale over which the galaxy has interacted with another system will be estimated and compared to that of the burst to determine how starburst activity evolves with interaction strength and duration. Within each galaxy, an understanding of the distributions of the old stellar populations will define conditions characteristic of starburst activity. The 2 μm fluxes define luminosities needed to determine the lower mass cutoff for star formation in these galaxies.

Prior to October 1992, we have imaged 11 starburst galaxies and one normal galaxy at the three wavelengths. Of the 36 observed bands, 24 have been reduced and calibrated. Images of NGC3690 (U6471/2) show several previously undetected small sources; these sources are probably regions of star formation triggered by the interaction.

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Imaging and Spectroscopy of VV114

Principal Investigator: B. T. Soifer
Division of Physics, Mathematics and Astronomy
California Institute of Technology

Co-investigators: R. Knop, J. Graham (U. C. Berkeley), K. Matthews,
G. Neugebauer, D. Sanders (U. Hawaii)

Subject Heading: Galaxies and Quasars

Over the last several years we have devoted a great deal of observing time to the study of the brightest galaxies discovered in the IRAS all-sky survey. VV114 is an interesting example of the interacting galaxies which comprise a major fraction of the galaxies discovered by IRAS. VV114 is very luminous in the far IR ($2x10^{11}$ $L_{\odot}$), but is close enough (80 Mpc) that it has a favorable spatial scale (0.4 Kpc/").

Figure 1 shows images of VV114 at 0.4 μm and 2.2 μm, as well as a radio (1490 MHz) image. The eastern peak, which is the brighter component in the IR, is not seen in the visual image. This would indicate the presence of a large amount of intervening dust, which absorbs the bulk of the visual radiation but allows the near-IR radiation to shine through. The peak of the eastern galaxy at 2.2 μm aligns well with the radio peak; the western IR and visual peak (marked with a cross in Figure 1) does not align with any radio peak.

Figure 2 shows a near-IR composite color image of VV114. Radiation at 1.27, 1.65, and 2.2 μm are shown, respectively, in blue, green, and red. This figure shows the two infrared components, separated by 15", with different IR colors. The brightness of the western (right) component has been artificially doubled at all wavelengths to allow it to be more easily seen. The eastern component is much redder than the western component, indicating it is brighter at longer IR wavelengths. Additionally, the IR colors vary across the face of this galaxy, and the peak at 2.2 μm is about 1.4" southwest of the peak at 1.27 μm and 1.65 μm.

Optical spectroscopy on VV114 indicates that there is massive star formation occurring within the various peaks. The infrared colors are consistent with a starburst coupled with dust obscuration. From the optical, IR, and radio images we believe that the two galaxies of VV114 interacted closely about $2x10^7$ years ago, triggering the starbursts in the nuclei of the galaxies. The galaxies now appear to be moving apart from each other.

