PALOMAR OBSERVATORY
CALTECH ASTROPHYSICS PREPRINT

PALOMAR OBSERVATORY

ANNUAL REPORT

1994

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

June 12, 1995

FORWARD

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.

Jim Westphal
Director

TABLE OF CONTENTS

THE SOLAR SYSTEM

High Resolution Spectroscopy of Earthshine

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

Co-Investigators: Steven Koonin (Physics), Hal Zirin (Solar Astronomy),
and Glenn Eychaner (Big Bear Solar Observatory)
California Institute of Technology

Subject Heading: Solar System

Using the Palomar 60-inch telescope in August of 1994, we have obtained the first ever (to our knowledge) spectrum of lunar "earthshine" — *i.e.*, the spectrum of sunlight reflected by the earth to the moon, which illuminates the otherwise "dark" portion of the moon facing earth. This new spectroscopic investigation was undertaken as an out-growth of a program which has been underway for roughly two years at Big Bear Solar Observatory (BBSO) to monitor the intensity and color of earthshine using CCD photometry. The photometry can be used to measure the earth's albedo — the fraction of incident sunlight striking the earth that is reflected back into space without altering the internal energy budget of the earth's atmosphere. The albedo therefore plays a large role in determining the energy balance of the earth's atmosphere and so is a crucial parameter for climate studies, but one which previously has been difficult to measure. While satellite observations provide important data on the albedo of portions of the earth, the conversion of these point observations to an integral value for the globe is not straightforward.

Measurements of earthshine, both photometric and now spectroscopic, allow us to study (with our ground-based telescopes) the global properties of the earth's atmosphere and its albedo from the vantage point of the moon. The light which illuminates the dark side of the moon — the earthshine — reaches the moon from all parts of the sunlit earth visible from the moon at the time of the observation. By accurately monitoring the intensity and color of the earthshine photometrically, Koonin, Zirin, and collaborators have begun to track seasonal and long-term variations in the earth's global albedo from BBSO. The spectroscopic investigation, which McCarthy has undertaken at Palomar, seeks to develop the capability to identify the main causes of the albedo changes (*i.e.*, whether due to changes in cloud coverage, ground cover, ice, aerosols in the earth's atmosphere, *etc.*). Furthermore, from the anomalous strengths of the lines in the spectrum of earthshine due to the earth's atmosphere, we hope to obtain *global* measures of atmospheric water vapour, carbon dioxide, and aerosol content by comparing the observed high resolution spectrum of earthshine to computer model predictions, work which is now just beginning to get underway.

The spectroscopic observations are made at Palomar Observatory using the 60-inch telescope equipped with the high resolution CCD echelle spectrograph. Nights approximately four to five days after (or before) new moon are best for this work, since the earth is then nearly "full" as seen from the moon and the lunar crescent is not so bright that it overwhelms the much fainter earthshine intensity. The set of observations necessary to determine the spectrum of earthshine includes spectra of the sunlit moon (as a reference), the earthshine (combined with the sky background) measured at the "dark" limb of the moon opposite the sunlit crescent, and finally the spectrum of the sky background just off the dark limb of the moon.

Shown below is the net result from two nights in August 1994, for the region of spectrum which includes the atmospheric A-band of O_2. The solar spectrum and the final pass through the atmosphere (from the moon to the telescope) have been removed by dividing the sky-subtracted earthshine spectrum by the reference spectrum. Note that the intensity of the earthshine is $< 0.04\%$ that of the sunlit moon, and that the overall intensity changes as a function of lunar phase (different on the two nights). While the similarity of the spectra validates our technique, they are not separated in time sufficiently to reveal changes in the earthshine spectrum; continued spectroscopic observations are planned for 1995.

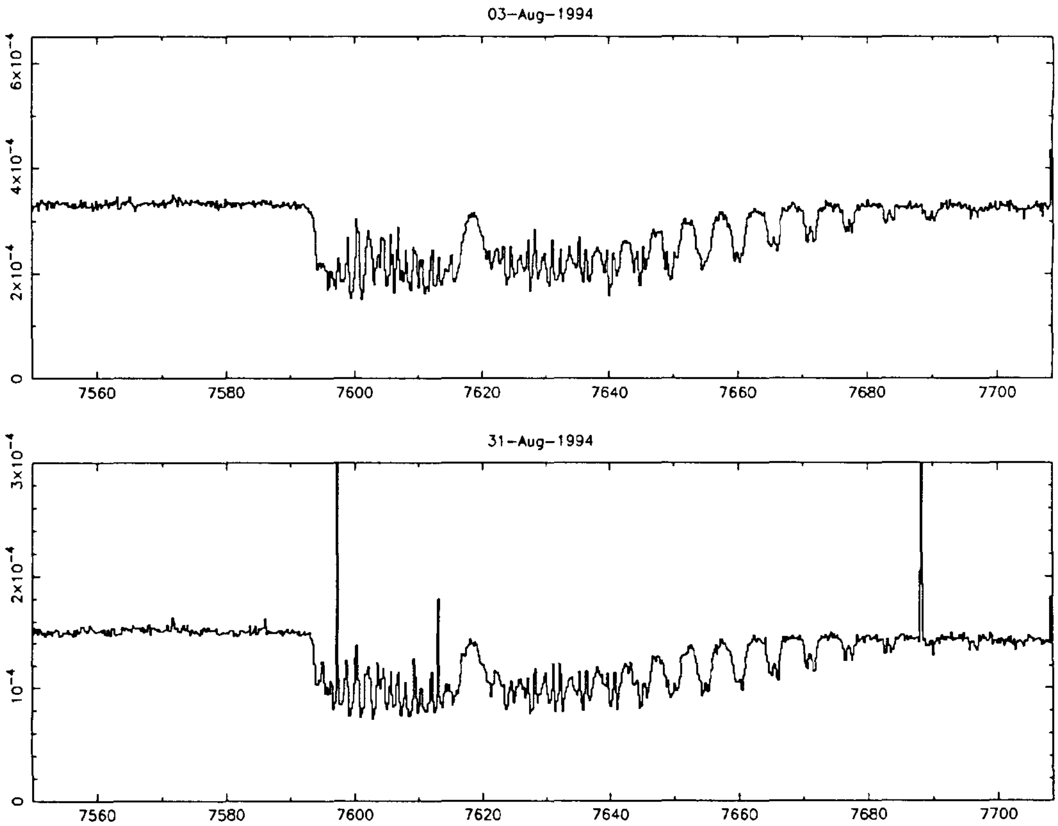


Figure 1: Spectrum of earthshine divided by sunlit moon

Observations of the Impact of Comet Shoemaker-Levy 9 with Jupiter

A. Weinberger, K. Matthews, G. Neugebauer, D. Shupe
California Institute of Technology

T. Hayward, J. Miles, J. Moersch, C. McGhee, P. Nicholson, J. VanCleve
Cornell University

Subject Heading: Solar System

The impact of Comet Shoemaker-Levy 9 with Jupiter from July 16-22, 1994 provided astronomers with a once in a lifetime opportunity to study the effects of a collision of a large body with a planetary atmosphere and to use these effects to probe the structure of the largest planet in our solar system. A full eight days of observing time was set aside for a collaboration of Caltech and Cornell astronomers to study the impacts.

Shortly after its discovery in March, 1993 at the Palomar 18-inch telescope, it was found that Comet Shoemaker-Levy 9 was broken into about 20 individual fragments. These were lettered from A to W, designating the first fragment destined to hit Jupiter as A. Of these fragments, four: B, F, R, and V were predicted to impact during times when we could observe Jupiter from Palomar. The impact sites could not be directly observed, however, from anywhere on Earth since they occurred on the back side of Jupiter, i.e behind the "limb", the border between the sides of Jupiter facing toward and away from the Earth. Fortunately, they did not occur too far behind, and in fact, any impact related event rising higher than 300 km over the visible cloud deck was directly observable from Earth.

On the 200-inch telescope, the impacts were observed with two instruments simultaneously: the mid-infrared camera SpectroCam-10 and a new near-infrared camera, D78. The advantage of infrared instruments for these measurements was three-fold. First, there are several bands of wavelengths in the infrared where methane in Jupiter's atmosphere absorbs almost all incident sunlight causing the planet to appear very dark. By observing in these bands, we maximized the contrast between the impact effects and the planet. Second, infrared measurements may be done during the day. Since Jupiter rose about four hours before sunset, this allowed us to spend much more time on the planet than if we had used optical instruments. Third, measuring two wavelengths simultaneously provides enough information to find the temperature of the events we observed.

The use of simultaneous measurements at different wavelengths has been applied particularly well to the impact of fragment R with the planet. We took pictures of the impact site every 30 seconds at 3.5 μm and every 10 seconds at 4.7 μm. The impact was characterized by three peaks in brightness: a faint one lasting only 10 seconds followed a minute later by a slightly brighter flash lasting a few minutes, and finally a huge peak which saturated the 4.7 μm detector and would have saturated the near-infrared detector had it not been for filters added to block the light. The time of the first flash corresponds closely to the time of impact as calculated from the position of the core of the site on the planet. Since the actual impact occurred behind the limb of Jupiter, this emission or reflection must come from very high in the atmosphere in order to be seen. The second peak, also seen while the impact site was not directly visible from Earth, probably results from a plume of gas heated by the comet's entry through the atmosphere which rose above the visible cloud deck of the planet. This plume of material might have risen as high as a few thousand kilometers over the visible clouds. The material in the plume probably fell back through Jupiter's atmosphere over the next ten or so minutes heating the atmosphere around it as it went. As the site itself rotated into view of Earth, we saw the remnant of the plume as a giant peak in the light curves at both wavelengths. Comparison of the 3.5 and 4.7 μm data for this time period indicates that the temperature was relatively constant, at about 500° K. Since the total brightness of this region increased over this time even though the temperature remained constant, we conclude that we were seeing a highly extended feature; the brightness levels indicate it was several thousand kilometers in size. This size is consistent with the size of a plume of gas ejected over a thousand kilometers above the visible cloud tops of the planet.

Simultaneous with the measurements at the 200-inch, the impact sites were imaged at several optical wavelengths with the CCD camera on the 60-inch telescope. These data are useful in studying the reflecting properties of the ejecta. Although the R impact occurred during the optical monitoring, no visible flashes were detected. This was expected because such an event is overwhelmed by the sunlight reflected off of the planet.

Another impact, that of fragment V, was also observed from the 200-inch. The character of this event was markedly different, however, from R. At the time of impact, a spot appeared on the limb of the planet, but it lasted for only 30 seconds. The character of this flash was similar to the precursor flashes of the R event, but in V it was not followed by a larger brighter spot. It is possible that fragment V only produced a hot peak during entry of the comet into the Jovian atmosphere, and that unlike R a plume never developed.

Work will continue on both of these events to further understand why they were so different.

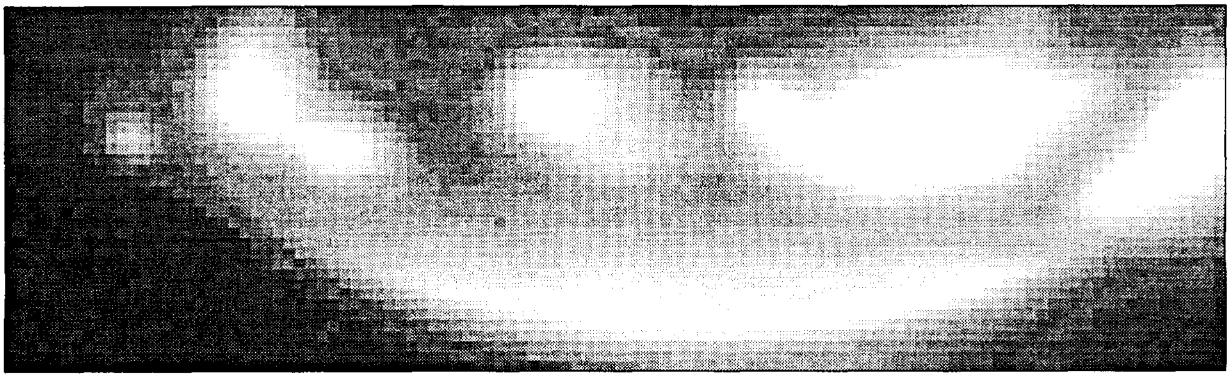


Figure Caption: A view of the South pole of Jupiter at the time of the V impact. The remnants of previous impacts are clearly visible, and, from left to right, are: V, H (which looks double), Q, R, G, and L. This picture was taken with the near-infrared camera on the 200-inch telescope at a wavelength of 2.3 μm.

PALOMAR PLANET-CROSSING ASTEROID SURVEY

Principal Investigator: Eleanor F. Helin
Division of Earth and Space Sciences
The Jet Propulsion Laboratory
California Institute of Technology

Subject Heading: Solar System

The Palomar Planet-Crossing Asteroid Survey (PCAS) is dedicated to the systematic search for asteroids and comets that cross or approach the orbit of Earth and the terrestrial planets. Using the 0.46m Schmidt telescope at Palomar, PCAS has discovered 16 Near-Earth Asteroids and many independent comet discoveries since June 1993.

This summary highlights a portion of the significant contributions that PCAS has made to planetary science in the last 16 months.

On July 4, 1994, we discovered Apollo asteroid 1994 NE moving 5.5 degrees per day in a prograde (SSE) direction. In the subsequent days, its orbital motion accelerated to over 35 degrees per day as it approached the Earth. Orbital calculations indicate that 1994 NE made its closest approach to the Earth on July 7, at a distance of 0.018 AU (1.67 million miles) or approximately 7 lunar distances. This is the closest approach to Earth of any known asteroid for the next 10 years. That "encounter" occurs with asteroid (4179) Toutatis at a distance of 0.010 AU (967,200 miles) in September 2004.

Apollo asteroid 1994 PM was discovered independently during our August run. It's an interesting object with a large eccentricity (0.74), and short period of 1.6 years. It made a close approach to Earth at 0.043 AU on August 18,1994. Orbital characteristics are strikingly cometary.

PCAS continues to add to the inventory of good mission candidates. Amor asteroid, 1994 AW1 is an excellent candidate with one of the most circular orbits among the NEAs ($e = 0.076$) and a small semi-major axis ($a = 1.1$ AU). (4660) Nereus, our PCAS discovery, is the Japanese ISAS target for an NEA sample return mission scheduled for 1998.

As well as Near-Earth Asteroids, 36 Mars-crossers and Mars-grazers have been discovered. Of particular note is 1994 JC, an unusual mars-crossing body which closely approaches the orbit of Jupiter, Q=5.1 AU. This planetary relationship suggests an unstable orbit and a short dynamical lifetime. With an H-magnitude of 14, it is a large body about 5 km in diameter. It seems likely, considering its orbital elements (a=3.4, e=0.5, i=31) that 1994 JC resides in a transitional comet-like orbit of relatively short duration. 1994 JC appears to be a degassed comet which evolved into an asteroid as a result of perturbations which brought it into the inner solar system, ultimately to become an Earth-crossing object.

Several PCAS Jupiter-family comets have been determined with orbits similar to P/Shoemaker-Levy 9, 1993e, leading to the conclusion that these types of objects are not as rare as first thought. Based upon integrations of their orbital motions, several PCAS comets have been found to have been temporarily captured by Jupiter, in the past or will be in the future (1994, Yeomans and Chodos; 1994, Yau orbital plots; 1993, Marsden; 1989, Helin and Roman).

Annual Report: 1994 Solar System Observations

Jeff Van Cleve, Phil Nicholson, and Peter Gierasch

October 28, 1994

We observed Saturn, and Titan with SC-10 during June and July, and observed Neptune with SC-10 and the Cass IR Camera in July. We also observed Jupiter in June to establish a baseline for the comet crash observations. We have been concentrating on comet crash data reduction from SC-10 runs in June, July, and August, and will present first results of that collaboration at the DPS meeting in Washington at the end of October. The Saturn and Titan data are partly reduced; highlights include 18μm mosaics of Saturn from one of the July nights, and a latitudinal profile of Saturn's 13.3 μm continuum. These Saturn results will allow us to map the tropopause temperature at a higher spatial resolution than any other telescope, except for Keck, exactly half a Saturn year after the Voyager visit, though we would like higher signal-to-noise (S/N) on the 18 μm images and better coverage of Saturn's disk with the 13.3 μm spectra.

The Neptune data showed striking atmospheric features in the near-IR, shown in the H-band image of Figure 1a. This motivated us to examine the visible and mid-IR data collected on Neptune using the collection of instruments and observers assembled at Palomar for the comet crash. We used Triton's psf to deconvolve the visible images of Neptune which we collected with the CCD at the Palomar 60″ telescope and found significant deviations from a circular disk. We also found features in C_2H_6 band images collected by SC-10 (Figure 1b), which correspond to those seen in the near-IR, though at substantially lower S/N. We also spatially resolved the C_2H_6 emission but are working on flat-fielding SC-10 hi-res spectra before deriving any result about the spatial variation of the line intensity of ethane emission on Neptune. This is the first time that Neptune has been imaged simultaneously between 0.4 and 12.5 μm .

Fig. 1.— (a) left panel: Neptune in H band, contoured in 3 σ intervals. Note prominent bright features in NE and SW of image. (b) right panel: Neptune at 11.7 μm , contoured in 3 σ intervals. A bright spot in the NE, and a bar at the S, may correspond to the H band features. We want to take images with double the S/N of this image to see if these features are real. Sky N up, E left, scale is 24 mm/arcsec for both images.

STARS

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
Stefan Jordan
University of Kiel

Subject Heading: Stars

White dwarf stars are one of the possible end stages of stellar evolution; they are electron degenerate objects which derive their luminosity from thermal cooling. A small fraction of them contain strong magnetic fields, and in a few cases the fields are enormously strong, up to a billion Gauss. The progenitors of these magnetic white dwarfs (MWD) are probably the magnetic Ap stars, which have fields thousands of times smaller, but as they shrink to become white dwarfs the magnetic flux is conserved and so the field is greatly increased. The detailed effect of the magnetic field in these stages of stellar evolution is unknown but probably important.

Our goals in studying the MWD are twofold. The first is to study the statistics of their occurence, to find their space density and test the hypothesis that they are the descendants of the magnetic Ap stars. Miss Angela Putney is working on this as one aspect of her thesis project. She wants to find the fraction of DC white dwarfs (those with a nearly continuous spectrum) which contain a magnetic field of 100,000 Gauss or more. She is doing this by measuring the degree of circular polarization in the spectrum, since the most dramatic change introduced by the magnetic field is polarization in the star's optical radiation. For this work Miss Putney is using the 5-meter Hale telescope with the double spectrograph and the polarimetry optics. She plans to observe 51 DC stars. As of July 1994 she had observed 16, of which three had a detectable field. 1994). She plans to observe the remainder of the list in the current year.

The second objective of this work is to model the magnetic field in the MWD, by studying the polarization spectra. This will form the second part of Miss Putney's thesis. In this work she is collaborating with Dr. Stefan Jordan of the University of Kiel, who has written a computer code for the radiation from the atmosphere of a magnetized white dwarf star. We have so far observed seven of these MWD with the Hale telescope, and three of them have now been fit to atmospheric models. The main results are that the use of polarization data largely eliminates the ambiguities that arise when the models are fit to the flux data only, and that reasonable fits can be obtained only when the magnetic field is more complicated than that due to a centered dipole. This work is now being prepared for publication.