VV114

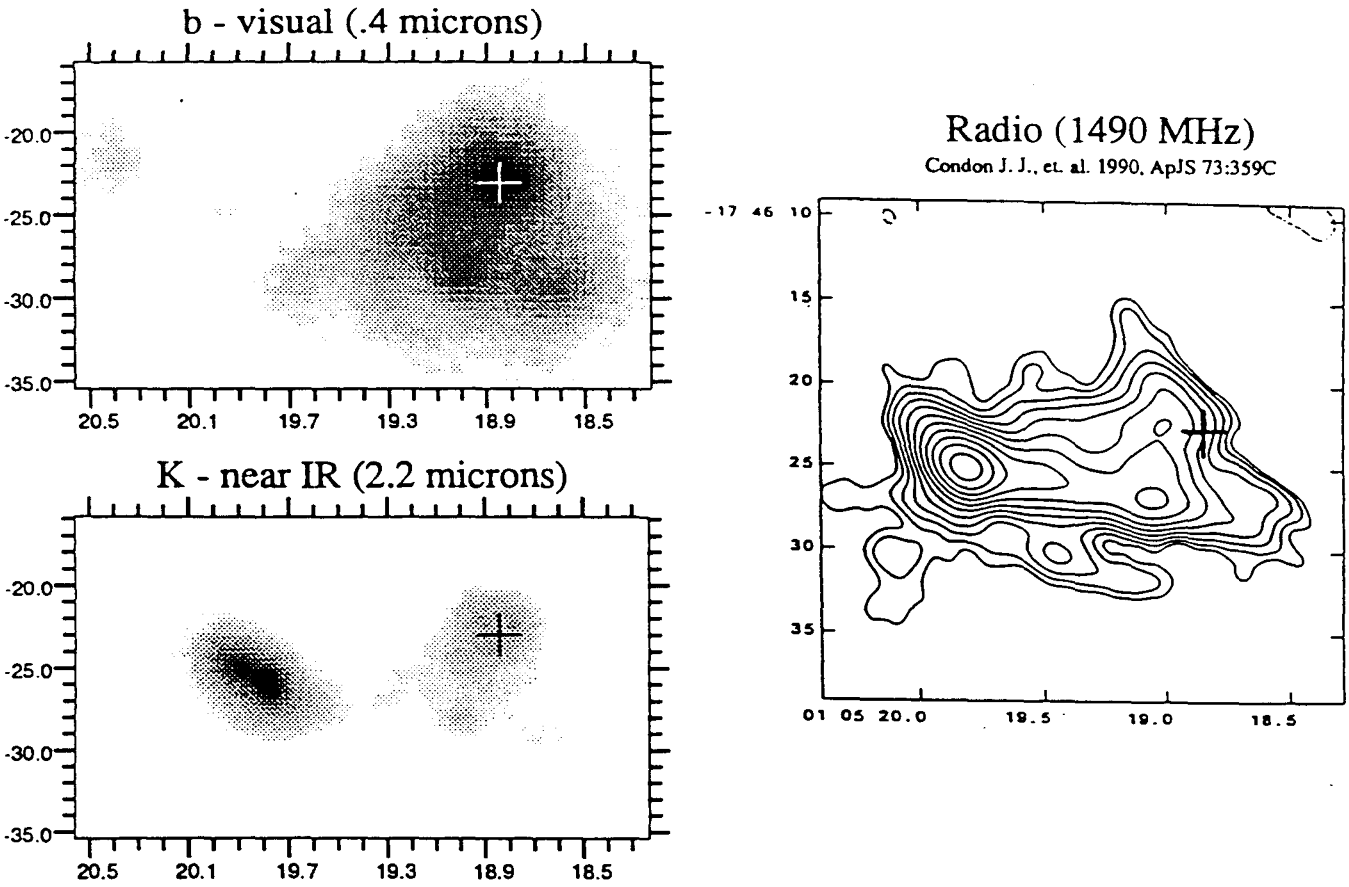

Figure 1: Images of the galaxy VV114 in the visual (0.4 μm), near-infrared (2.2 μm) and radio (1490 MHz). All images have the same scale. The cross indicates the position of the western visual and near-IR peak.