Stellar Identification of the Soft Gamma-ray Repeater SGR 1806−20

S.R. Kulkarni, K. Matthews, G. Neugebauer, I.N. Reid,
M.H. van Kerkwijk and G. Vasisht

Palomar Observatory and California Institute of Technology

Subject Heading: Stars

The soft γ-ray repeaters (SGRs) undergo intense γ-ray flashes (which last for a fraction of a second) repetitively on timescales varying from minutes to years. This behavior distinguishes them from the classical γ-ray bursters which have no evidence for recurrent bursting. Ever since the early days of their discovery, a great aura has surrounded these outbursts, especially the famous single March 5, 1979 burst which was localized to lie within the confines of a bright young Large Magellenic Cloud supernova remnant called N49. If this event was due to a young neutron star within N49, then there was a release of a stupendous 10^{45} ergs of unexplained energy, brighter than the steady emission of a few galaxies put together.

SGRs are uncommon and far away in the Galaxy, which makes them hard to study. So far, attempts to understand them have relied on their high energy emission, because the confining error circles on the sky are crude and thus counterparts at other wavelengths were not known. Last year, Kulkarni and Frail suggested in a Nature publication that SGR 1806−20, the most prolific SGR with over a hundred known bursts, was associated with the radio supernova remnant (SNR) G 10.0−0.3. Subsequent studies in the radio and X-ray have confirmed this hypothesis, especially the observations by the X-ray satellite ASCA which serendipitously detected a hard X-ray burst emanating from the bright central "core" of G 10.0−0.3. ASCA also discovered a quiescent X-ray counterpart to the SGR.

The mechanism causing the tremendous amounts of energy released during a SGR burst is a mystery. Binary models, specifically models appealing to accretion from a companion onto a neutron star, have considerable appeal on grounds of energetics. With the help of a good localization, the binary hypothesis can be tested with searches for an optical counterpart. We have conducted such a search at Palomar, using a sub-arcsecond position determined for 1806−20 from radio studies.

We carried out a series of observations of SGR 1806−20 at the Palomar 60-inch and 200-inch telescopes. Imaging was done at various optical and infrared bands. Careful astrometry of the data revealed a highly reddened star at the position of the SGR ($A_V \sim 30$ mag). This is the star marked "A" in Figure 1. Grism spectra of star A at K-band help us put constraints on its spectral nature: from the lack of molecular bands in the spectrum we conclude that its spectral type must be an earlier than late G. The high extinction of star A inferred from our data is well accounted for by a Giant Molecular Cloud in this direction at a distance of 6 kpc. In fact, a similar extinction is determined for the SGR from X-ray data, lending support to the idea that both objects are at similar distances. Using this as a minimum distance the absolute K magnitude of the star is restricted to < -8.5 mag, i.e., the star must be a supergiant or even a hypergiant. Given the typical stellar population encountered towards this direction in the galaxy, the probability of chance coincidence of a hot supergiant star with SGR 1806−20 is exceedingly small, $\sim 2 \times 10^{-5}$.

From the good positional coincidence, the consistency of the reddening estimates, and the probability estimates, we conclude that star A is a very good candidate for being the stellar counterpart of SGR 1806−20. Purely on phenomenological grounds, further investigations of this star are warranted. (These are, in fact, being undertaken.) The underlying physical mechanism of SGRs is still an open question, however, although our observations certainly have strengthened the idea that these sources may be a special class of binary systems. Moreover, they have led to the first optical identification of a high-energy transient. A paper about these results has been submitted to Astrophysical Journal (Letters).

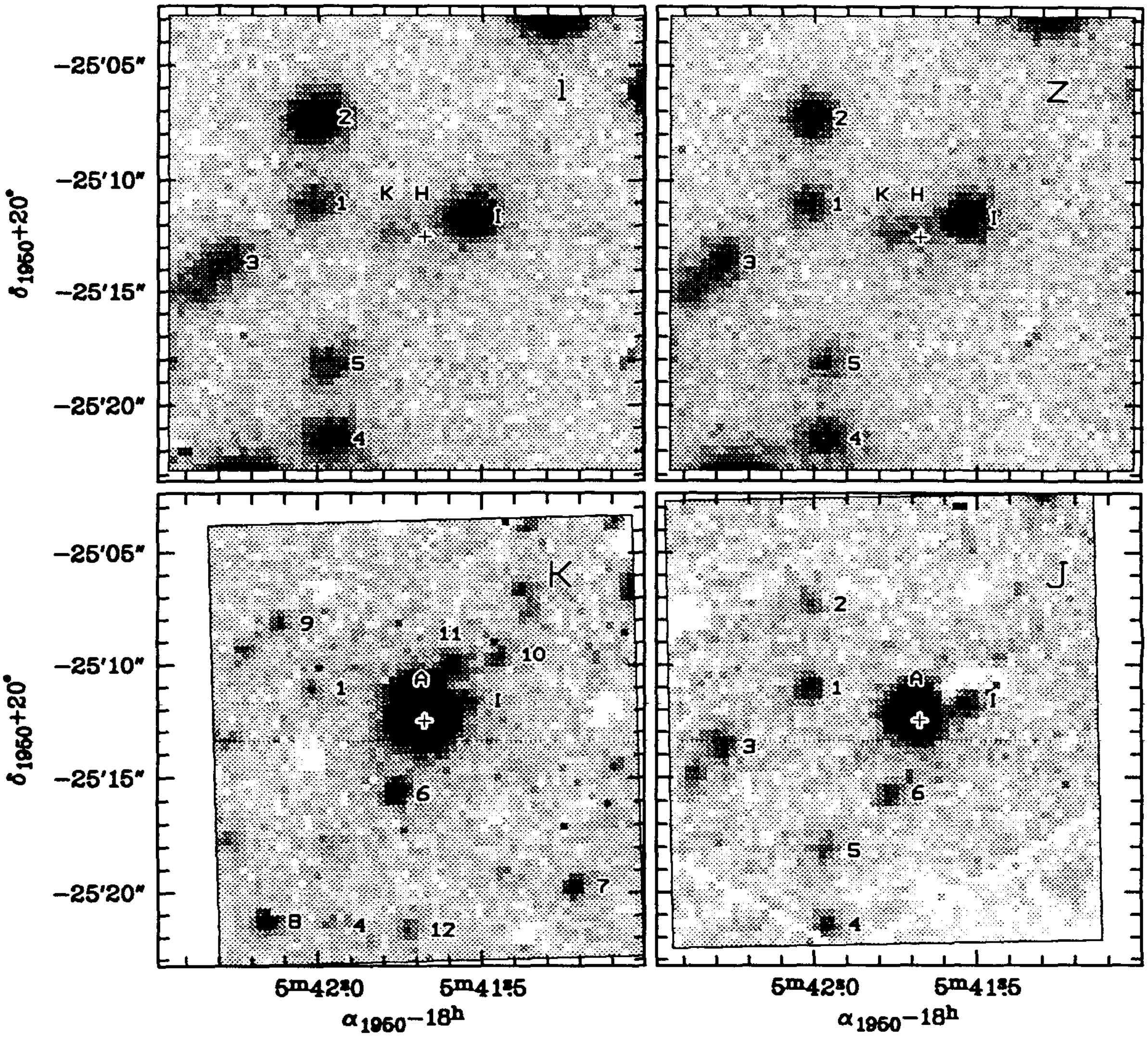


Figure 1. Optical (Gunn i and z) and infrared (J and K bands) images of the field surrounding SGR 1806−20. The position of the radio counterpart as determined from high-resolution VLA observations is indicated with a cross. Stars for which positions were determined are indicated with a number or character to the right or over the stellar image. Star A, a highly reddened supergiant star is the possible counterpart to the SGR 1806−20.

Optical and Infrared Observations of SGR 1900+14

S.R. Kulkarni, M.H. van Kerkwijk and G. Vasisht

Palomar Observatory and California Institute of Technology

Subject Heading: Stars

Soft γ-ray repeaters (SGRs) are high energy transients that have distinct spectral and temporal properties compared to the classical γ-ray bursters (refer to the report titled "Stellar Identification of the Soft Gamma-ray Repeater SGR 1806−20" in this volume). Of the three known repeaters, two are associated with young supernova remnants, the by-products of death throes of massive stars. Apart from this fact, which seems to indicate they may have something to do with young neutron stars, their nature is shrouded in mystery. This motivated us to look for a supernova remnant association for SGR 1900+14, the third and only other known SGR.

SGR 1900+14 is localized within an elongated error box of $11^\circ \times 10'$, located in the first quadrant of our galaxy. This large error box is known as the KONUS error box. We did an exhaustive multi-wavelength search for a supernova remnant counterpart to SGR 1900+14 in the KONUS error box. In our search, we identified two remnants, G 43.9+1.6 and G 42.8+0.6, within or overlapping the KONUS error box. G 43.9+1.6 appeared especially interesting because it was classified as a "plerion", a pulsar powered nebula, in the Green Catalogue of supernova remnants. The remnant has the morphology reminiscent of a fast moving neutron star overtaking the shocks from the initial supernova. However, on careful inspection it was realized that this structural peculiarity was unpolarized and probably due to a line-of-sight H II region. We obtained images of this region from Palomar, in the Hα band, to ascertain if this really was an H II region, but were only able to put upper limits on Hα emission.

In the meantime, a revised and smaller Inter Planetary Network (IPN) localization was published by Hurley and collaborators. This position excluded G 43.9+1.6, but was close to the other remnant, G 42.8+0.6. We did wide field radio observations from the Very Large Array of this region, which were moderately sensitive. These did not reveal any obvious radio counterparts to SGR 1900+14. However, on searching the ROSAT sky-survey database, we were able to locate a number of X-ray point sources in the vicinity of the IPN error box. One source, RX J190717+0919.3, lies at the edge of the IPN diamond, close to G 42.8+0.6. In a publication in the Astrophysical Journal immediately after the discovery of the X-ray source, we proposed that RX J190717+0919.3 was the X-ray counterpart of SGR 1900+14, a fast moving neutron star which had now overtaken its parent SNR G 42.8+0.6.

We also took images from the 200″ at Palomar, to look for an optical counterpart to the ROSAT source. At the same time, Hurley et al. were pursuing the ROSAT source as well, and they obtained both optical and infrared images. They found that there were two stars in the ROSAT error box that were peculiar because of their brightness in the infrared. We decided to combine force, and in August we obtained spectra of these two stars with the Double Spectrograph at the 200". It turned out that both stars were M stars. Although the analysis is not yet complete, it seems likely at this point that these stars are the source of the X-ray emission seen with ROSAT, even though it is not quite clear how stars with a dense, slow wind (as inferred from the large infrared excess) could produce X-rays. (Also, it is interesting that two such star are present in the ROSAT error box: given the paucity of similar stars in the surrounding field, they might be physically associated.) In any case, it seems very unlikely that they are associated with SGR 1900+14.

A Coronagraphic Search for Brown Dwarfs

Principal Investigator: Tadashi Nakajima
Division of Physics, Mathematics and Astronomy
California Institute of Technology

Co-Investigators: Shrinivas R. Kulkarni, California Institute of Technology
David A. Golimowski, Johns Hopkins University

Subject Heading: Stars

Stellar coronagraphy is a technique used to image the vicinity of a bright star with high sensitivity to faint objects in the region. The technique involves occulting the bright star with a small mask at the focal plane of the telecsope and using a second "apodizing" mask to reduce the light of the star that is scattered and diffracted by the telescope optics. Successful coronagraphic imaging requires that the star be centered on the mask, which is only one two a few arcseconds in diameter. Basic adaptive optics can vastly improve the image quality. This basic adaptive optics is simply an image stabilizer that senses the motion of the image of a star caused by atmospheric effects. The motion is sensed every ten milliseconds and corrected by and actively controlled tip-tilt mirror. The Johns Hopkins University Adaptive Optics Coronagraph (AOC) is an innovative instrument that improves the performance of its coronagraph with the basic adaptive optics described above.

Using the AOC, we have searched for brown dwarfs around nearby stars. A brown dwarf is a star that is not massive enough to ignite the hydrogen fusion reaction in its core. However, brown dwarfs are still luminous, mostly in the infrared region, since the contraction of the star releases its gravitational energy. Only a limited number of brown dwarf candidates are known, perhaps because they are very faint, perhaps because brown dwarfs are inherently rare, or perhaps because of a combination of these two reasons. To identify a brown dwarf, its absolute luminosity must be known. Since nearby stars have well determined distances, a faint companion of such a nearby star will have a well determined distance and absolute luminosity. It is expected that a brown dwarf orbiting a nearby star will be fainter than the star by four orders of magnitude at 0.8μm, the wavelength of our search. The AOC is capable of finding such a companion, and even one as faint as five orders of magnitude less luminous than the parent star at an angular separation of 4 arcseconds.

We have searched around fifty-seven nearby stars and detected 38 stellar objects. Based on a color-magnitude diagram, which provides information relating the temperature and expected luminosity of each object, we have classified two of these objects as new very-low-mass stars ($M < 0.1\ M_\odot$), two as brown dwarf candidates ($0.07M_\odot < M < 0.08M_\odot$), and one as a white dwarf candidate. A very-low-mass companion star found only 3.5 arcseconds from the main star is shown in Figure 1. The rest of the 31 objects are likely to be background field stars. A brown dwarf candidate becomes a definite brown dwarf when its companionship to the main star is proven. A nearby star moves quickly (on the order of 0.5" per year), and its motion relative to fixed distant stars can be measured in a few years. If the candidate moves with the main star, it is assumed to be a true candidate orbiting the main star. Thus, the distance and luminosity of the companion are confirmed. We plan to apply this space motion test to the candidates we have found.

Our results appear in a series of two papers (Nakajima *et al.*, 1994a, and Nakajima *et al.* 1994b).

Nakajima, T., Durrance, S. T., Golimowski, D. A., & Kulkarni, S. R. 1994a, ApJ, **428**, 797.
Nakajima, T., Golimowski, D. A., & Kulkarni, S. R. 1994b, ApJ, submitted.

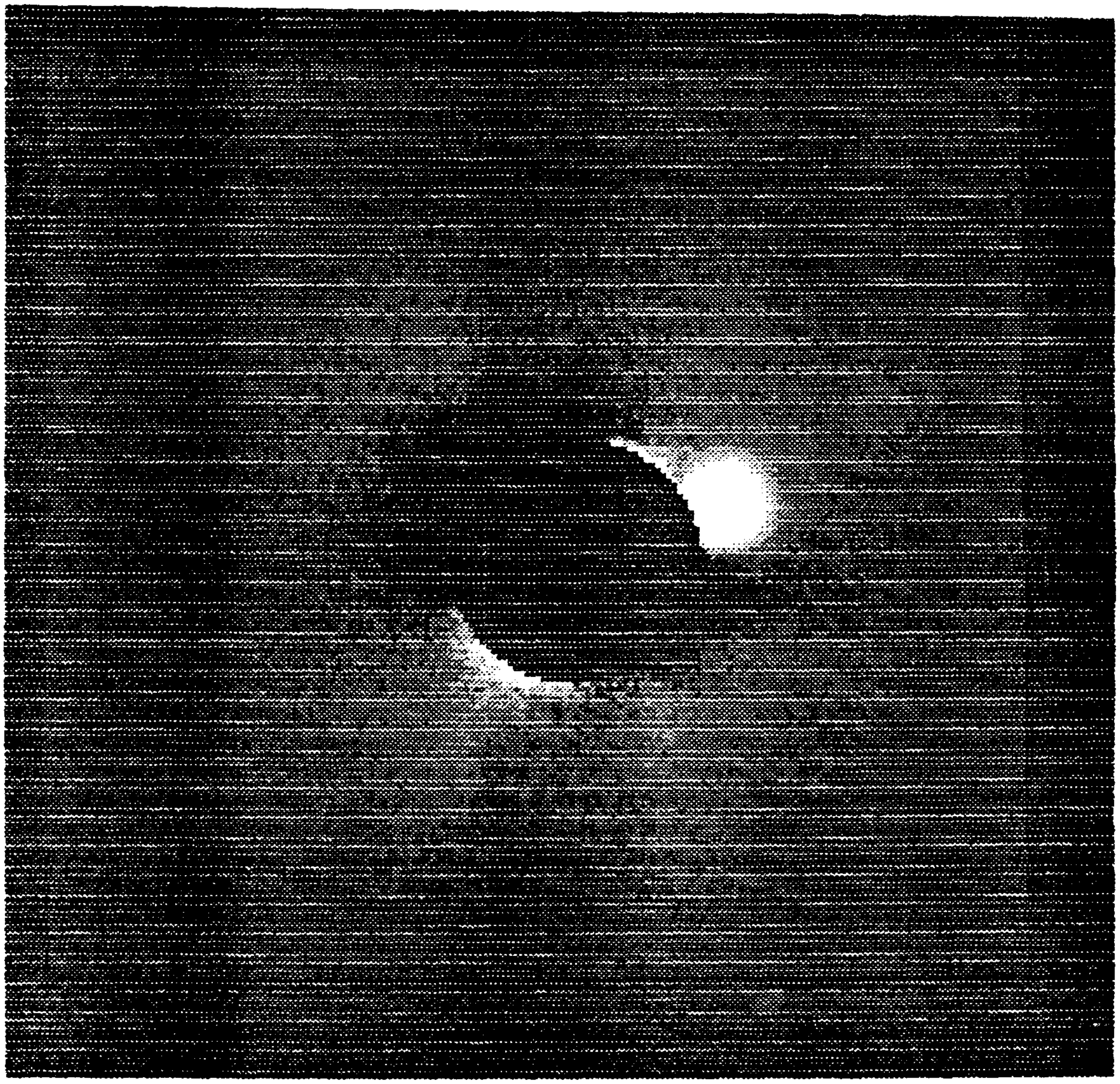


Figure 1. A very-low-mass companion star was found only 3.5 arcseconds of a bright star, GL105A. The bright primary star is masked by the dark disk. The companion star is barely massive enough to ingnite internal hydrogen fusion reaction. The brightness ratio between the primary and the companion is 10^4:1.

Coronagraphic imaging of young stars

Principal Investigator: Tadashi Nakajima
Division of Physics Mathematics and Astronomy
California Institute of Technology

Coinvestigator: David A. Golimowski, Johns Hopkins University

Subject Heading: Stars

We have been studying the environment of T Tauri stars. A T Tauri star is a newly-born sun, which is often surrounded by left-over dust material from the parental cloud. In most cases, the dust material is gradually blown away to distance by a strong solar wind of the young sun. However, in some cases it is suspected that the dust material may be fed into inner circumstellar disks where planets may be formed in the future. In understanding the fate of the dust material that is thought to be the remnant of star formation, we need to know the detailed morphology of the faint dust nebula reflecting the light from the young sun, using a special observing technique.

Stellar coronagraphy is a technique to occult a bright star by a small mask at the focal plane of the telescope with a special care to reduce scattered light by the telescope optics, and to image the vicinity of the star with high dynamic range. This technique permitted to obtain detail morphology of the reflection nebulae around seven young stellar objects (YSOs).

One of the most important discoveries of this study is that YSOs with reflection nebulae are strong far-infrared emitters without exception. Further more, far-infrared emission and the reflection nebulae can be cospatial in some cases. This implies that the dust nebulae are often directly shine by the star light and a part of the light is reflected by the dust and the rest is absorbed and reemitted in the far infrared. The energy budget argument suggests that the either optically thin dust nebula or the surface of an optically thick nebula can explain the cospatiality.

According to the newly obtained morphological information, the dust nebulae of T Tau, Z CMa, and DG Tau, may be feeding the inner star/disk systems, while the detached nebula of FU Ori is unlikely feeding the star. We have found a spectacular cometary nebula around SU Aur, which is shown in Figure 1.