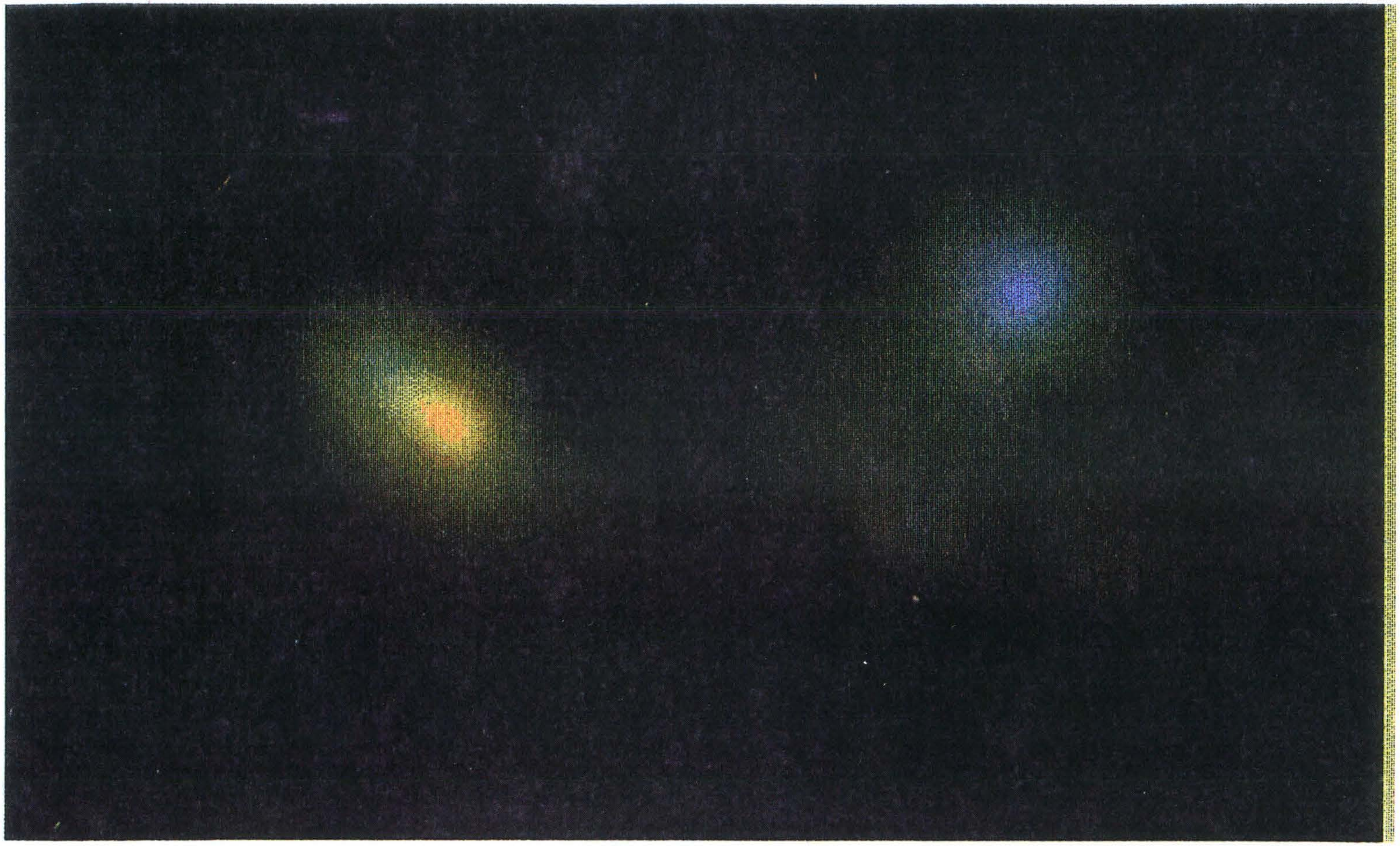

Figure 2: Three color composite image of VV114 in the near-infrared. 1.27 μm, 1.65 μm, and 2.2 μm are represented, respectively, by blue, green, and red. The brightness of the western (right) half of the image has been artifically doubled at all wavelengths.

Imaging of Infrared Luminous Galaxies

Principal Investigator: B.T. Soifer
Division of Physics, Mathematics and Astronomy
California Institute of Technology

Co-Investigators: J. Larkin, K. Matthews, G. Neugebauer,
J. Mazzarella, L. Armus, J. Graham (UCBerkeley),
S. Beckwith (MPI), and T. Herbst (MPI)

Division of Physics, Mathematics and Astronomy

Subject Heading: Galaxies and Quasars

The IRAS infrared all sky survey provided astronomers the first unbiased view of the extragalactic sky from 10 μm to 100 μm. To fully understand the importance of infrared emission in galaxies, and how such emission might relate to the processes by which galaxies evolve, we have been studying in great detail the ~300 brightest galaxies detected in the IRAS survey.

Most recently we have been studying the nuclear regions of the most luminous of these galaxies via near infrared imaging. In the infrared bright galaxies, there are large quantities of interstellar dust that is responsible for the prodigious infrared luminosity. This dust also efficiently absorbs radiation at visible wavelengths, so that studies of these galaxies in the visible do not penetrate to the centers of the galaxies, where the energy that powers the infrared luminosity is generated.

Near infrared imaging, on the other hand, is able to penetrate most of this dust, because the dust is much less opaque in the near infrared than in the visible. Our observations of these galaxies have used both broad band filters to trace the distribution of stars and hot dust, and narrowband filters in specific spectral lines that trace gas in either the ionized or molecular phase.

One of the galaxies that we have studied extensively is the nearby system M82. It has been known for decades that this system is undergoing a period of vigorous star formation, called a starburst. Figure 1 shows the composite color image made from our broadband images at 1.27, 1.65, and 2.2 μm of the central plane of this galaxy. The color coding is blue = 1.27 μm, green = 1.65 μm, and red = 2.2 μm, while the relative brightness in each color is the brightness at the corresponding wavelength. This image, when compared to the visible images of M82, dramatically illustrates how the dust extinction drastically alters our views of dusty galaxies. In this image the core of the galaxy is quite bright, but is invisible in optical images. The reddest parts of this image are most likely the regions where the dust is most opaque. Analysis of this image has suggested that M82 has a central bar-like structure that is unseen in the visible.