Our results are written in a paper submitted to the *Astronomical Journal.*

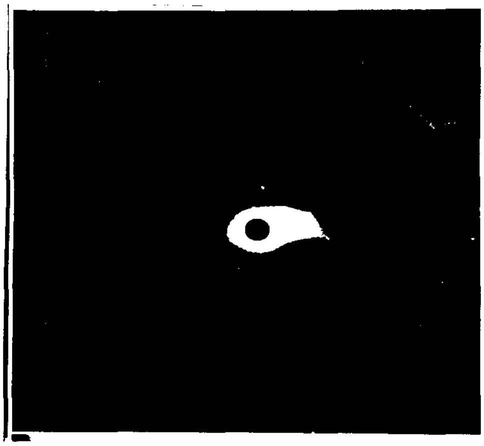


Figure 1. Reflection nebula around a young stellar object, SU Aur. The length of the cometary nebula is about 1000 AU.

The reddest stars - brown dwarfs in masquerade?

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

Co-investigator : J. R. Mould
Mount Stromlo and Siding Spring Observatory
Co-investigator : C. G. Tinney
European Southern Observatory

Subject Heading : Stars

The search for 'dark matter' has been part of astronomy since Jan Oort's discovery in the 1920s of an apparent discrepancy between the amount of mass directly observable in the Galactic disk and the gravitational field deduced from the motions of stars at large distances above the Galactic Plane. The search intensified in the 1970s and 80s, when observations of spiral galaxies showed that material at large radii is rotating significantly faster than predicted, implying the existence of a spheroidal, dark halo. In order to explain the 'invisible' nature of these heavy halos, we require material which has a mass-to-light ratio (in solar units) of at least 300. The two most obvious candidates for this dark matter are low-mass stars, with masses of $\sim 0.1 M_{\odot}$ and luminosities of $\sim 0.001 L_{\odot}$, and the even lower-mass brown dwarfs - objects with masses less than $0.08 M_{\odot}$ (80 Jupiter masses), which fail to ignited hydrogen fusion in the core and, as a result, fade into oblivion on the (astronomically) relatively short timescales of $\sim$ 100 million years.

Neither hypothesis, however, is free from problems. Recent observations, particularly the extensive survey by C. Tinney (CIT Ph. D., 1993), have shown that there are insufficient low-mass stars to make any significant contribution to the missing-mass problem - at least within the disk of our Galaxy. Recently, however, there have been suggestions that the reddest (i.e. the coolest) M-dwarfs are not, in fact, main-sequence stars, but are actually brown dwarfs. If this were the case, the picture changes completely - since brown dwarfs have such short visible lifetimes, the few objects that are known would be the tip of a very substantial iceberg, each representing at least 100 older, dimmer compatriots.

Given spectroscopic information, there are a number of techniques which can be used to attempt to distinguish between main-sequence stars and sub-stellar mass brown dwarfs, and we have been applying these methods to analysing 200-inch double-spectrograph observations of a very low-luminosity M-dwarf (VLM) sample (including half of the stars known to have luminosities $< 0.001 L_{\odot}$). First, one can apply the lithium test - lithium burns at a temperature of $\sim 3 \times 10^6$ degrees, well below the temperature required for the ignition of hydrogen fusion. Since low-mass stars are fully convective, all of the stellar material is passed through the stellar interior in a matter of a few million years. Hence, if the star is burning hydrogen on the main-sequence ($M \geq 0.08 M_{\odot}$), all of the primordial lithium (originating in the Big Bang) will be consumed in less than 10 million years. Brown dwarfs - or, at least, brown dwarfs less massive than 0.065 $M_{\odot}$ - fail to achieve such high interior temperatures and, as a result, lithium survives at, or near, the primordial abundance. Li I is also considerate enough to have a transition which produces an absorption feature at 6707 Å - a readily accessible wavelength. This line is clearly present in young, late-type T Tauri stars, but not amongst the unequivocally H-burning M5 or M6 dwarfs.

None of the stars amongst our sample show any lithium absorption - nor, indeed, do any other brown dwarf candidates observed elsewhere, not the highly unusual star PC0025 (fig. A), one of the three coolest M-dwarfs known. However, these observations are not conclusive, since there is a small niche in mass - from 0.065 to 0.08 $M_{\odot}$ - where brown dwarfs achieve interior temperatures high enough to incinerate lithium. Clearly, placing all of the observed objects in the narrow range involves some form of special pleading, but since these higher-mass objects also have longer visible lifetimes, one does not require a total suspension of disbelief.

An alternative method of probing the nature of the low-luminosity, late-type M-dwarfs is to examine their statistical properties - specifically, their space motions. As stars(brown dwarfs) circle the Galaxy, they encounter massive objects such as molecular clouds which perturb the stellar orbits. Hence, the overall velocity dispersion of coeval objects increases with time. Solar generation stars, age $\sim 4\times10^9$ years or half the age of the Disk, have an overall velocity dispersion of $\sim 54kms^{-1}$. Young brown dwarfs, on the other hand, should have a significantly lower dispersion - $< 20kms^{-1}$, consistent with an age of $< 10^8$ years. If we consider the full sample of VLM dwarfs, the velocity dispersion is $41kms^{-1}$ - but if we exclude all stars identified through proper motion surveys (i.e. by transverse velocity, a possible source of bias), the dispersion falls to $23kms^{-1}$. The problem is that the sample size also falls - to only ten stars.

Thus, neither our nor any other observations have succeeded in providing unambiguous evidence for the existence of sub-stellar mass, brown dwarfs (apart, of course, from the gas giants in the solar system). However, the statistical properties of the small sample of known VLM dwarfs are intriguing enough to merit further study once sufficient new stars have been found.

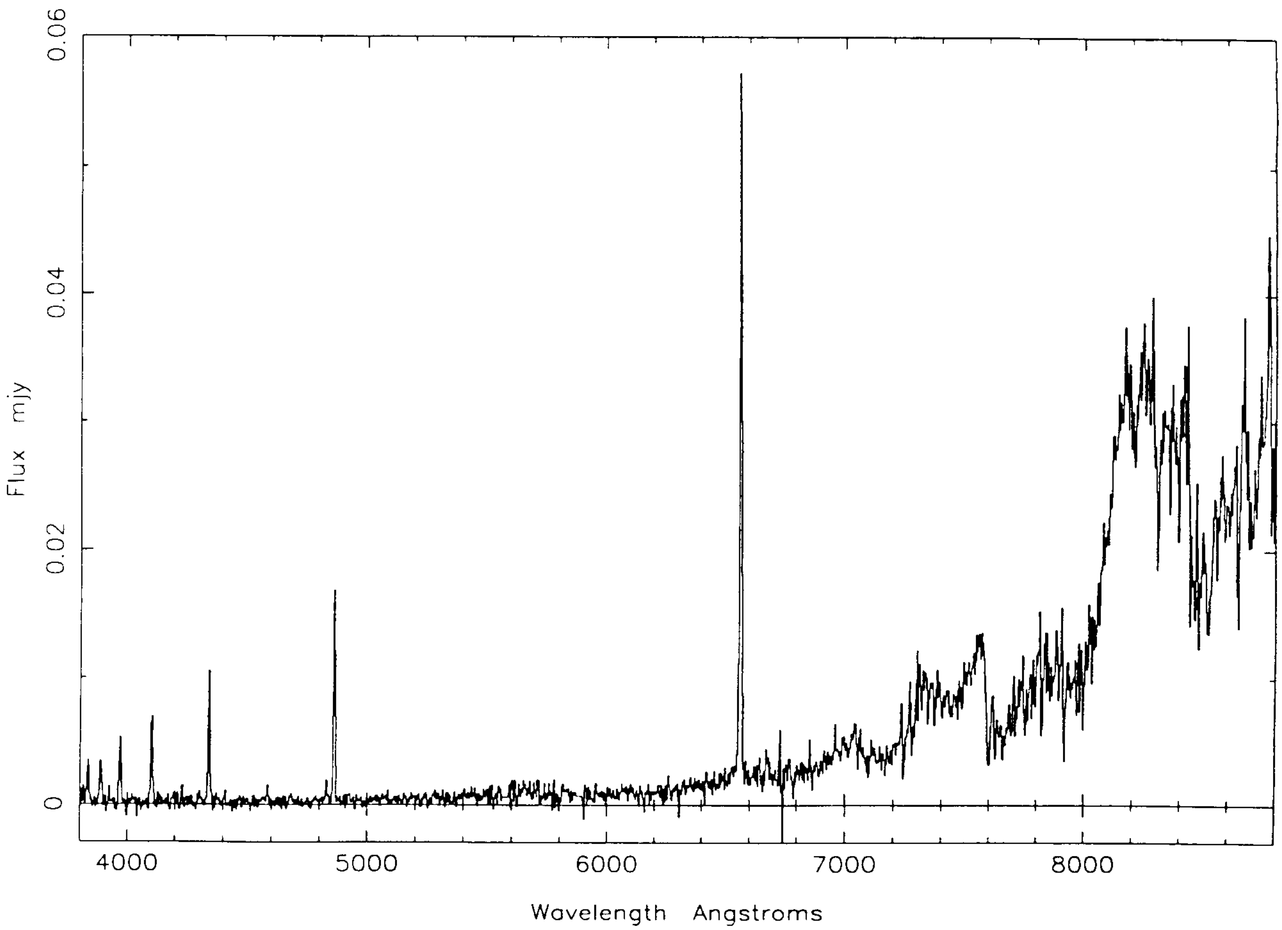


Figure A1: Keck LRIS spectrum of PC0025. The strong hydrogen emission lines show that this very cool star has an extremely active chromosphere.

A Spectroscopic Survey of the Solar Neighbourhood

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

Co-investigator : J. Gizis
California Institute of Technology
Co-investigator : S. L. Hawley
Michigan State University

Subject Heading : Stars

M dwarfs are defined as those main-sequence stars which are cool enough to exhibit the absorption bands due to the molecule TiO, with the bandstrength increasing from early (M0) to later (M5, M6..) spectral types as the surface temperature decreases. This classification corresponds to stars with luminosities less than $\sim 0.1L_{\odot}$, temperatures less than $\sim$ 4000 K and masses less than $\sim 0.65M_{\odot}$, and encompasses over 80 % of the stars in the Galaxy. These stars have main-sequence, hydrogen-burning lifetimes longer than a Hubble time - thus, a local sample includes stars spanning all ages since the formation of the Galactic disk. Moreover, these stars are subject to chromospheric activity (as evidenced by $H\alpha$ emission) which decays relatively rapidly with time, allowing the possibility of segregating a sample into different age groups. Hence, these stars have considerable potential as probes of important parameters in Galactic structure, such as the form of the velocity dispersion in the Galactic disk and its variation with time; the density law perpendicular to the Plane; and perhaps even the differential rate of star formation over the last 1-2 Gigayears.

In order to study these quantities, we require a large, well-defined sample of stars that is also close enough to allow the measurement of accurate radial velocities, proper motions (tangential velocities) and distances. Such a sample exists in the form of the third catalogue of nearby stars (CNS3), compiled by Jahreiss and Gliese (Heidelberg Univ.), including some 3800 stars, 2200 of which are classified as type M. However, this catalogue is simply a compilation from the literature of objects identified, however tenuously, as being within 25 parsecs of the Sun. As a result, the catalogue is extremely heterogeneous with, in particular, the incompleteness increasing with decreasing intrinsic stellar luminosity, and with many stars lacking basic quantitative information.

Nonetheless, this catalogue offers a starting point for our investigations. In order to remedy the defects and allow us to construct a well-defined sample, we have been obtaining spectroscopy of all accessible potential M-dwarfs in the sample. The latter subset includes not only those stars designated as type M, but also all stars listed with $M_v > +8$ which are not identified explicitly as white dwarf degenerates. One hundred of these stars are close companions of brighter primaries and cannot be observed directly. We have divided the resultant sample of 2100 stars into two declination zones, with stars south of -30^o being observed from Cerro Tololo Interamerican Observatory, and the remaining stars from Palomar. This division also reflects astronomical history - northern hemisphere observatories have been operating longer and, as a result, the most detailed proper motion surveys (in particular, Luyten's Oschin Schmidt surveys) cover the regions of the celestial sphere accessible from the north. The imbalance in the contribution to the CNS3 is obvious - while there are 613 stars listed north of $\delta = 30^o$, there are only 351 stars in the corresponding south polar region. For this reason, it is statistically (as well as observationally) convenient to limit analysis to the northern sample.

Most of our observations have been obtained using McCarthy's spectrograph mounted on the Palomar 60-inch telescope, although approximately 100 stars are fainter than 16th magnitude and have been observed using the double spectrograph on the Hale 200-inch. In both cases, our data cover the red part of the spectrum, $\lambda\lambda 6200-7400$ at a resolution of $\sim 1\AA$, including several important features

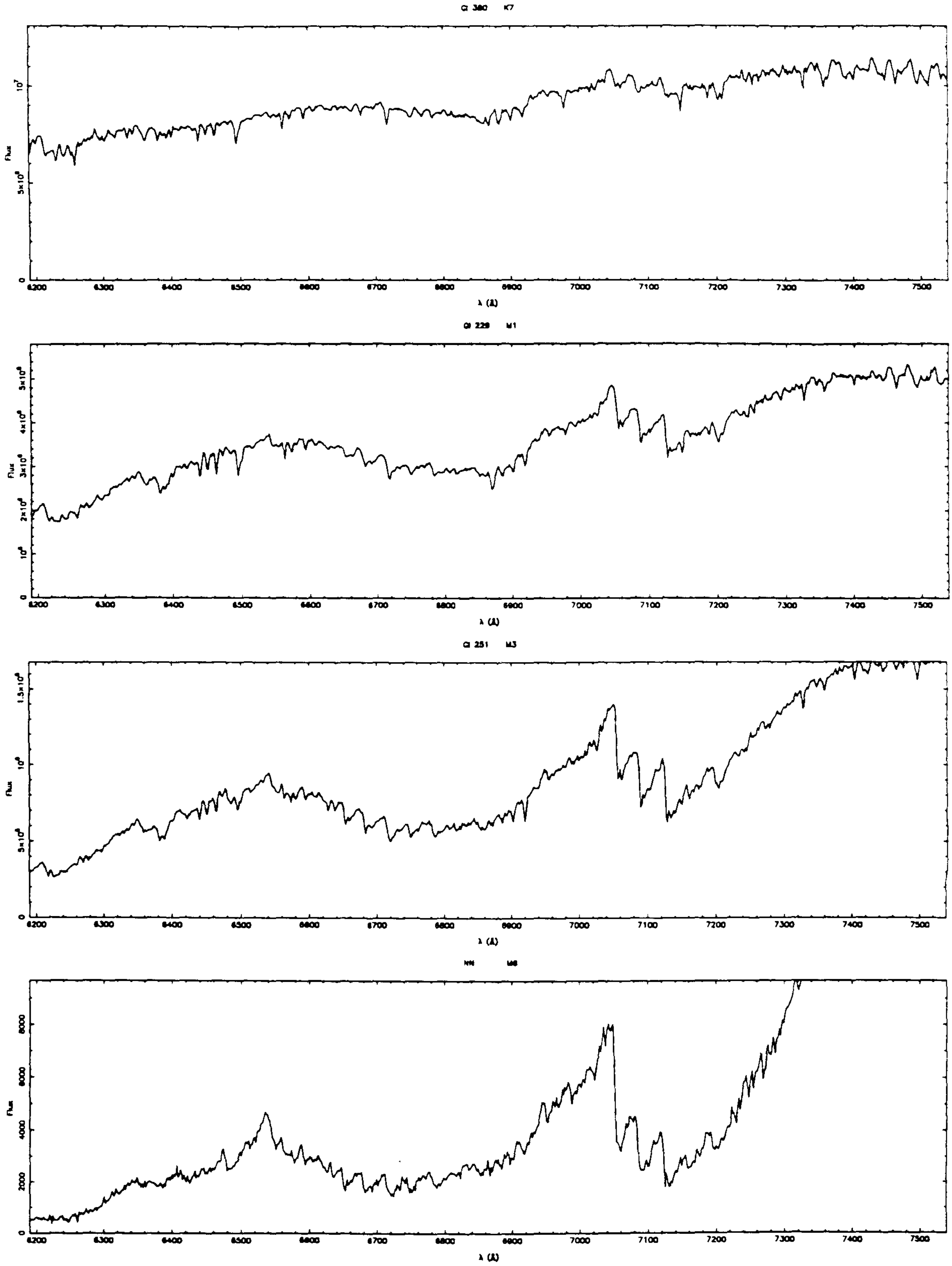


Figure B1: Spectra of red dwarfs - note the increasing strength of the TiO bands at λλ 6550-6750 and λλ 7050-7150 Å as the temperature decreases from ~ 4200° (K7) to ~ 2800° (M6).

(figure B1). First, the TiO bands at $\lambda 7100$, which increase in strength with decreasing temperature, can be used to estimate luminosity, and hence distance, for stars lacking direct trigonometric parallax measurements. Second, our spectra include the Balmer line, $H\alpha$, allowing us to identify the fraction of stars showing emission as a function of spectral type (figure B2). Finally, our data cover CaH bands at ~ 6400 and $\sim 6900\AA$, features which are strongest in metal-poor stars, allowing us to identify any halo subdwarfs in the sample (figure B3).

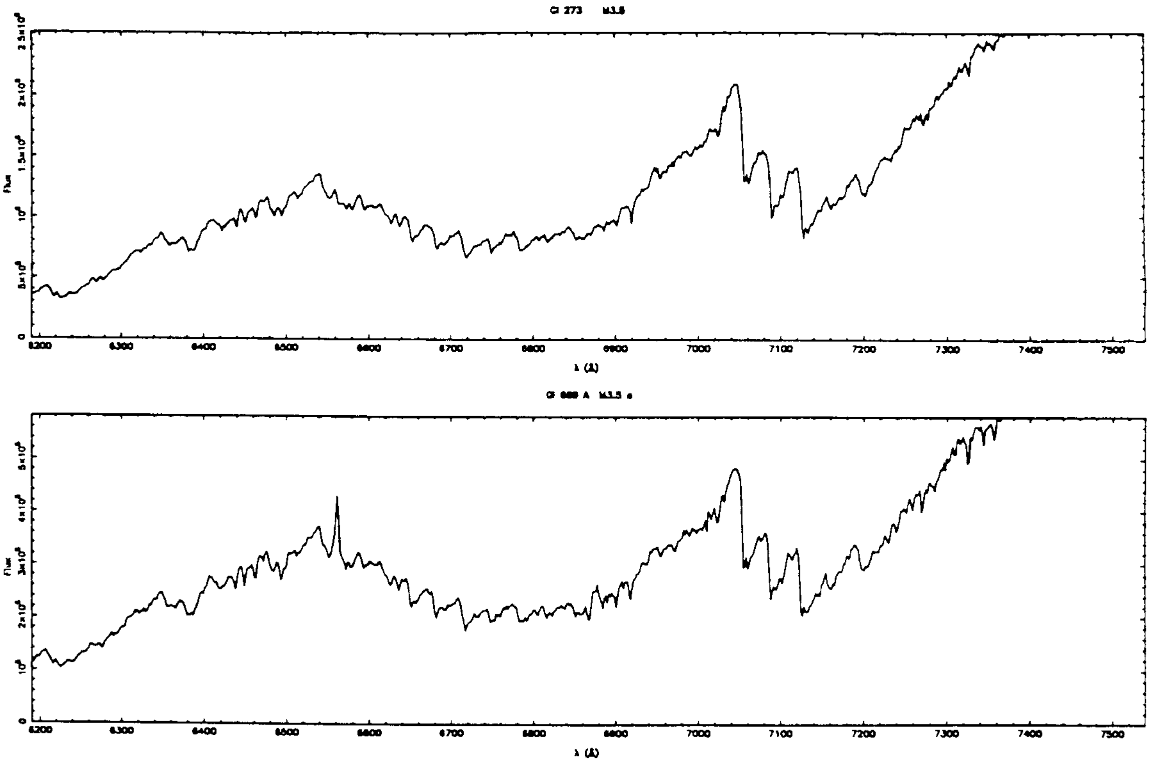


Figure B2: Spectra of two red dwarfs of similar temperature. The emission spike at $\lambda 6563$ in the lower star, Gl 669A, is due to hydrogen.