Figure 2 shows the images of the Brγ recombination line of neutral hydrogen in the central regions of M82. These images were taken with the Cassegrain infrared camera coupled to a Fabry-Perot in a collaborative project with S. Beckwith and T. Herbst of Cornell and the Max Plank Institute of Heidelberg. The images show the continuum radiation from the core of the galaxy (upper left), the total Brγ radiation (upper right), and images of the Brγ radiation at −100 Km/s and +100 Km/s from the mean velocity of the galaxy. Brγ emission is produced in the regions of ionized hydrogen in the galaxy, which is produced by hot young stars ionizing clouds of gas. The images show where the hot young stars are that are believed to power the infrared luminosity in M82. Most importantly, these young stars do not follow the distribution of broadband light, but appear to form a ring surrounding the core of the galaxy.

M82 in Infrared Bands
K – red, H – green, J – blue

Figure 1: A composite color image of the nearby starburst galaxy M82 in the near infrared. Blue corresponds to the J (1.27 μm) filter, Green to the H (1.65 μm) filter and Red to the K (2.2 μm) filter. This image is made from a mosaic of 11 frames at each wavelength, and covers $\sim$ 110" along the major axis of the galaxy. The bright core is invisible at optical wavelengths, and much of this image is dominated by the effects of dust extinction on the underlying galaxy.