Our analysis of the survey has only started (the final observations were obtained in mid-October, 1994), but the preliminary work shows some interesting results. First, it is clear that while the fraction of stars showing $H\alpha$ emission increases with later spectral type, there are inactive stars even amongst the coolest stars. This is contrary to standard wisdom. Second, the velocities, accurate to $\sim 10 kms^{-1}$, derived from our relatively low-resolution data show that the Galactic disk includes a significant number of relatively high velocity stars (space motions of $100 kms^{-1}$ or more). These are not halo subdwarfs (there are only 2 in our sample) - again, there are more of these high-velocity stars, presumably the oldest stars in the disk, than the standard picture would predict. In the near future, besides completing our analysis of these data, we will obtain echelle observations of a smaller, volume-complete sub-sample of $\sim$ 600 stars, investigating the space motions, chromospheric activity and abundance distribution in the greater detail permitted by these higher-resolution observations.

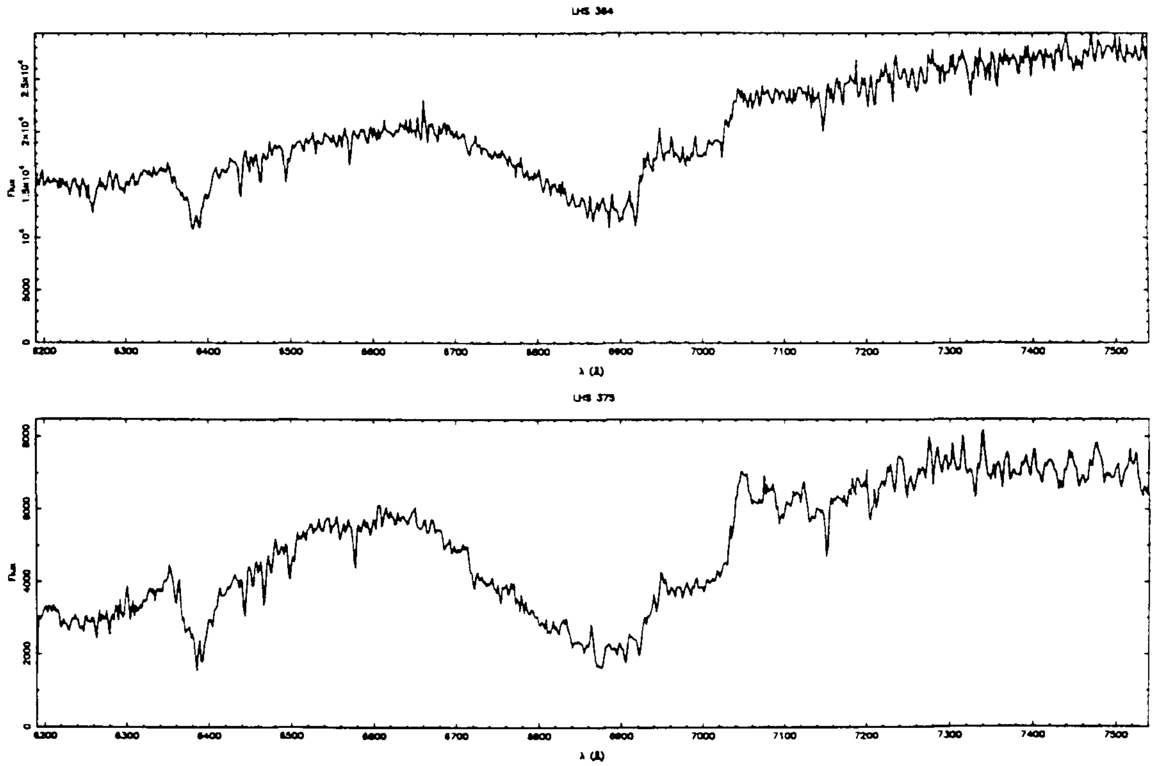


Figure B3: Spectra of two metal-poor subdwarfs from the halo population of the galaxy. The deep absorption bands at λ6400Å and from λ6700 to λ7100Å are due to CaH, and are a characteristic feature of extremely metal-poor (< 2% solar abundance) stars.

Radial Velocity Survey for Binary Stars in Globular Clusters

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

Subject heading: binary stars, globular clusters

This report describes briefly the progress that has been made for a project which was started in 1993. We believe we can finish the project with the data now in hand, and do not intend to apply for more observing time for this project next year.

The goal of the project is to determine the binary fraction in globular clusters. The major scientific motivation for this project lies in the fact that binary star populations have dramatic influence on the dynamical evolution of globular clusters. A primordial binary frequency as small as 3% can fundamentally change the dynamical evolution of an entire globular cluster (Heggie & Aarseth 1992). Globular clusters composed solely of single stars would develop central near-singularities ("collapsed cores") through two-body relaxation (Cohn 1980). Binary stars have internal (orbital binding) energy which can be extracted and converted into kinetic energy during encounters with other stars. The extracted energy can supply a central heat source to stave off or reverse core collapse. Although the existence of binary stars in globular clusters has been demonstrated by several observations (see the detailed review by Hut *et al.*, 1992), the binary frequency in globular clusters is still very uncertain.

The observations for this project were made with the Norris multi-fiber spectrograph on the 200 inch telescope at the Palomar observatory. The newly installed 2048x2048 CCD allowed us to sample 75 giant stars with magnitude range of 15.3 to 18.3 in NGC 5053. Our survey samples twice as many stars as the previous study (Pryor,*et al.*, 1989) and goes one magnitude fainter, which allows us to detect binaries with orbital periods as short as 18 days. Last year we had two runs, a total of 6 nights, of which 4 nights were usable.

The preliminary reduction of the first two epochs data from 1992 shows there are 5 radial velocity variable candidates among 60 stars; we confirmed one binary which was previously identified as a possible binary star by Pryor *et al* (1991). The reduction of the 1994 data is in progress, and a more accurate binary frequency will be derived upon the completion of the full data analysis.

REFERENCES

Cohn, H. 1980, ApJ 242, 765.

Heggie, D.C. & Aarseth, S.J. 1992, MNRAS 257, 513

Hut, P., McMillan, S., Goodman, J., Mateo, M., Phinner, E.S., Richer, H.B., Verbunt, F., and Weinberg, M., 1992, PASP 104, 981.

Pryor, C., McClure, R.D. and Fletcher, J.M. 1989 *Dynamics of Dense Steller Systems*, ed. D. Merritt, (Cambridge: Cambridge U. press), 175

Pryor, C., Schommer, R.A., Olszewski, E.W. 1991 *The Formation and Evolution of star clusters*, ed. K. Janes, 439

Optical Spectra of Orion X-ray Sources

Principal Investigator: Steven H. Pravdo
Observational Systems Division
Jet Propulsion Laboratory
California Institute of Technology

Co-investigator: Lorella Angelini
High Energy Astrophysics Science Archive Research Center
Goddard Space Flight Center

Subject Heading: Stars

Scientific Context:

Stellar sources in the Orion star-formation region have been the subject of a number of X-ray imaging studies . The majority of the X-ray-emitting sources are pre-main sequence (PMS) stars and their X-ray emissions are factors of 10^2-10^4 larger than main sequence stars of the corresponding spectral types. The source of X-rays from PMS stars is of continuing interest. It is not clear why some PMS stars are strong X-ray sources while others nearby are not detected. Are optical emission-line (ePMS) stars preferentially X-ray strong? Eight of the 19 strongest X-ray sources are ePMS stars (Pravdo & Angelini 1993) in a field of the *ROSAT* X-ray satellite (Zombeck *et al.* 1990) . These eight were among the 15 optically brightest ePMS stars in the field. In these observations at Palomar we continue our study of these sources by using optical spectroscopy to identify the spectral types of the strong X-ray sources in a region of Orion located about 1° south of the Trapezium in the L1641 molecular cloud.

Results:

We used a CCD camera (McCarthy 1990) mounted on the Palomar 60-inch telescope for low resolution (≈7Å/pixel), broad-band (≥3000Å) spectroscopy of the optical counterparts to *ROSAT* X-ray sources. The optical observations were performed on the nights of 21-23 December 1993.

We identified A6013 ("A" sources are from Andrews 1981), V942 Ori, V823 Ori, and A4815 as ePMS stars based upon their Hα emission, location in a star-formation region, and the fact that their X-ray and optical luminosities are larger than main sequence dwarfs. For P2188 and P2300 we found upper limits to Hα absorption. These imply that the stars are also PMS albeit with absorption lines filled in by emission. We also observed A5353 and V988 Ori which we identified with previously observed X-ray sources (Pravdo & Marshall 1981). Strom *et al.* (1990) assign A5353 a spectral type of G8eα with 0.2Å Hα E.W. Our spectrum appears significantly later than this, K4, and we only found an upper limit to an absorption feature, that is not, however, inconsistent with the prior result. V988 Ori is typed by Strom *et al.* as M4e with 4.8Å Hα E.W. We found a similar type but only an upper limit to Hα emission.

Three observations of V942 Ori showed an emission line that either disappeared or was overlaid by an absorption feature. More surprisingly, the central wavelength of the emission line shifted from 6551 ± 4 to 6570 ± 6 Å (~870 ± 450 km s^{-1}) between observations 1 and 2, taken less than 0.5 h apart. To test the wavelength calibration we examined the Hα background lines in nearby areas of the CCD for both observations. We found central wavelengths of 6564 ± 1 and 6565 ± 1 Å for observations 1 and 2, respectively. Thus the variability is attributed to V942 Ori.

We were unable to identify the optical counterpart of the *ROSAT* source "NW of P1792." The dimmer NW neighbor of P1792 is not apparent on the available images, nor could we isolate it spectroscopically using a 1.3 arcsec slit. We did verify the presence of such a source by the variations of the optical spectrum with different slit positions near P1792. In the SE position the spectrum is K-star-like, while in the NW position the spectrum looked A-star-like. This compares with the B8-9 spectral type measured by Strom *et al.* The large ratio of the brightness of P1792 to its neighbor and the pointing uncertainties make it impractical for us to determine a difference spectrum.

Summary:

We have identified most of the dimmer optical counterparts to X-ray sources in this Orion field. All of these are may be low-mass ePMS stars. Many of the brightest ePMS stars in the field have similar properties (Pravdo & Angelini 1993). The four new identifications in this category based on optical spectra obtained at Palomar are V942 Ori, A6013, V823 Ori, and A4815. The similarity in the optical spectra of P2188, P2300, and A5353 suggest that the first two may be weak ePMS, as is the last. Time variability of Hα emission in stars like V942 Ori is a subject for further study. Pravdo & Angelini (1994) give a full discussion of these results.

Bibliography:

Andrews, A. D. 1981, *A Photometric Atlas of the Orion Nebula*, published in collaboration with H. H. Grossie, Armagh Observatory (Coleraine, Northern Ireland: B. K. S.)
McCarthy, J. 1990, "*P60 Echelle Spectrograph Observing Manual*," Caltech document
Pravdo, S. H. & Angelini, L. 1993, *Ap. J.*, **407**, 232
Pravdo, S. H. & Angelini, L. 1994, submitted to *Ap. J.*
Pravdo, S. H. & Marshall, F. E. 1981, *Ap. J.*, **248**, 591
Strom, K. M. *et al.* 1990, *Ap. J.*, **362**, 168
Zombeck, M. V. et al 1990, *Proc SPIE*, **1344**, 267

INTERSTELLAR MEDIUM

New Upper Limits on the Local Metagalactic Ionizing Radiation Density

T. T. Hamilton, S. N. Vogel, R. Weymann and M. Rauch

We have obtained observations with the Maryland-Caltech Fabry-Perot Spectrometer attached to the Cassegrain focus of the p60 telescope at Palomar Observatory in order to set limits on the number of ionizing photons from the local metagalactic radiation field. We have observed the SW component of the Haynes-Giovanelli cloud HI 1225+01, an intergalactic cloud which should be optimum for measuring the metagalactic flux because it is nearly opaque to ionizing photons, it does not appear to be significantly shielded from the metagalactic radiation field, and the limits on embedded or nearby ionizing sources are unusually low. For the area of the cloud with an HI column density greater than 10^{19} cm^{-2} we set a 3 σ limit of 1.7×10^{-19} erg cm^{-2} s^{-1} arcsec^{-2} (30 mR) for the surface brightness of diffuse Hα. This yields a firm upper limit on the local metagalactic photoionization rate of $\Gamma < 3 \times 10^{-13}$ s^{-1}, or, assuming a radiation field of the form $J_\nu \sim \nu^{-1.4}$, implies an upper limit for J_ν at the Lyman limit of $J_{\nu_o} < 1 \times 10^{-22}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}. We also observed the 7 arcmin diameter region centered on 3C273 in which Hα emission at a velocity of $\sim$ 1700 km s^{-1} was initially reported by Williams and Schommer (1993). In agreement with Williams (private communication) we find that the initial detection was spurious. We obtain a 3 σ upper limit of 2.7×10^{-19} erg cm^{-2} s^{-1} arcsec^{-2} (48 mR) for the mean surface brightness of diffuse Hα, about a factor of four below the published value.

This project used 3 nights of p60 time from the Caltech allocation (Hamilton) and 4 nights of p60 time from the Carnegie allocation (Weymann, Rauch). The results are being published Vogel, Weymann, Rauch and Hamilton, Ap, J in press.

Jet-like Molecular Hydrogen Features in Planetary Nebulae

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

Coinvestigators: L. Armus, R.A. Knop, J.E. Larkin, K. Matthews, B.T. Soifer (Caltech)

Subject Heading: Interstellar Medium

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

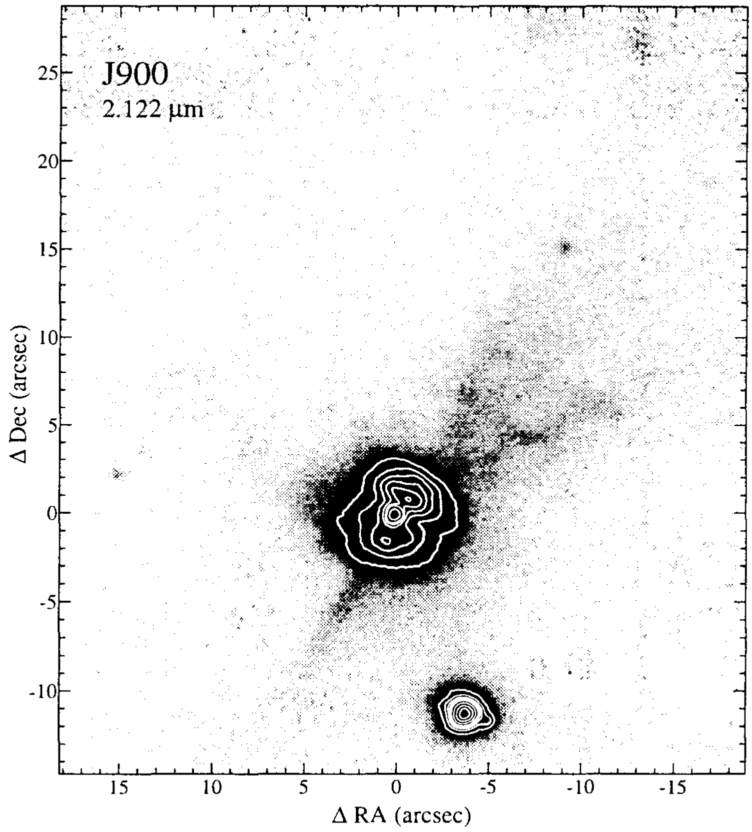
The bulk of the circumstellar envelope consists of molecular hydrogen (H_2). In its quiescent state this molecule does not radiate. However, in a planetary nebula, emission from H_2 can be excited by either hydrodynamic "shocks" caused by the collision of the supersonic stellar wind with the molecular envelope, or by absorption of ultraviolet radiation emitted by the hot central star. By reaching a better understanding of the distribution of molecular hydrogen emission and the means by which it is excited, we gain valuable insight into the physical processes that are shaping these objects. PNs which contain jets and outflows serve as laboratories for the study of hydrodynamical flows, with applications to similar phenomena in proto-stellar objects and active galactic nuclei.

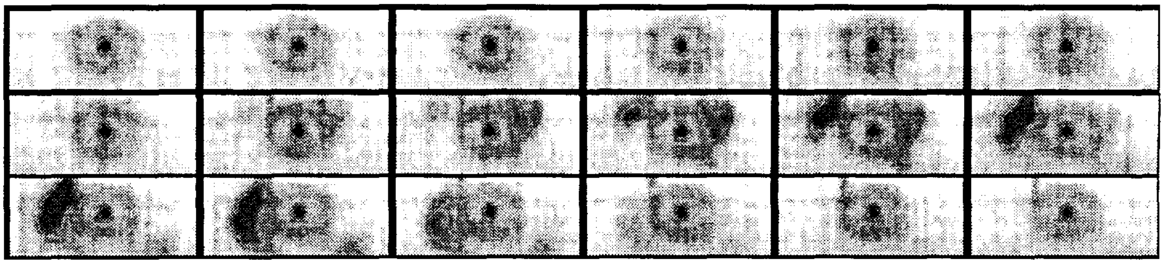
Our goal for this program is to build a picture of planetary nebula formation and evolution by carefully examining molecular hydrogen emission in a several young PNs. Our procedure consists of two steps which take advantage of recent improvements in infrared instrumentation at the 200-inch. The first step is to use the infrared camera to obtain narrowband images in and out of the brightest H_2 line, to determine where the molecular hydrogen emission is. The second step employs other diagnostics to determine the means of excitation of the emission. The most direct method is infrared spectroscopy to measure a number of H_2 emission lines. Another diagnostic is to image the emission from small dust particles, which presumably trace regions excited by ultraviolet radiation.

As part of the imaging program, in February 1994 we observed J900, a small but high-excitation planetary nebula. This PN was known to contain H_2 emission from large-aperture infrared spectroscopy, but had not been imaged before. Our narrow-band image of molecular hydrogen emission revealed a striking set of jet-like features (see Figure) which did not appear at any other wavelength or in previously published optical images. At this point, we cannot determine whether these remarkable structures are excited by radiation leaking from the inner nebula, or are instead due to shocks caused by material ejected from the vicinity of the central star. Details of the imaging are published in Shupe *et al.* (1994).

To initiate the spectroscopy portion of the project, and to demonstrate the capabilities of the new infrared spectrograph, a series of spectra of the planetary nebula BD+30°3639 were obtained. A spectrum in the high-resolution mode showed remarkable differences in velocity from one side of the nebula to another. Accordingly, we made a map of the entire nebula by stepping the spectrometer's entrance slit across the object. The result is a position-position-velocity "data cube", whose frames may be displayed one after another like a movie. A few frames of this cube are shown in the Figure. The H_2-emitting regions are not part of a quiescently expanding shell, but instead appear to form two or three flows with approaching and receding components. Molecular gas moving with respect to ambient material at the velocities observed in BD+30°3639 would be expected to be shock-excited. However, we also obtained a full spectrum of the 2.2 μm band which contains no fewer than 14 H_2 emission lines, and demonstrates conclusively that the emission is excited by UV radiation. This means that the ambient material must be moving with the same velocity as the H_2-emitting regions. We are at work on a model of this peculiar gas configuration.

Shupe, D.L., Armus, L., Matthews, K., & Soifer, B.T. 1994, accepted for publication by the *Astronomical Journal.*





Top: Narrowband image of the planetary nebula J900 in the light of molecular hydrogen emission. A striking set of jet-like features are revealed. The emission could be caused by material ejected from the vicinity of the central star. *Bottom:* "Movie" of molecular hydrogen emission in BD+30°3639. Each frame represents a different velocity of the emission. The H_2 emission appears to form two or three flows with components both blue-shifted (approaching us) and red-shifted (receding). This data was obtained with the new infrared spectrometer.

Spectrocam-10 Investigations of HII Region-Molecular Cloud Interfaces: M17 SW

Principle Investigator: G. J. Stacey
Department of Astronomy, Cornell University

Coinvestigators: H. Latvakoski, L. Peng, T.L. Hayward
Department of Astronomy, Cornell University

Subject Heading: Interstellar Medium

To understand the process of star formation, it is crucial to both understand how molecular clouds contract to form clumps - which then form stars - and what effect these young stars have on their parent molecular cloud. We have constructed a broad scientific program designed to answer these questions, with particular emphasis on the interface regions between regions ionized by young, hot, massive stars (HII regions) and the molecular cloud which parented these stars. Previous studies of these interfaces in the far-IR ($\lambda > 35\ \mu m$) fine-structure lines of [CII], [OI], and [SiII], as well as the far-IR continuum have shown that these interfaces are both warm and dense. Much of the luminosity of the young stars is absorbed by dust in these interfaces, so that their study is important to understand the energetics of young stars and their parent molecular clouds. Perhaps most interesting, however, is the indication that these interfaces may be highly clumped, with clump interclump density ratios in excess of 3. These clumps may have formed as a result of interactions between the expanding HII region, or they may be structures inherent in the molecular cloud itself. The observed large scale distribution of [CII] emission (which traces UV photons) suggests the latter is the case. Since it is molecular clumps which ultimately contract to form stars, investigations of this clumpy structure is crucial to understanding the star formation process. Unfortunately, it is impossible to fully image these clumps in the far-IR due to their small size ($\sim$ 0.01 pc) and the poor spatial resolution in the far-IR (at best 9" ⇔ 0.1 pc). Fortunately, with we can achieve spatial resolutions approaching 0.5" at 10 μm with the 200" Palomar telescope, and this 10 μm window contains several important tracers of the clumpy interstellar medium.

The primary laboratories for such studies include the M17 SW molecular cloud and the Orion molecular cloud. Both of these clouds have prominent HII regions (Ω Nebula and Orion Nebula) powered by main sequence O stars, and newly formed clusters of massive stars ~~embedded~~ still embedded in the molecular cloud. The M17 SW HII region/molecular cloud interface is of particular interest, since the interface is presented to us edge-on. We may therefore study the distribution of interstellar gas and dust as a function of distance from the ionization source, i.e. as a function of the local UV flux.

We were awarded two nights in June 1994 on the Palomar 200" telescope to study the M17 interface region with Spectrocam-10. Spectrocam-10 has a 6 filter mid-IR ($\sim$ 10 μm) filter set, by which one may obtain low spectral resolution ($R = \lambda/\Delta\lambda \sim 10$) images, and both medium ($R \sim 100$) and high ($R \sim 2000$) spectral resolution long slit grating spectrometers. We employed the filter set to obtain very high ($\sim$0.5") spatial resolution images of the interface region. These images trace emission from Polycyclic Aromatic

Hydrocarbons (PAHs) at 7.7, 8.6, and 11.3 μm, emission from the silicate dust band at 9.7 μm, and continuous emission from dust over the entire mid-IR band. The PAH features are associated with very small "grains" which are transiently heated by single UV photons to high temperatures. As such, this emission traces the regions closest to the HII region. The silicate feature which is found both in emission or absorption, arises from significantly larger grains of silicate.

Our high spatial resolution imaging with Spectocam-10 reveals for the first time the clumpy structure of the dust in the M17 interface region. There are both clumps of silicate emission, and towards a radio point source, a strong silicate absorption feature. The emission features indicate external heating from the M17 HII region, while the absorption feature likely indicates that the radio point source is in fact self-luminous - what is typically termed an "ultracompact", or very young HII region.

We also obtained preliminary long-slit spectroscopy in the LoRes mode. When completed, this work will trace the density and ionization structure of the ionized gas in the interface. Our first results are rather surprising. There is strong emission in the [SIV] (10.5 μm) line but essentially no emission in the [NeII] (12.8 μm) line. If verified on our next run, this either means that the M17 HII region is powered by a somewhat hotter star than previously thought, or the ionization structure is anomalous in this region of the nebula.

We plan to complete this project in the 1995 by obtaining images of two more regions in the interface in the 6 mid-IR filters, plus complete LoRes long slit spectra of these regions. In addition we will obtain high sensitivity HiRes long slit spectra across the interface in the $\nu = 0$ $J = 4 \rightarrow 2$ (12.28 μm) pure rotational transition of H_2. This line traces the column density of molecular gas, which combined with planned 9" spatial resolution Kuiper Airborne Observatory imaging in the [SiII] 35 μm line and 40 μm far-IR continuum, and theoretical models of the interface region will constrain the physical conditions (temperature and density) and clumping of the molecular gas.

THE MILKY WAY GALAXY

A Deep Mid-Infrared Search for Sgr A*

Principal Investigator: Susan R. Stolovy
Center for Radiophysics and Space Research
Cornell University
Coinvestigators: Thomas Hayward and Terry Herter
Cornell University
Subject Heading: The Milky Way Galaxy

1. Scientific Context

The physical nature of the object associated with the bright radio source Sgr A* situated at the dynamical center of the Galaxy has been a topic of intense study and debate for 20 years. Kinematic measurements of the surrounding gas and stars, the lack of a significant proper motion for Sgr A*, and comparisons to cores of external galaxies have led many to believe that the Galactic Center harbors a ~1 million solar mass black hole.

We undertook these observations in an attempt to detect a mid-infrared continuum source at the position of Sgr A*. A detection of the source or an upper limit for this emission will help to confirm whether the source exhibits radiative characteristics of a thin accretion disk. Various physical parameters, including the mass of the central black hole and the mass accretion rate, can be constrained with these observations.

2. Observing Program

The search for Sgr A* described here is part of a larger infrared study of the Galactic Center for Susan Stolovy's thesis. Deep continuum images of the central parsec of the Galaxy at 8.8μm were obtained with SpectroCam-10 in June and July 1994. This mid-infrared wavelength was chosen in order to maximize the ratio of expected flux to background dust continuum. The predicted flux from a thin accretion disk around a 10^6 solar mass black hole at the position of Sgr A* is 19 mJy at 8.8 μm based on the detection of a near infrared source at K≈12 coincident with Sgr A* (Close, McCarthy, and Melia 1994). Unfortunately Sgr A* is situated on a steep gradient of dust emission, so a definitive detection or non-detection depends on excellent flat-fielding and modeling of the background dust emission.

Because these observations required optimal spatial registration and seeing, we adopted an observing scheme in June whereby very short (2 second) exposures were taken in order to freeze seeing motions. In July, we were fortunate to be able to use Keith Matthews' tip-tilt secondary mirror. This improved our spatial resolution substantially and allowed us to take 10 second exposures.

3. Preliminary Results

Figure 1 is a preliminary mosaic of 16 images collected in 100 minutes (real time) on July 25. The images were spatially registered by comparing centroids of IRS 7, IRS 3, and IRS 21. We calculated the expected position of Sgr A* (marked with a plus sign) using the relative radio positions of Sgr A* and IRS 7. IRS 7 is a mass-losing supergiant that is clearly visible both in the radio and at 8.8 μm .

Various methods are being employed in an attempt to detect a point source at the position of Sgr A*, including modeling and subtracting the dust continuum and deconvolving the image.

Several notable features in Figure 1 deserve comment:

- No point source is readily apparent at the predicted position of Sgr A* upon cursory inspection, but more analysis is needed before setting an upper limit or claiming a detection.
- A new source was detected 1.5″ to the west southwest of Sgr A* (marked "New Source"). However, we estimate our absolute positioning to be correct to better than 0.5″, so it is unlikely that this source is coincident with Sgr A*. This source may have one or more near infrared counterparts.
- A "tail" of continuum emission extending ~3″ north of IRS 7 was detected. This tail was previously observed in the radio continuum (Yusef-Zadeh and Melia 1992) and is thought to be a cometary feature created by strong stellar winds originating from the IRS16 cluster. This is the first infrared continuum detection of the feature, but it is unknown at this point whether ionized emission from ArIII contributes to the flux within the bandpass.
- IRS2 has been marginally resolved into the northern and southern components seen in the radio continuum.
- With the possible exception of IRS7, we resolve extended dust envelopes around most of the IRS sources.

The July 25 data alone represent an improvement of a factor of 10 in sensitivity over a similar map at 12.4 μm (Gezari 1992). Once the June data have been included, these observations will result in the most sensitive continuum map of the central parsec ever obtained at any mid-infrared wavelength, and thus the most meaningful upper limit or detection of a mid-infrared counterpart to Sgr A*.

References

Close, L., McCarthy, D., and Melia, F. ApJ, 1994, in press.

Gezari, D., The Center, Bulge, and Disk of the Milky Way, L. Blitz, ed. Kluwer Academic Press, 1992

Yusef-Zadeh, F. and Melia, F. 1992, ApJ, 385, L41.

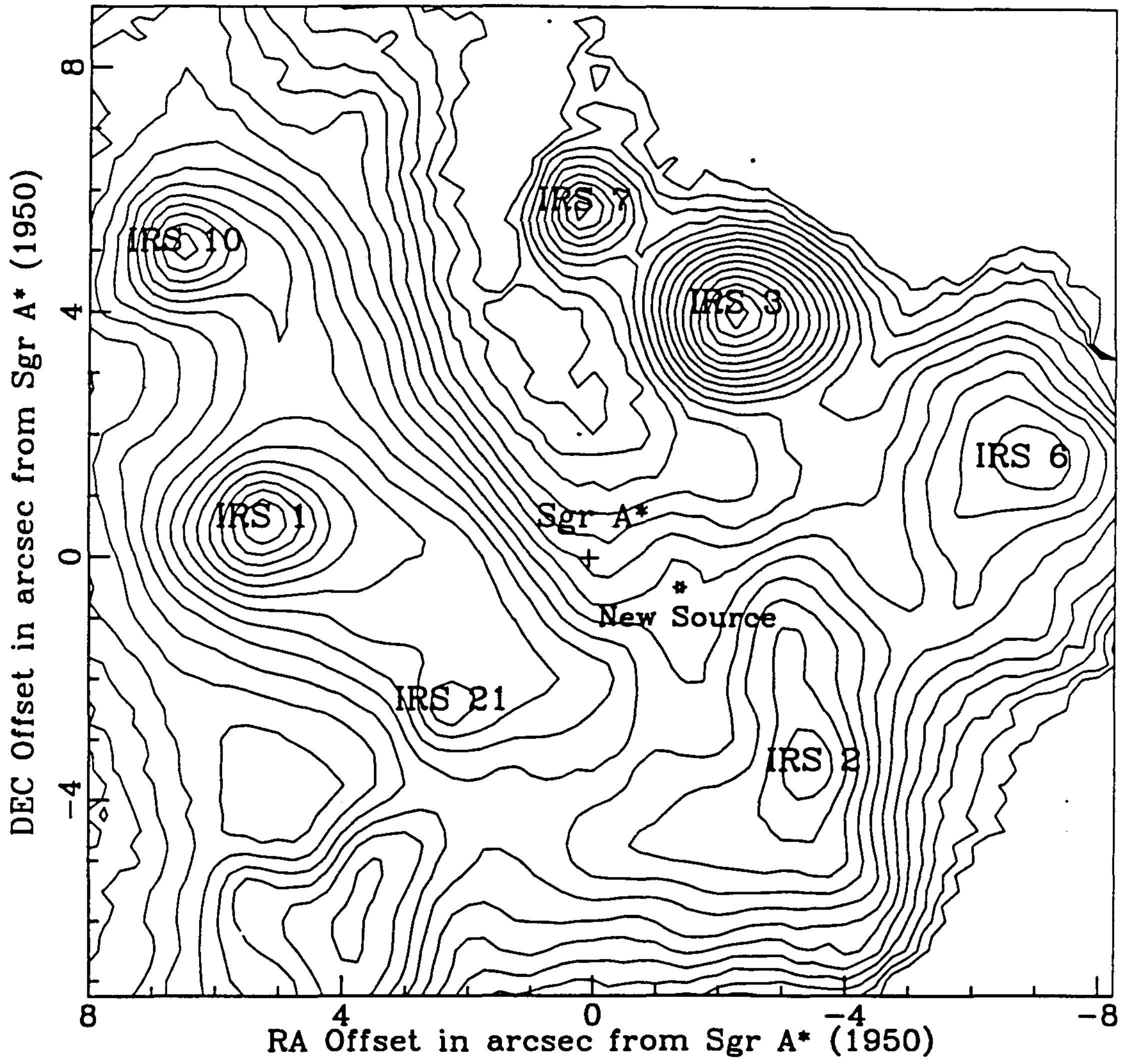


Figure 1. Mosaic of July 25 observations of the central parsec of the Galaxy at 8.8 μm in logarithmic contours. For this mosaic, $1\sigma = 0.75$ mJy/pixel (3 mJy/(arcsec)^2). The lowest contour is at 0.14 Jy/(arcsec)^2 and the highest at 17 Jy/(arcsec)^2 in increments of 133%.

GALAXIES AND QUASARS

Near-Infrared and Optical Imaging of Ultraluminous Infrared Galaxies

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

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

and M.A. Strauss (IAS, Princeton)

Subject Heading: Galaxies and Quasars

Ultraluminous infrared galaxies are sources of tremendous luminosity. They outshine ordinary galaxies by factors of 50–100, and are more luminous than one trillion suns. Despite their brilliance, these objects were only recently discovered as a class because most of their light emerges in the far infrared part of the spectrum — a region inaccessible to ground-based telescopes. Large amounts of dust in these galaxies reprocesses short wavelength light into the far infrared. Optical imaging of the ten brightest (and thereby closest) of these galaxies by Sanders *et al.* (1988) showed all ten to have distorted morphologies indicative of colliding galaxies. Moreover, optical and infrared observations by Sanders *et al.* (1988), Carico *et al.* (1990), Graham *et al.* (1990), and Armus *et al.* (1994) reveal seven of these ten to have double nuclei, further supporting the idea that these objects are galactic mergers in progress. The action of merging nuclei helps to funnel molecular gas toward the nuclei where huge bursts of star formation and possibly the feuling of a massive black hole produce the tremendous energy output we observe.

While the ten brightest ultraluminous infrared galaxies suggest that galactic collisions are responsible for the formation of these objects, a larger sample is needed in order to make such a claim with any statistical significance. Therefore, we have begun studying a much larger sample of galaxies (53 in all) taken from the complete, deep survey of Strauss *et al.* (1990). These galaxies are fainter (because they are much more distant, on average) than the ten galaxies previously studied.

We have been imaging the larger sample of 53 galaxies in both infrared and visible light. We have used the Hale telescope to obtain infrared images at $2.2\mu m$ of 50 of the galaxies in the sample. We obtained optical images of all 53 galaxies using the Palomar 60 inch telescope. Of the 53 galaxies, 23 appear double. Of these, 14 are separated by less than a typical galaxy's radius. These close doubles are clearly in the final stages of a merger. The optical images show that 43 of the 53 galaxies have morphologies typical of merging systems — tidal tails, extended structures, etc. Figure 1 shows two of the galaxies in our sample in both optical and near-infrared light. Both have two nuclei, although the second nucleus in IRAS1524 + 1019 is obscured by dust in the optical image. The two samples, therefore, have similar statistics, bearing in mind that if the nearby sample were moved to distances typical of the larger sample, we would only expect to see five double nuclei out of the sample of ten.

It has been suggested that ultraluminous infrared galaxies represent a stage in the formation of quasars, the most luminous objects in the Universe. The source of the quasars' impressive energy output is thought to be the result of the accretion of gas onto a central black hole. A merging pair of galaxies could lead to such an object after the dust settles and the nuclei coalesce into one. One major goal of our study is to determine the lifetime of this ultraluminous phase in the evolution to a quasar. Based on dynamical arguments, as well as the separation of the nuclei, we calculate an average lifetime of $\sim$ 500 million years — about 3% of the age of the Universe. Our study has provided us with a wealth of data which we are continuing to analyze and from which we are gaining important insights into this most intriguing phenomenon.

References:

Armus, L., Surace, J.A., Soifer, B.T., Matthews, K., Graham, J.R., and Larkin, J.E. 1994, *A.J.*, **108**, 76.

Carico, D.P., Graham, J.R., Mattews, K., Wilson, T.D., Soifer, B.T., Neugebauer, G, and Sanders, D.B. 1990, *Ap.J.*, **349**, L39.

Graham, J.R., Carico, D.P., Matthews, K., Neugebauer, G., Soifer, B.T., and Wilson, T.D. 1990, *Ap.J.*, **354**, L5.

Sanders, D.B., Soifer, B.T., Elias, J.H., Madore, B.F., Matthews, K., Neugebauer, G., and Scoville, N.Z. 1988, *Ap.J.*, **325**, 74.

Strauss, M.A., Davis, M., Yahil, A., and Huchra, J.P. 1990, *Ap.J.*, **361**, 49.

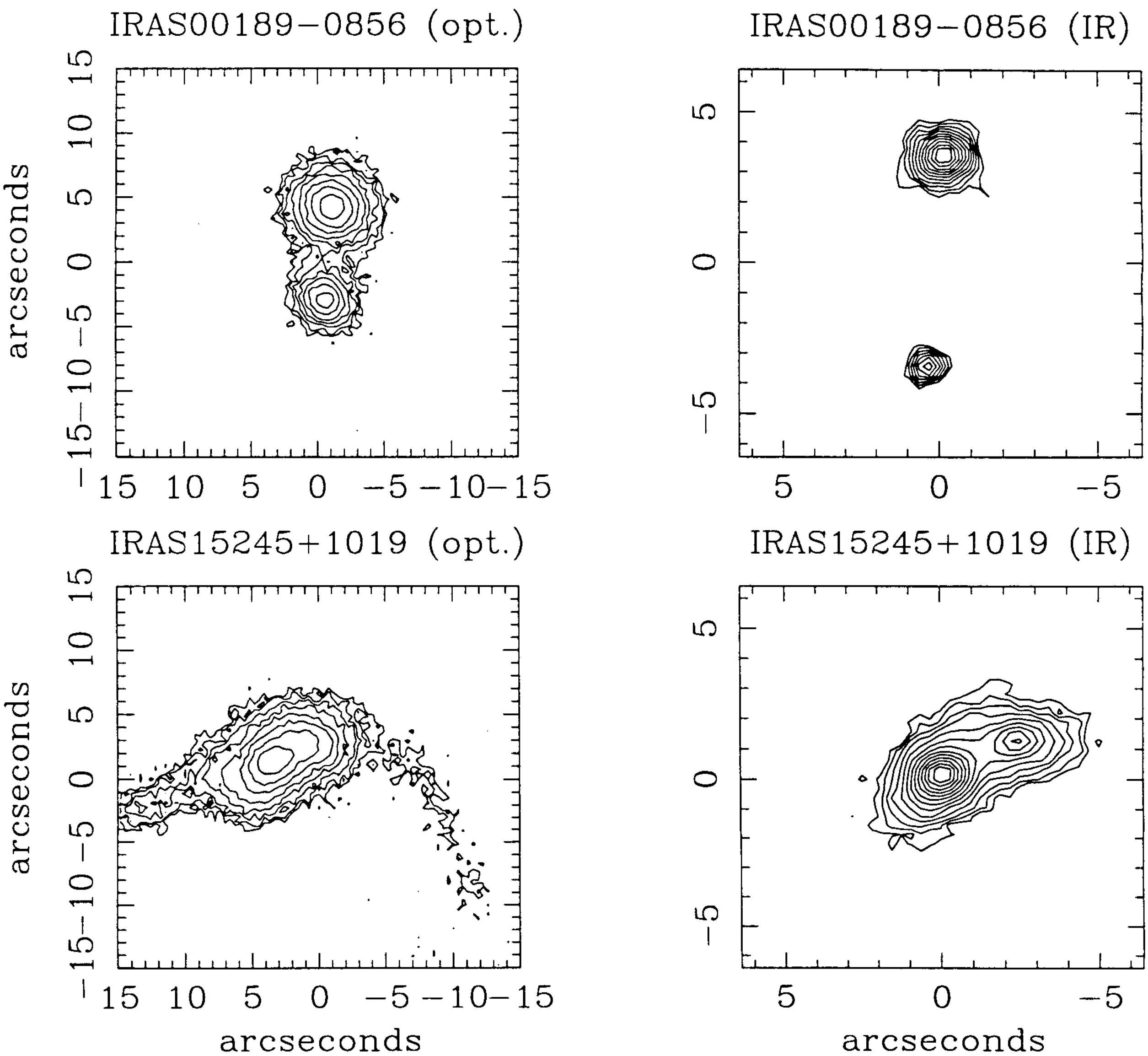


Figure 1. Two of the galaxies in our sample, shown in both optical and near-infrared light. Note the different image scales for the different wavelengths. The second nucleus in IRAS15245 + 1019 is obscured by dust in the optical image.