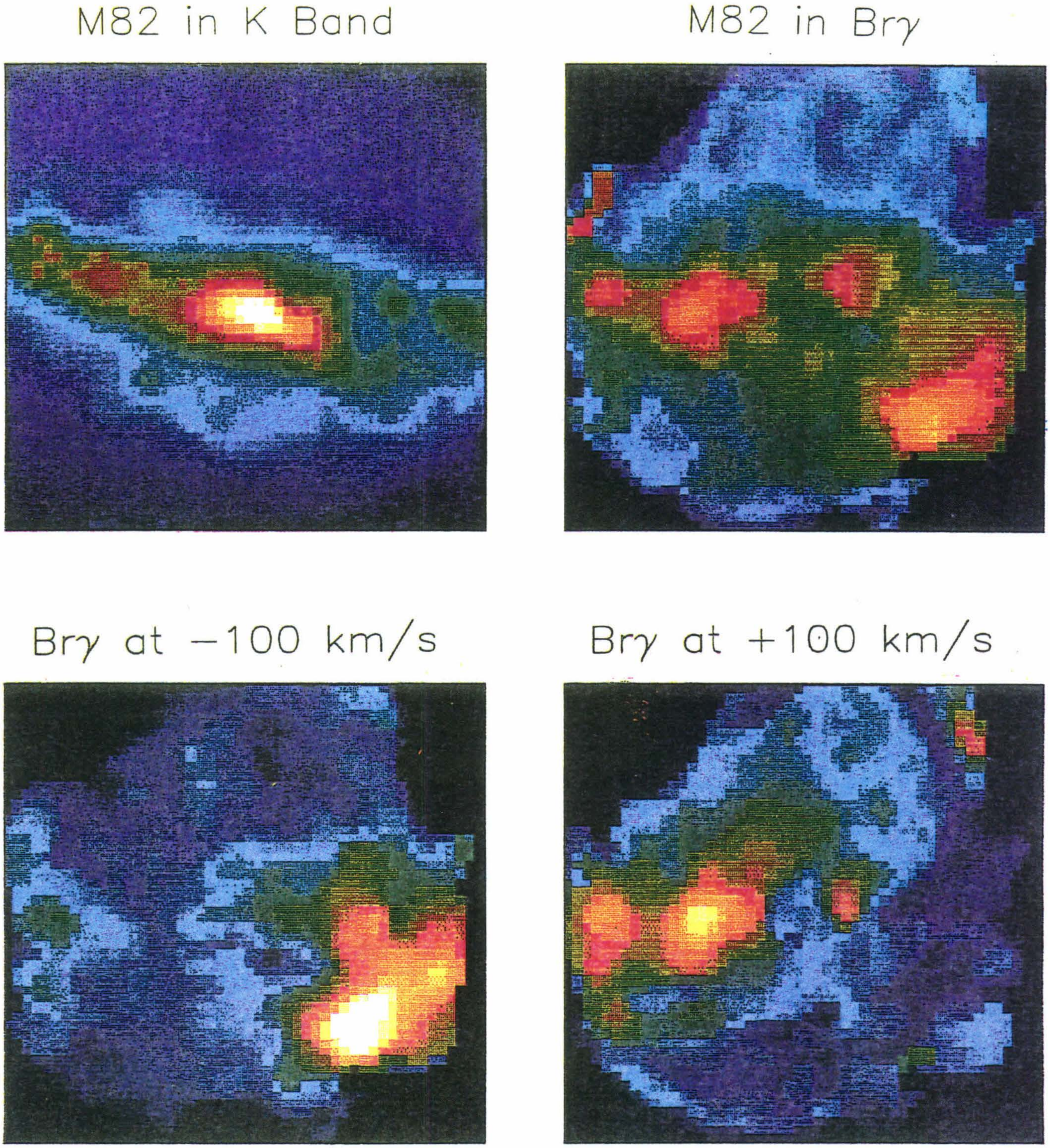

Figure 2: Four images of M82 in the near infrared. Each image is 15" square, with blue faintest and yellow/white brightest. The upper left is a 2.2 μm continuum image. The other three panels were all obtained using the Cassegrain camera in combination with the Cornell Fabry-Perot system to achieve imaging with a resolution of 90 km/sec. The line images have all been continuum subtracted. The upper right image is the total intensity of Brγ, while the lower panels show the emission at +100 km/sec and −100 km/sec from the systemic velocity of the galaxy. The major sites of current star formation are clearly seen in their Brγ emission, as is the rotation of the ionized hydrogen about the nucleus.

Near Infrared Spectroscopy of Infrared Bright Quasars and Ultraluminous Galaxies

Prinicipal Investigator: B.T. Soifer
Division of Physics, Mathematics and Astronomy
California Institute of Technology

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 left panel shows the spectrum of the infrared bright quasar Markarian 1014 plotted as flux vs. wavelength in the rest frame of the quasar. This spectrum shows the expected very strong recombination line of hydrogen at 1.87 μm. In addition, two unexpected lines appear very faintly. The line at 1.81 μm appears to arise from singly ionized iron, while the line at 1.95 μm is a combination of emission from molecular hydrogen and highly ionized Silicon. These spectral features show that there is a substantial amount of gas previously undetected within the nuclear regions of the host galaxy of this quasar. The right panel shows a similar spectrum of the IRAS discovered ultraluminous galaxy IRAS0100-22. This spectrum shows the strong hydrogen recombination line at 1.87 μm and the line at 1.95 μm that is due to some combination of molecular hydrogen and highly ionized Silicon emission. The spectrum of the IRAS discovered ultraluminous galaxy is not showing any spectral features uniquely produced in the environment of a quasar. These spectra illustrate the power of this technique in probing previously invisible regions in these dusty environments.