The Globular Cluster System of M31

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

Co-Investigator: Keith Matthews
California Institute of Technology

Subject Heading: Galaxies and Quasars

The globular cluster system of M31 presents a tempting target at all wavelengths. It is populous, with more than 341 probable members, and the clusters are bright enough that detailed study is possible. The definitive optical study is that of Huchra, Brodie & Kent (1991), where abundances and radial velocities for a sample of 150 clusters in M31 are given.

Huchra et al found some things that made us suspicious that their observations might not have been as accurate as they believed. In particular, they found a group of extremely metal rich globular clusters located in the outer parts of M31, whereas naive intuition would predict that such objects be confined to the nuclear regions. We obtained infrared photometry with an array detector at the 200−inch telescope for 23 globular clusters in M31, 16 of which have projected galactocentric radii of less than 1.1 kpc. A comparison with the metallicity determined for these objects by Huchra et al using optical spectra indicates that the errors in [Fe/H] determined optically have been underestimated. The apparently very metal rich objects in the outer parts of M31 were simply the statistical tail of a distribution whose standard deviation was larger than presumed.

Combining our sample with previously published infrared photometry of M31 globular clusters produces a total sample of 84 objects. A comparison of the properties of the M31 globular cluster system as viewed in the infrared with that of the Milky Way globular cluster system indicates that the two are very similar in terms of mean metallicity of the entire
globular cluster system and in terms of mean metallicity of the nuclear globular clusters.

Aside from a general enhancement in metallicity in the nuclear sample in M31, there is no evidence among the outer globular clusters for a spatial gradient of metallicity in the M31 globular cluster sample. This too is in agreement with expectations based on what is observed in the Milky Way globular cluster system.

References:

Huchra, J.P., Brodie, J.P. & Kent, S.M. 1991,ApJ,370,495

Polarization Studies of Active Galactic Nuclei

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

Coinvestigators: Patrick Ogle and Hien Tran
Division of Physics Mathematics and Astronomy
California Institute of Technology

Subject Heading: Galaxies and Quasars

Our work on active galactic nuclei (AGN) can be subdivided into three parts: Seyfert galaxies, radio galaxies and quasars, and broad-absorption-line quasars. In all these the general objective is to investigate the geometry of the nucleus. We do this by measuring the polarized spectrum, which gives information on emission, absorbing and reflecting clouds, and on their orientation relative to axes revealed by any radio measurements. These axes are thought to define the orientation of the accrection disk, and the rotation axis of the black hole which is in the center and powers the nuclear activity.

Seyfert Galaxies

We observed four Seyfert II (narrow-line) galaxies which have multiple nuclei and are interacting with other galaxies. Nuclear activity is particularly strong in galaxies of this type, possibly because the interaction has released a large amount of gas and dust into the nuclear region. In three of these galaxies there are hints of polarized broad emission lines. This suggests that they contain a broad-line emission region like the Seyfert I galaxies, and is further evidence that many Seyfert I and Seyfert II galaxies contain a dusty central torus and are basically the same objects but viewed from different directions. The fourth galaxy is unusual in that its strong narrow emission lines are polarized but there are no broad lines. This may be due to dust in the galaxy. We plan to observe more of these multiple-nuclei Seyfert II galaxies, and study in depth those which appear to be of special interest.

Radio Galaxies and Quasars

During the year we measured the polarization spectrum of five radio galaxies and seven radio-loud quasars. Two of these have strong polarization ($> 3\%$), one is unpolarized, and the rest are weakly polarized, around 1% or 2%. In about half the objects the continuum radiation is polarized differently from the line radiation. A few objects show rapid changes in polarization (as a function of wavelength) in the wings of the strong broad emission lines. A paper describing the results on the radio galaxies is now in preparation, and we plan to write a second paper on the quasars.

Broad-Absorption-Line Quasars

The broad-absorption-line (BAL) quasars are all radio-quiet and form about 10% of the general quasar population. They have broad deep absorption lines on the blue side of some of the broad emission lines; evidently the absorption is due to gas streaming out of the nucleus at high speed (5,000 - 30,000 km/sec). The mechanism for accelerating this gas is in dispute, as is the clumpiness of the wind. It seems likely that all radio-quiet quasars are the same and that the absorption lines merely appear when the viewing circumstances are favorable, but it is possible that there are two rather different subclasses. On the other hand, the total lack of the BAL phenomenon in the radio-loud quasars remains a deep mystery.

The BAL quasars are faint but we now have made preliminary studies of five of them with the Hale telescope. During this year we confirmed the hints from earlier work that the polarization rises in the broad absorption troughs and is reduced in the emission lines. Our picture is that the absorption is complete in the waveband for atomic resonance, and in that band we do not see the nucleus directly but rather along another line of sight which involves scattering and hence polarization. This second component covers all wavelengths but is diluted by the emission lines, which are unpolarized.

A detailed study of these BAL quasars requires the Keck telescope. We plan to survey a number of them at Palomar, and pick the most promising ones for study at Keck.

Massive Stars at the Edge of the Milky Way and External Galaxies

Principal Investigator: Eugène J. de Geus
Division of Mathematics and Astronomy
California Institute of Technology

Co-investigators: Stuart Vogel (Univ. of Maryland)
Neil D. Tyson (Princeton Univ.), Jan Brand (Univ. of Bologna)
Jan Wouterloot (Univ. of Cologne), Seth Digel (NASA, Goddard)

Subject Heading: Galaxies

The disks of many external spiral galaxies show the interesting phenomenon that gas and stars co-exist only out to a certain distance from the center, where the number of stars drops steeply but the gas disk (at least as traced by atomic hydrogen) extends much further out. The same appears to be true for the Galaxy, where the optical disk extends to about 15 kpc but the atomic-gas disk goes to 30 kpc from the center. Little is known about the distribution of *molecular* gas in these remote regions, despite the fact that clouds of molecular gas are known to be the sites of star formation. In order to understand the differences between the extents of the stellar and gaseous disks of the Milky Way and other galaxies, we think it is crucial to understand the distribution and star forming properties of *molecular clouds* at the edges of galaxies. A recent survey for molecular gas in the outer parts of the Milky Way by Digel *et al.* (1993) has uncovered a molecular cloud that is likely to be at an unusually large distance from the Galactic center (28 kpc), but in many important ways is similar to molecular clouds closer in. A caveat with Galactic molecular cloud research is that distances are derived from assumptions about Galactic kinematics. De Geus *et al.* (1993), using the Maryland-Caltech Fabry-Perot on the Palomar 60", however, discovered a region of ionized hydrogen and a related hot star near this cloud, which enabled an independent distance determination confirming the large distance from the galactic center. The Fabry-Perot result clearly indicates that massive-star formation can indeed occur beyond the Galaxy's optical disk. Nevertheless, to reveal detailed morphology of the Galactic disk from within remains a great challenge.

Our two programs at the Palomar 60" directly address this challenge. First of all we are looking in our own Galaxy to study regions of ionized gas right on the edge of the stellar disk. We already know the existance of molecular gas in these parts, but we need to know to what extent these clouds are also forming hot stars. Our observations in March of 1994 enabled us to locate a few more regions of massive star formation, but the results need to be augmented by our observations of last October before we can draw any conclusions.

Much can also be learned by inference from the study of the edges of external galaxies. There is already some limited evidence that external galaxies also have massive star formation well beyond the optical radius in the form of presence of supernovae (from young massive stars) that exploded well outside the stellar disk, but inside the gaseous disk of their "host" galaxy. We are using the Palomar 60" telescope to search for the faint emission of regions of ionized gas in the outskirts of four external galaxies. A preliminary analysis of images from our March observations shows a faint ionized gas in the galaxy NGC 2403, indicating that star formation does occur at the edge of galaxies albeit sporadically.

de Geus, E.J., Vogel, S.N., Digel, S.W. & Gruendl, R.A. 1993. Ap.J. **413**, L97.
Digel, S., de Geus, E.J., & Thaddeus, P., 1993. Ap.J. **422**, 92.

A Serendipitous Long-Slit Spectroscopic Survey

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

Subject Heading: Galaxies and Quasars

We have been conducting a serendipitous long-slit spectroscopic survey for PGs, targeting the Lyα line as the observable signature. As a byproduct, we detect numerous emission-line galaxies at lower and intermediate redshifts, which can be used to probe the evolution of normal galaxies over the last half of the Hubble time.

Most of the surveys for primeval galaxies (PGs) have relied on the detection of strong line emission from them. This is an expected consequence of massive star formation, which must have taken place at some level as indicated by the significant metallicities seen in elliptical galaxies. This inference is relatively insensitive to the form of the stellar IMF since it is only the massive stars which both produce the UV ionizing radiation and ultimately enrich the interstellar medium with metals through supernovæ. One of the strongest emission lines is expected to be that of Lyα. The expected rest-frame Lyα luminosity from a star formation rate of 100 $M_\odot$/yr is 2.45×10^{43} erg/cm^2/s, assuming no significant dust absorption. For objects at high redshifts, and for a range of standard cosmologies, the Lyα line can be expected to show an observable line flux in the range of $\sim 10^{-16\pm1}$ erg/cm^2/s.

The data were obtained over the course of 6.75 years at Palomar Observatory, using the Double Spectrograph and 4-Shooter instruments on the Hale 200-inch telescope. The main advantage in this project is that no dedicated telescope time had to be proposed for, with all of the data being obtained during the course of other projects. An early result in this effort was the chance discovery of an apparently normal galaxy at a redshift of 1.018 (Thompson & Djorgovski 1991).

A total of 421 independent spectroscopic frames, covering an area of 14.97 square arcminutes, was surveyed over a 2500Å span from 5000Å to 7500Å, with lesser areas surveyed across the entire optical passband. Out of 65 emission-line candidates found, we were able to determine firm redshifts for two quasars and 30 galaxies. An additional 20 galaxies have only tentative redshifts assigned, based on the identification of a single emission line as [O II]. The sample of galaxies with firm redshifts has a median redshift of 0.52, and reaches out to $z \sim 1$. The spectroscopic properties of these galaxies are consistent with the field galaxy populations identified in the deep spectroscopic surveys. No high-redshift tail is seen, consistent with the no-evolution models, though the majority of the data is not sensitive to [O II] beyond a redshift of 1.

The remaining few objects are candidate Lyα galaxies at high redshift, with isolated, unidentified emission lines and little or no continuum. They require further spectroscopy to check on their nature.

Assuming a Friedman cosmology with $H_0 = 75$ km s^{-1}Mpc^{-1} and $\Omega_0 = 0.2$, we have surveyed a restframe comoving volume of 20,400 Mpc^3 to a limit sufficient to detect unobscured star formation at a rate of 10 $M_\odot$ yr^{-1}, and 102,600 Mpc^3 to a limit of 100 $M_\odot$ yr^{-1}. These volumes surveyed are sufficient to contain of order 20 and 100 galaxies with $L \geq L_*$, respectively, assuming the local space density of spheroids and elliptical galaxies and no density evolution. These limits are comparable to those achieved in narrow-band imaging surveys, while probing a different region of the relevant parameter space. The lack of detection of a population of Lyα-luminous objects could be due to dust quenching of the Lyα line, higher redshift of formation than surveyed, short lifetimes in the Lyα-bright phase, or even masking of the star-formation emission-line signature by an active nucleus.

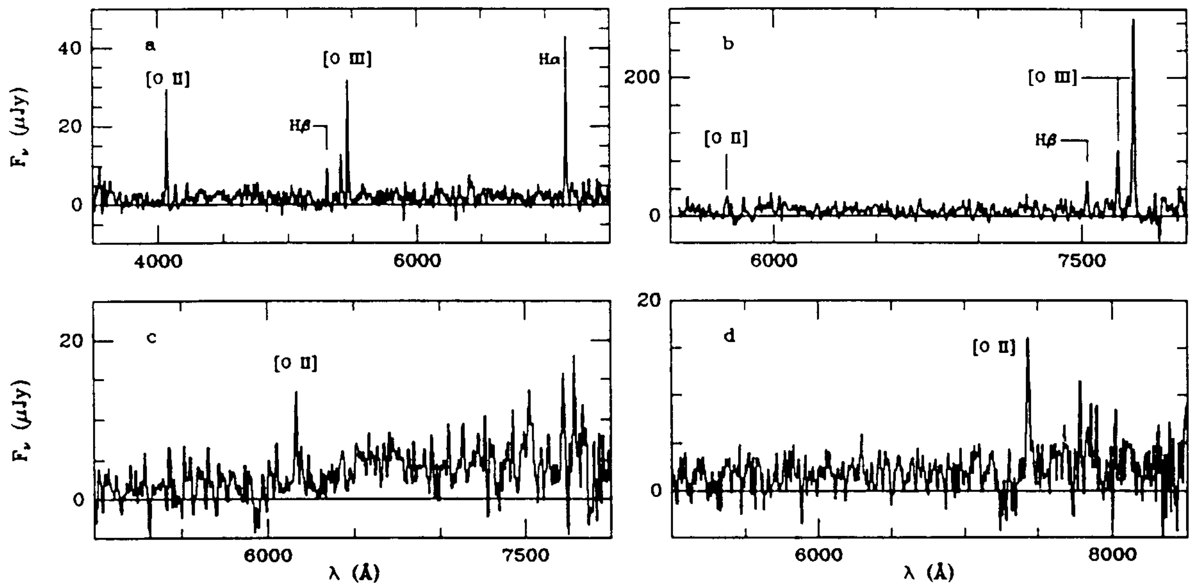


Figure 1. Example spectra of 4 of the serendipitously discovered galaxies from this survey. They are identified as a) a $z = 0.091$ galaxy with strong [O II]3727, [O III]5007, and Balmer emission lines, found in the field of the radio galaxy B3 0123+402; b) a $z = 0.548$ galaxy in the field of PC 1233+4752, with strong [O III] and Hβ, but only weak [O II]; c) a $z = 0.654$ galaxy from the FP 1454+34, a Fabry-Perot survey field, where the 4000Å break confirms that the single line is [O II]; and d) a $z = 0.995$ galaxy found in the FP 0031+23 field. For the latter case, a weak 4000Å break and strong blue continuum blueward of the emission line, as well as an absence of other emission lines, confirms the identification of the isolated emission line as [O II]3727.

References:

Djorgovski, S., Thompson, D., and Smith, J.D. 1993, "Searches for Protogalaxies and Protoclusters", in B. Rocca-Volmerange *et al.* (eds.), *First Light in the Universe*, p. 67. Gif sur Yvette: Editions Frontières.

Thompson, D., and Djorgovski, S. 1991, "Discovery of a Normal Galaxy at z = 1.018", *Astrophys. J. Letters* **371**, L55.

Thompson, D., and Djorgovski, S. 1995, "A Serendipitous Long-Slit Spectroscopic Survey for Primeval Galaxies", submitted to the *Astron. J.*

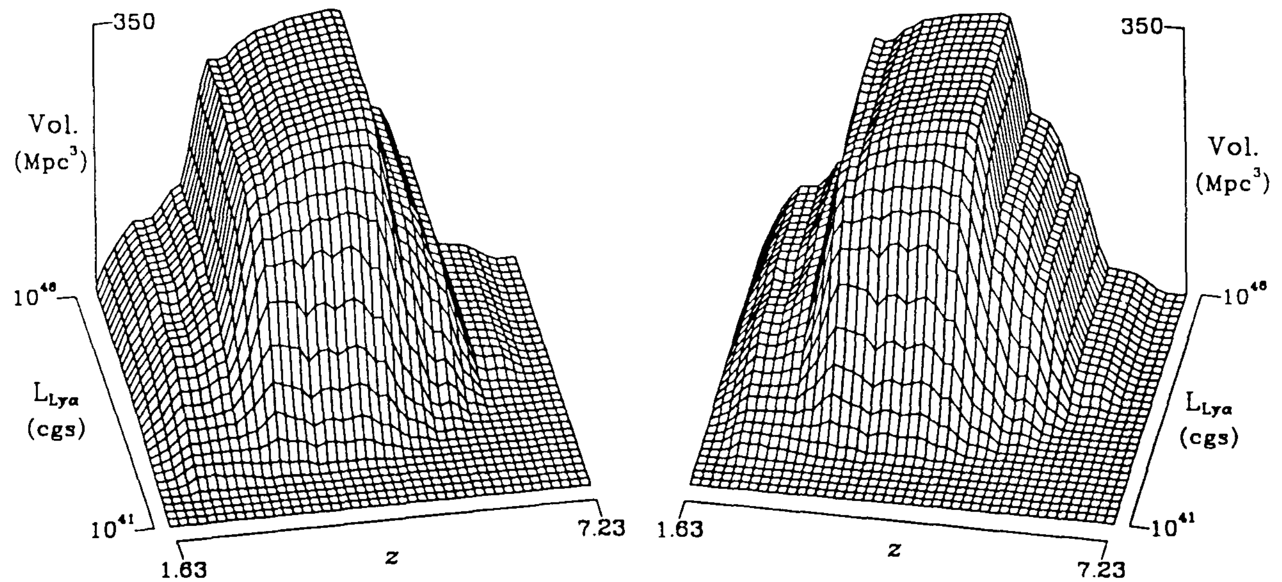


Figure 2. A 3-dimensional representation of the restframe comoving volume surveyed, expressed as a function of both the redshift of Lyα and the Lyα emission-line luminosity limit. The full restframe datacube was binned by a factor of 15 in both the wavelength and flux dimensions to produce this plot, and a cosmology of $H_0 = 75$ km s^{-1}Mpc^{-1} and $\Omega_0 = 0.2$ was assumed for the conversion from observed coordinates.

A Narrow-Band Imaging Survey For Primeval Galaxies

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

Co-Investigators: D. Thompson (CIT), 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 a milestone of cosmology. By primeval galaxies (hereafter PGs) we mean young ellipticals or bulges undergoing their first major burst of star formation at large redshifts.

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

We reach limiting line fluxes of a few $\times 10^{-17}$ erg/cm^2/s. Typically, we find $\sim 10-20$ emission-line object per datacube, only a few of which are judged to be high-priority candidates due to their faintness, the absence of a detectable blue continuum, strength of the possible emission line, etc. So far, conclusive spectra have been obtained only for the brightest candidates, all of which turned out to be emission-line galaxies at $z < 1$. We hope to observe our fainter, more interesting candidates with the Keck. Even if none of our fainter candidates are actually PGs, our limits are the strongest to date, and are already in conflict with the simple CDM-based theoretical predictions

Figure 1 shows the limits on the surface number density of Lyα PGs as a function of the limiting line flux, translated into comoving volume number density and restframe Lyα luminosity, assuming $H_0 = 75$ km s^{-1}Mpc^{-1} and $\Omega_0 = 0.2$. All limits plotted are for a 1σ detection within an aperture equal to twice the seeing FWHM. The top x-axis shows the star formation rate corresponding to the Lyα luminosity on the bottom x-axis, while the right y-axis gives the number of $L \geq L^*_B$ galaxies expected within the comoving volume surveyed (normalized to the $z = 0$ space density of L^* galaxies). As in Figure 12, regions to the upper left of the limit lines are excluded by the surveys, and the model PG luminosity function is as described in the text. Scaling to lower SFR moves the model to the right. The limits for several other Lyα narrow-band imaging surveys are plotted for comparison. For comparison, the known radio galaxies and QSO companions typically have observed Lyα line fluxes of $10^{-15} - 10^{-16}$ erg/cm^2/s.

References:

Djorgovski, S., Thompson, D., and Smith, J.D., 1993, "Limits on Lyman-alpha Luminous Protogalaxies", in C. Akerlof and M. Srednicki (eds.), *Texas/PASCOS'92: Relativistic Astrophysics and Particle Cosmology*, *Ann. N.Y. Acad. Sci.* **688**, 515.

Thompson, D., Djorgovski, S., and Trauger, J. 1995, "A Narrow-Band Imaging Survey for Primeval Galaxies", *Astron. J.* in press

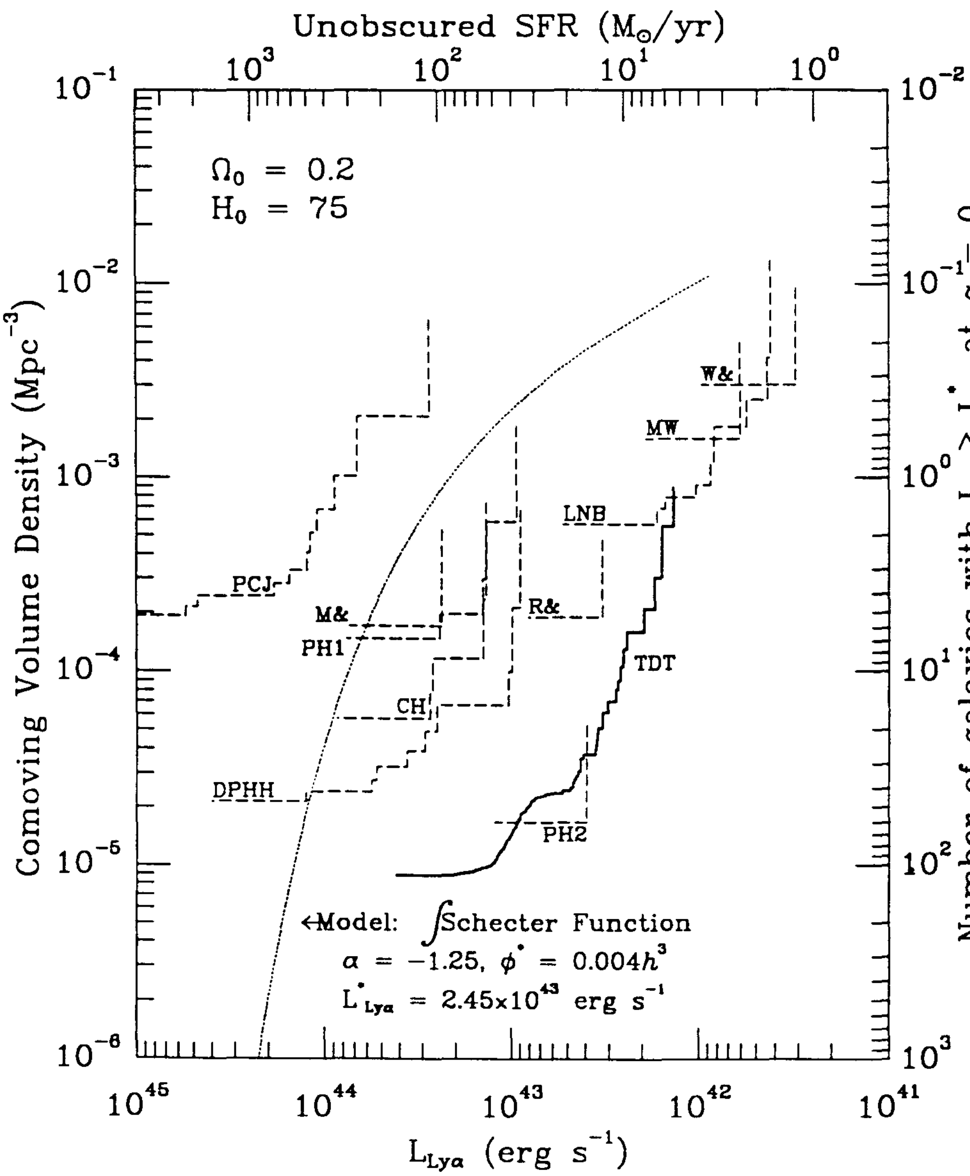


Figure 1. See the text for an explanation.

A Search for Quasars at z $\gtrsim 4$, Using Multicolor Imaging

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

Subject Heading: Galaxies and Quasars

Quasars at $z > 4$ are valuable probes of the early universe, and the physics and evolution of the intergalactic medium (IGM) at large redshifts. They must be among the first objects which formed, and may mark sites of galaxy and cluster formation. The evolution of their luminosity function is still controversial and poorly understood. Luminous (e.g., $R < 19^m$) quasars at such high redshifts are particularly valuable for high-resolution spectroscopic studies of the primordial IGM, and would make excellent Keck HIRES targets.

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

For these reasons, we started a couple of different searches for $z > 4$ quasars. Our method is multicolor imaging in three bands, e.g., Gunn-Thuan gri, for the CCD work, or JFN for the photographic work. 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.

To date, the primary sample of bright, $z > 4$ quasars is that found by Hazard, McMahan, and collaborators, and most of these objects are still not widely available. As a test of our methodology, we managed to rediscover several of their quasars, by searching in the fields where we knew the quasars are. In the process, we also discovered a previously unknown, intriguing quasar at $z > 4$ (Smith et al. 1994a, 1994b).

Digitized POSS-II provides an excellent opportunity to find more of such objects. We use the multicolor method on the catalogs of stellar objects detected in the POSS-II JFN plates, calibrated to the gri system. We are now generating the first sets of candidates, and starting the follow-up spectroscopy.

Our scientific goals include better constraints on the quasar luminosity function st $z > 4$, and identification of targets for protogalaxy and protocluster searches. These quasars would presumably also be used by other Caltech astronomers for HIRES studies of the absorption-line systems at high redshifts.

References:

Smith, J.D., Thompson, D., and Djorgovski, S. 1994a, "Multicolor Detection of High-Redshift Quasars: I. Two Objects at $z > 4$", *Astron. J.* **107**, 24.

Smith, J.D., Djorgovski, S., Thompson, D., Brisken, W., Neugebauer, G., Matthews, K., Meylan, G., Piotto, G., and Suntzeff, N. 1994b, "Multicolor Detection of High-Redshift Quasars: II. Five Objects at $z \geq 4$", *Astron. J.* **108**, 1147.

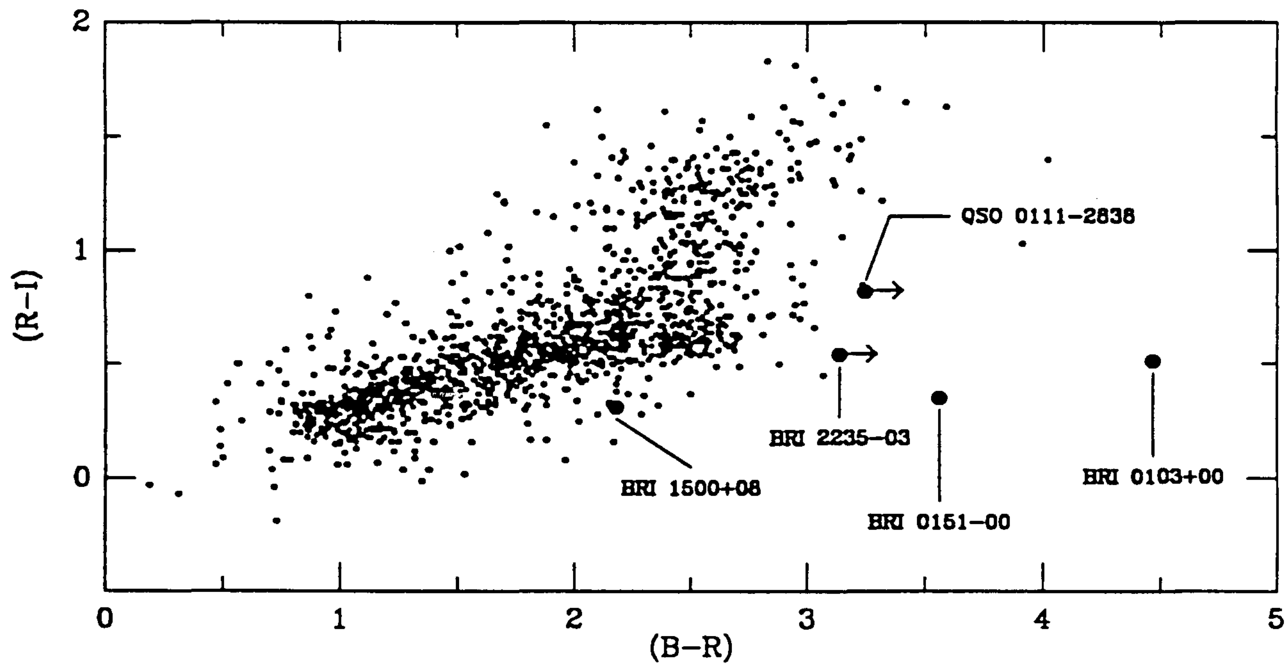


Figure 1. The *BRI* color-color diagram of all objects with $14.0 < R < 20.0$ in a 15 arcmin square field containing the "rediscovered" BRI quasars and the new quasar QSO 0111−2838. The solid circles represent the quasars, which are well separated from the stellar locus. Arrows designate that the $(B - R)$ color is a lower limit.

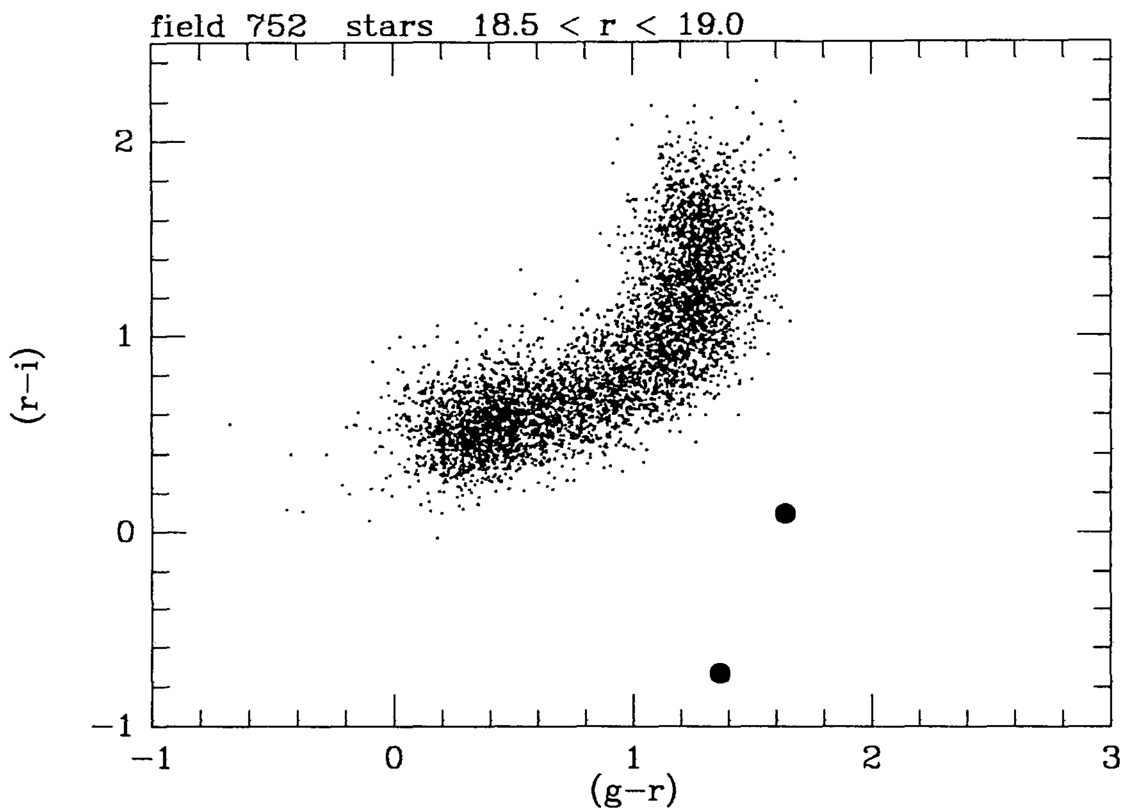


Figure 2. An example of a color-color diagram of stellar objects in the POSS-II field # 752 (dots), with two high-z quasar candidates plotted as solid circles. Only the stars in a narrow magnitude interval are plotted, for clarity. We hope to obtain spectra of these objects in a forthcoming P200 run.

Identifications of Faint Radio Galaxies from the B3 Survey

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

Subject Heading: Galaxies and Quasars

Studies of high-redshift radio galaxies have attracted much attention over the past few years, especially since the discovery of the so-called alignment effects. The observed evolutionary effects in these objects far exceed the cosmological effects, and some may even be genuine forming galaxies. Yet, despite much observational and theoretical effort, our understanding of these objects, their evolutionary status, and the alignment effects are still very shaky. It is not even clear how much of the observed light, including the IR, is starlight, rather than a scattered quasar continuum.

We are conducting an effort to identify and study a complete sample of moderate flux radio galaxies from the B3 survey. Our scientific goals include systematic comparisons of galaxies with a wide range of radio power at similar redshifts, including the radio-optical alignment effects, a search for extremely distant galaxies and clusters of galaxies, steep-spectrum quasars, and other unusual types of objects, including possible forming galaxies.

We are obtaining redshifts for a complete subsample of steep-spectrum sources from the B3VLA survey. We probe the flux range ($S_{408} \sim 1$ Jy) where the deviations of source counts from the euclidean geometry are the largest, and thus the cosmological volume coverage may be the highest. Our sample is selected in flux, spectral index, and apparent diameter in a way which should maximize the chances of discovering high-redshift galaxies. The most distant galaxies now known were selected using this type of criteria, and we may well found a redshift record ourselves.

Even with our limited sample identified so far, we see some intriguing trends in comparing the moderate-flux B3 sources with the high-flux 3CR sources. At a given redshift, B3 galaxies tend to have lower optical luminosities, lower surface brightness, redder colors, and weaker emission lines than the high-flux 3CR galaxies. However, more data are needed in order to check these trends. If real, they may indicate important connections between the radio source power, and the optical properties of their host galaxies. A systematic comparison of properties of radio galaxies with a range of power at as a function of redshift is one of the principal scientific goals of this study.

So far, several tens of IDs have been obtained at Palomar. Redshifts have been obtained for a couple of dozen of the faint galaxies, reaching out to $z = 3.21$ for B3 1232+397B, with an additional few sources at $z > 2$. Redshifts have been also obtained for a number of quasars and brighter, $< 20^m$, galaxies. We have also found several high-z clusters of galaxies. We plan to pursue the spectroscopy or the remaining faint IDs at both Palomar and the Keck.

References:

Djorgovski, S., Thompson, D. J., Vigotti, M., and Grueff, G. 1990, "Spectroscopy of Radio Sources from the Third Bologna Survey", *Publ. Astron. Soc. Pacific* **102**, 113.

Thompson, D. J., Djorgovski, S., Vigotti, M., and Grueff, G. 1992, "Identification and Spectroscopy of Radio Sources from the Third Bologna Survey", *Astrophys. J. Suppl.* **81**, 1.

Thompson, D., Djorgovski, S., Vigotti, M., and Grueff, G. 1994, "Identifications and Spectroscopy of Faint Radio Galaxies from the B3VLA Survey", *Astron. J.* **108**, 828.

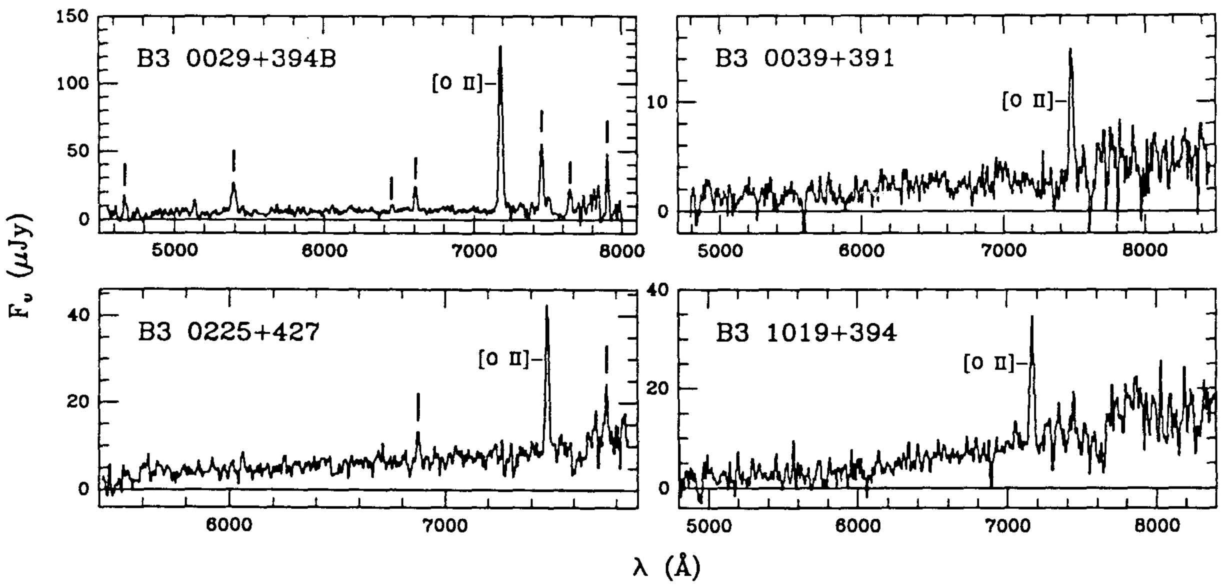


Figure 1. Representative spectra of some of the new Palomar IDs. Strong emission lines are indicated. The redshifts are: $z = 0.9274$ for B3 0029+394B, $z = 1.006$ for B3 0039+391, $z = 1.006$ for B3 0225+427, and $z = 0.9226$ for B3 1019+394.