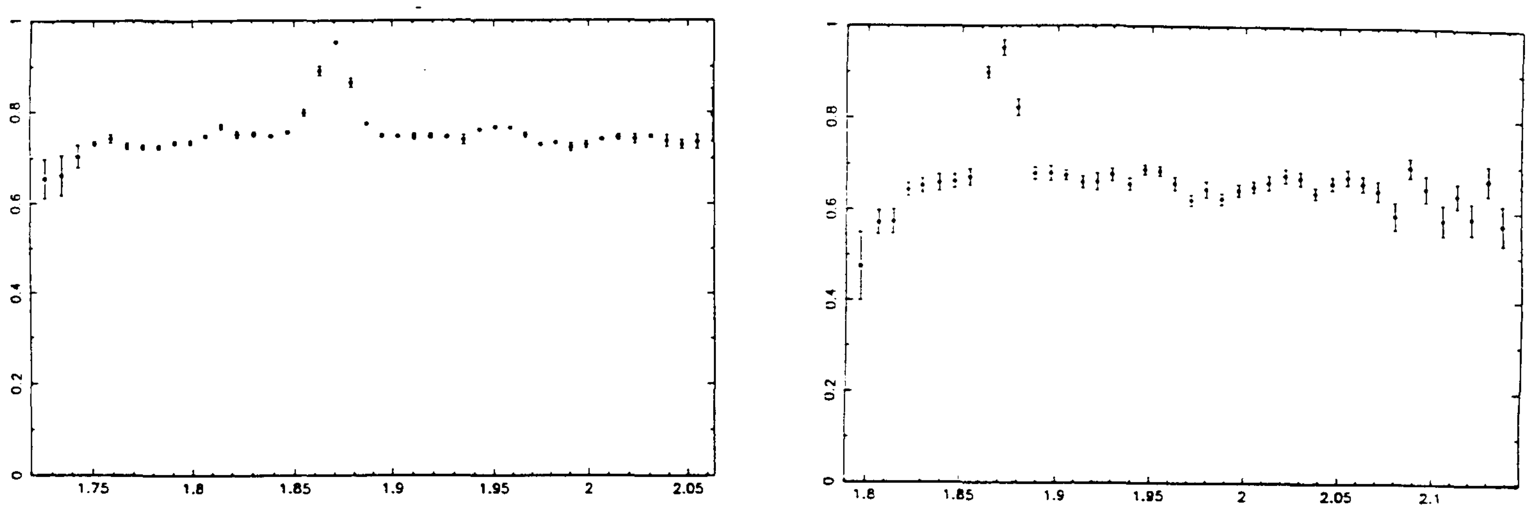

Figure 1: The near infrared spectrum of two highly luminous objects found in the IRAS all sky survey. The panel on the left is the quasar Markarian 1014, while the panel on the right is the source IRAS 0100-22. Both spectra were obtained from 2.0 – 2.4 μm using the grism in the Cassegrain Infrared Camera 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 line in both spectra is the Paschen α recombination line of hydrogen.

Rotation Curves of Spiral Galaxies in the Hercules Supercluster

Principal Investigator: Nicole Vogt
Department of Astronomy
Cornell University

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

Subject Heading: GALAXIES

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.

This program makes use of the Double Spectrograph on the Hale 5.08 meter telescope. Optical imaging of these galaxies has been performed or is planned at KPNO and MDM, and H I spectra have been obtained at Arecibo.

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Analysis of the Palomar - ST ScI Digitized Sky Survey

Principal Investigator: N. Weir
Division of Physics, Mathematics and Astronomy
California Institute of Technology
Co-Investigator: S. G. Djorgovski

Subject Heading: Galaxies and Quasars

Space Telescope Science Institute has begun producing digital scans of the nearly 3000 blue, red, and near-infrared photographic plates which will comprise the Second Palomar Observatory Sky Survey (POSS-II). These will be the highest quality sets of images covering the entire northern sky produced to date, and will almost certainly not be surpassed for at least a decade. They represent quite an investment as well as a unique resource for Caltech, as we will have access to these scans a few years before they will be available to the public at large. Their scientific value is enormous. We estimate that ultimately $> 10^7$ galaxies and $> 10^8$ stars should be detected on the POSS-II plates.

To handle this onslaught of data, we have investigated techniques for the optimal extraction of information from the digitized survey for a wide variety of scientific programs (e.g., constructing star and galaxy catalogs, performing multi-color quasar searches, etc.) The prototype system we have developed in conjunction with the JPL Artificial Intelligence Group can produce classified object catalogs from the digitized POSS-II pixel data as well as facilitate their calibration and analysis.

In order to accurately photometer (measure the true sky brightness of) and classify the objects within a set of POSS-II plates, we have conducted a program of obtaining CCD image sequences on the Palomar 60" telescope. These digital images of small portions of the plate fields are of sufficient quality to serve essentially as 'ground-truth' in establishing the plates' instrumental to standard magnitude transformations and in determining the correct classification (star, galaxy, or artifact) of objects on the plates. In the latter role, the CCD calibration data serve as training and test sets for constructing automatic object classifiers which will ultimately be applied to the full survey.

Initial results of our analysis system, SKICAT, indicate our ability to achieve very high rates of reliable object classification down to between 0.5 and 1.0 magnitude of the estimated detection limit of each plate. In comparison, previously digitized plate surveys of the southern sky achieved comparable levels of classification accuracy 1.5 magnitudes from the detection limit. As we will be measuring both more distant and intrinsically fainter objects, we expect to obtain at least twice the density of classified galaxies in our catalogs relative to those of the South. With our extensive set of CCD sequences, we will also be able to more accurately photometrically calibrate the resulting catalogs.

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