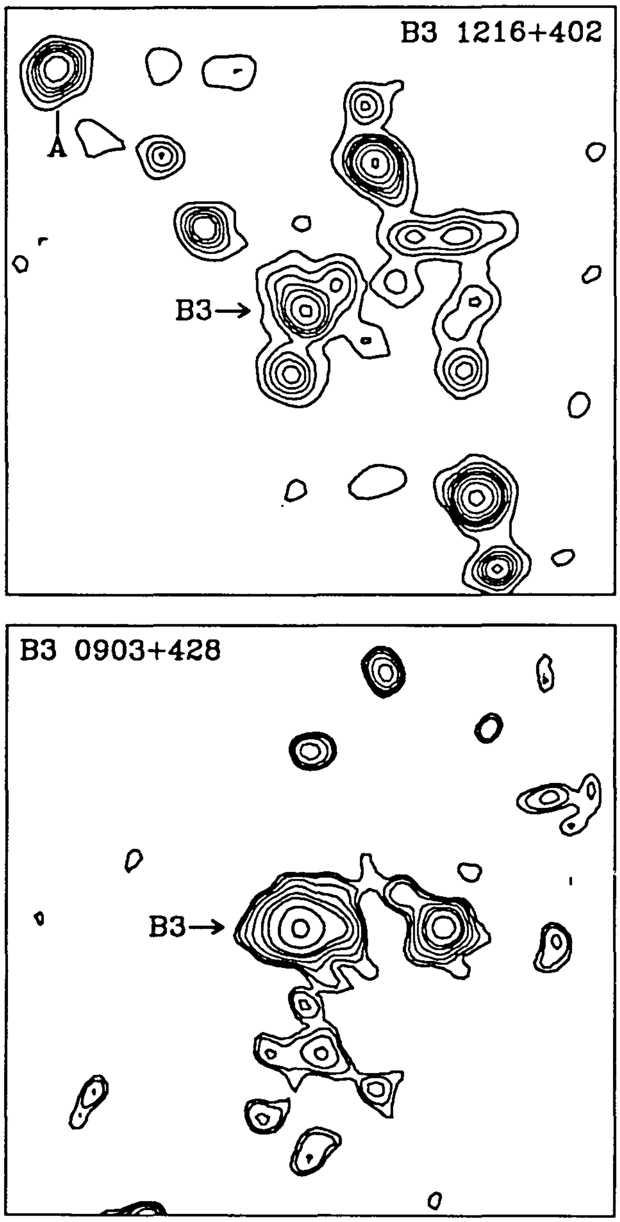


Figure 2. Zoom-in on the fields of possible rich clusters around B3 1216+402 at $z = 0.7562$ (top) and B3 0903+428 at $z = 0.907$ (bottom). The fields shown are 30 arcsec square, with N up and E to the left.

Calibrations and Analysis of the Palomar–STScI Digital Sky Survey

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

Co-Investigators: N. Weir, T. Brainerd, R. de Carvalho, J. Smith (CIT)

Subject Heading: Galaxies and Quasars

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

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

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

Our initial results on galaxy counts in two colors (photographic J and F, calibrated to Gunn g and r bands) have been done for a multi-plate region near the north Galactic Pole, covering 4 Survey fields ($\sim$ 100 square degrees). Our data set, truncated at the magnitudes where our star/galaxy classifications become unreliable, consists of $\sim 2 \times 10^5$ galaxies, and a comparable number of stellar objects.

Individual plate galaxy counts in both bands are in excellent mutual agreement, much better than in the previous efforts which used a comparable plate material, and are fully consistent with the poissonian and magnitude zero-point errors. The observed power-law slopes of the counts are 0.49 dex/mag in the g band, and 0.46 dex/mag in the r band. Our galaxy counts are fit well by the models with little or no evolution at low redshift, in contrast to some dramatic claims in the literature.

We have also started investigations of the large-scale structure in the universe, using two-point galaxy correlation functions. Again, our preliminary results show an excellent internal consistency, and are in a good agreement with the old Lick counts, when scaled to the appropriate depth. We may be seeing less power on very large scales than in some of the previous investigations, but this remains to be tested further.

We are now starting to explore algorithms to define uniform and objective catalogs of groups and clusters of galaxies from the DPOSS catalogs, which should be very useful for a number of different projects.

References:

Weir, N., Fayyad, U., and Djorgovski, S. 1995, "Automated Star/Galaxy Classification for Digitized POSS-II", *Astron. J.* in press

Weir, N., Djorgovski, S., and Fayyad, U. 1995, "Initial Galaxy Counts From Digitized POSS-II", *Astron. J.* in press

Weir, N., Djorgovski, S., Fayyad, U., Smith, J.D., and Roden, J. 1994, "Cataloging the Northern Sky Using a New Generation of Software Technology", in H. MacGillivray *et al.* (eds.), *Astronomy From Wide-Field Imaging*, Proceedings of the IAU Symp. #161, p. 205. Dordrecht: Kluwer.

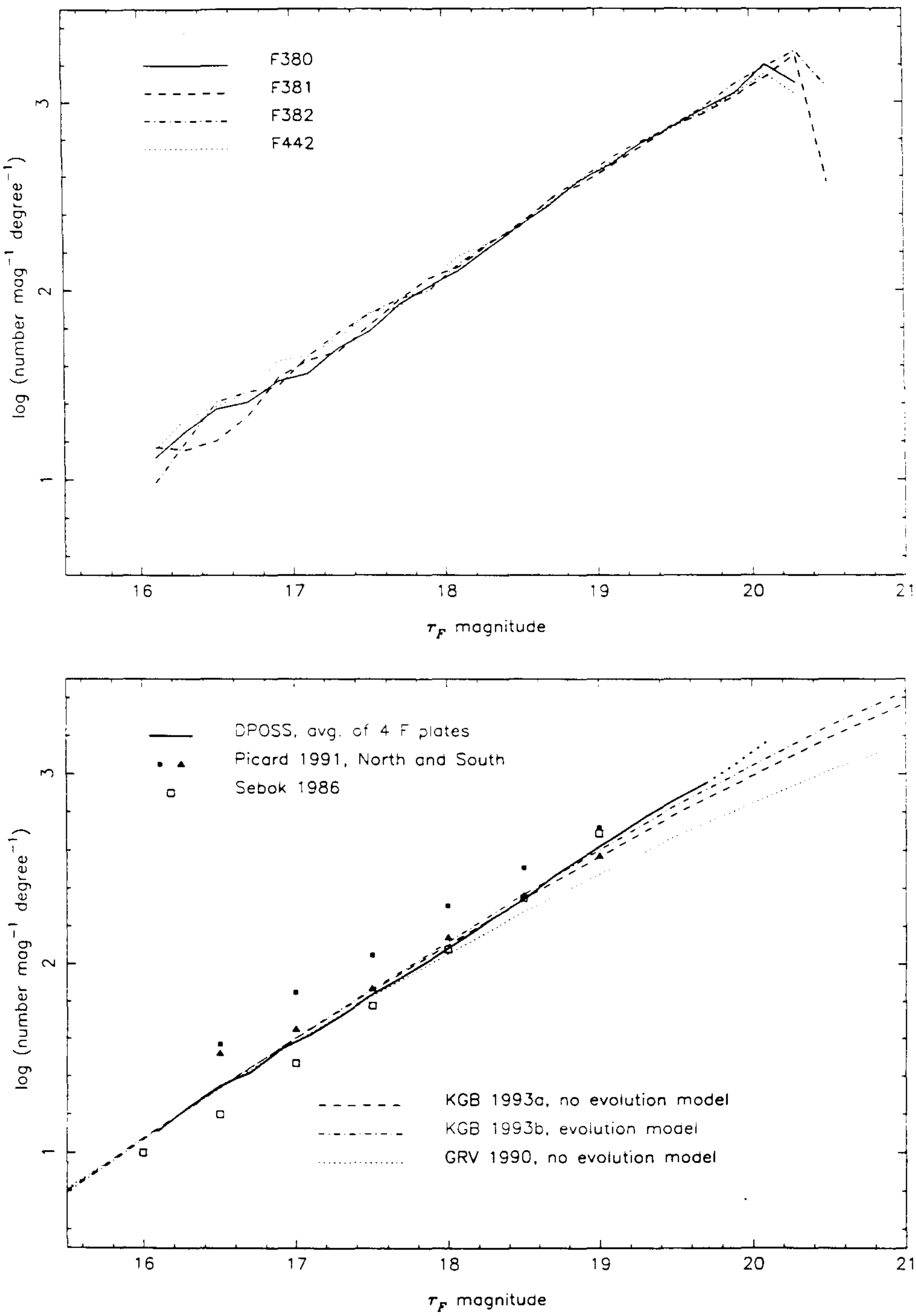


Figure 1. Top: Internal consistency of galaxy counts in the red band, for four sky survey fields near the North Galactic Pole. The rollover at $r \approx 20^m$ (roughly, $B \approx 21.5^m$) is due to the star-galaxy classification limit, not to the detection limit. Bottom: A comparison of our galaxy counts (solid line) with some of the previous measurements, and with three theoretical models.

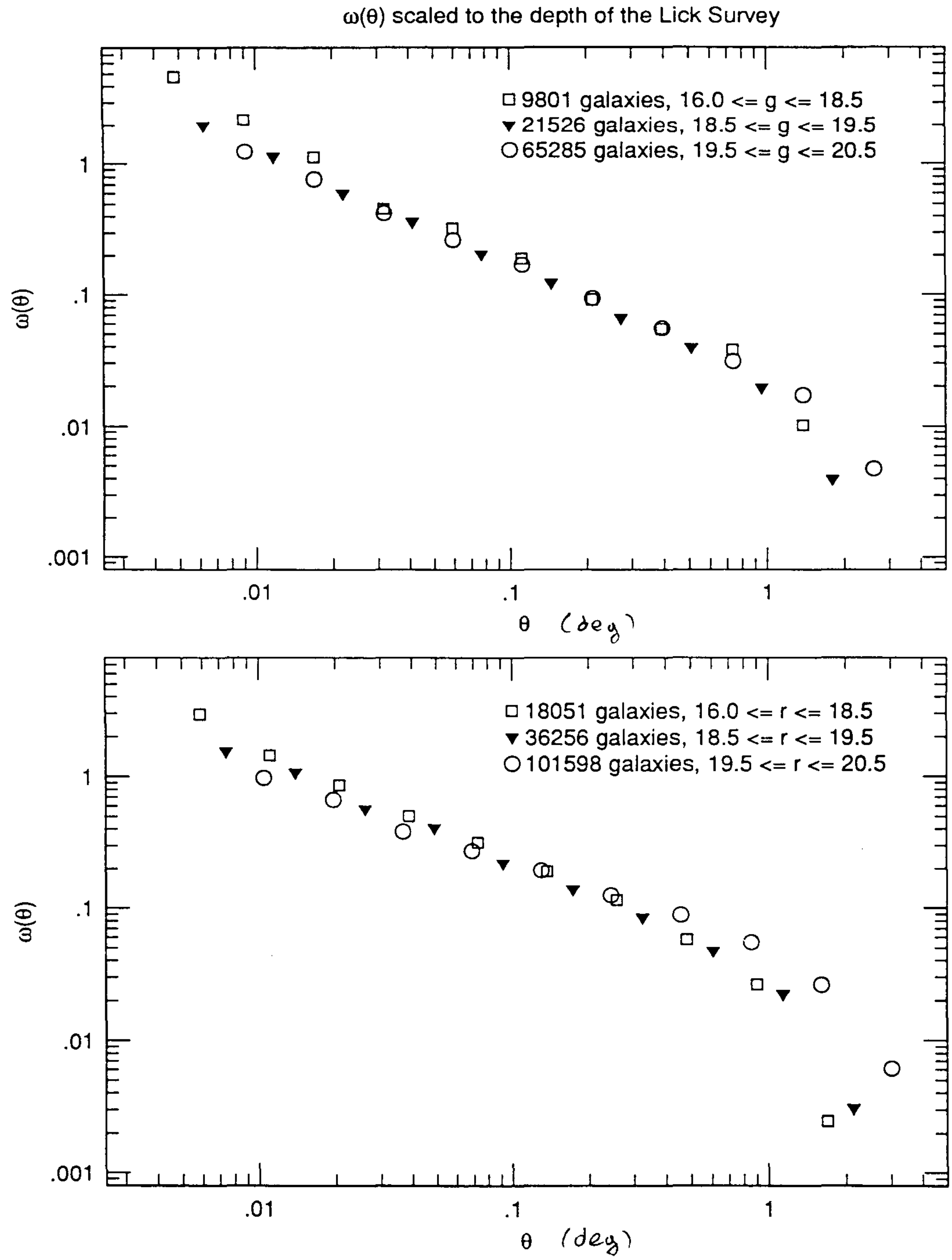


Figure 2. Galaxy two-point correlation functions for a four survey fields area near the North Galactic Pole, for the green plates (top) and the red plates (bottom). The correlation functions have been scaled consistently to the depth of the old Lick survey, a standard comparison in this kind of work.

Near Infrared Spectroscopy of the Arp 220 Nuclei

J. E. Larkin, L. Armus, R. A. Knop, K. Matthews, B. T. Soifer
Palomar Observatory, California Institute of Technology, 320-47, Pasadena, CA 91125

Subject Heading: Galaxies and Quasars

Arp 220 is the nearest and best studied example of an infrared ultraluminous galaxy. Such galaxies were found by the IRAS satellite to produce huge quantities of energy primarily in the infrared portion of the spectrum. Arp 220 is one of the most extreme cases, having approximately 98% of its energy emerge in the infrared (Telesco, 1988). It is believed that most if not all of these galaxies result from the collision and subsequent merger of two galaxies. In Arp 220, this hypothesis received a strong boost when James Graham and collaborators (1990) discovered in the near infrared that Arp 220 contains two very close nuclei, suggesting that Arp 220 was once two galaxies.

We observed Arp 220 on 26 July, 1994 with the recently completed near infrared spectrometer (see annual report). The galaxy is part of James Larkin's Ph.D. thesis project to observe LINER galaxies with the spectrometer. LINER galaxies are extremely common, making up almost 30% of all galaxies, but exhibit unusual and unexplained spectral features which result from an unknown power source in the nucleus, perhaps a black hole. Arp 220 is one of the most energetic examples of a galaxy with a LINER-like spectrum and was an early target for Larkin's thesis.

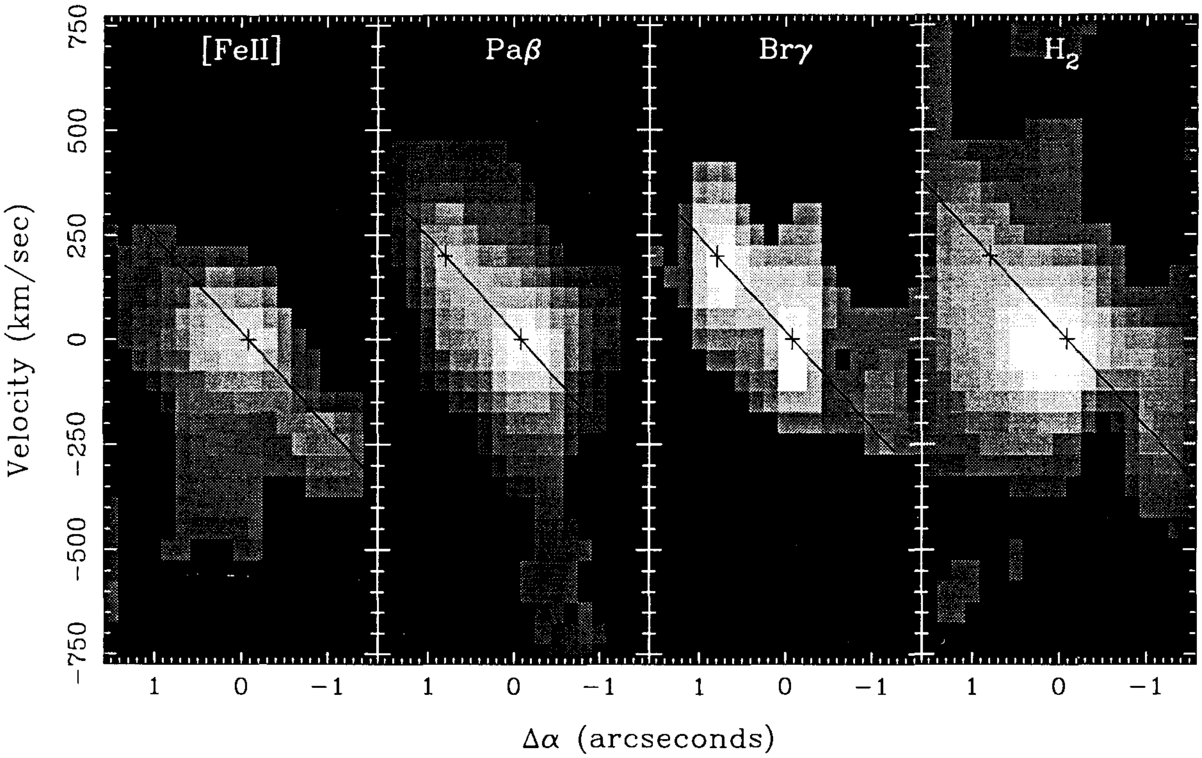
The spectra of Arp 220 were taken under extremely good atmospheric conditions. One of the most exciting results of the observations was a velocity shift between the two nuclei most likely resulting from orbital motion about one another. Being able to measure this orbital velocity allows a lower limit to be placed on the mass of the central region of Arp 220 of about 1.5 billion times the mass of the sun. The accompanying figure shows the spectra of four near infrared lines within Arp 220. Each plot shows gas velocity versus position along the spectrometer's slit. The velocity shift between the nuclei is visible in the two panels labeled Brγ and Paβ. These two lines trace ionized gas and are often strong in active galactic nuclei. The other two lines, H_2 and [FeII], do not show a velocity shift between the two nuclei. These lines are most commonly associated with shock wave propagation, although both are excitable through other means. The ratios of these emission lines were inconsistent with the idea that the energy was produced from a starburst, or episode of extremely active star formation. The observations are most consistent with enormous shock waves propogating within the inner region perhaps as the result of the collisions of gas clouds caused by the merger of the two original galaxies, or from winds of material being thrown out from the nuclei, perhaps due to the action of a black hole.

We would like to thank the night assistants and other staff of Palomar Observatory for their assistance with operating the spectrometer and telescope. Infrared astronomy at Caltech is supported by grants from NASA and the NSF. These results have been submitted to the Astrophysical Journal Letters for publication.

References

Graham, J. R., Carico, D. P., Matthews, K., Neugebauer, G., Soifer, B. T., & Wilson, T. D. 1990, ApJ, 354, L5.

Telesco, C. M., 1988, ARA&A, 26, 343.



Spectra of four infrared emission lines within Arp 220. In each box, gas with increasing velocity is towards the top, and position along the slit is left to right. The two lines labeled Paβ and Brγ result from the recombination of ionized hydrogen atoms. The other two, [FeII] and H_2 usually come from regions with medium to high velocity shock waves. Note that the recombination line emission is slanted in these plots showing a velocity gradient across the nucleus. This we interpret as rotation of the two nuclei about each other. The shocked gas does not exhibit this tilt and is moving differently within the nucleus. The two crosses mark the location of the two nuclei in each plot.

The Star Formation Histories of Galaxies:
Using Spatial Moments as a New Observational Probe

Principal Investigator: Christopher Martin
Division of Physics, Mathematics, and Astronomy
California Institute of Technology

Co-Investigator: Dr. Peter Friedman
Columbia University

Subject Heading: Galaxies and Quasars

We have initiated a program of precise measurements of faint galaxy properties, in order to explore the evolutionary history of faint field galaxies. To date, studies have been limited to number counts in various bands, redshift distributions for brighter galaxies, and high resolution imaging with HST for the brightest galaxies. We are utilizing a new observational discriminant: the low order spatial moments of the galaxies, with emphasis on the moment shifts in different bands. While HST will compete for brighter galaxies, the Keck Telescope will provide much higher sensitivity for faint galaxies, much better detection of low surface brightness extended emission, a much larger statistical sample, and an observational methodology specifically designed for this work. Recent refinements to the bright count normalization may indicate that the evolutionary effects appear strongly only for B>25, implying that Keck data will be definitive for discriminating among evolutionary models at moderate and large redshifts.

There is mounting evidence in nearby galaxies for multiple star formation episodes. We expect that for a significant fraction of the life of a galaxy , the old and young stellar populations will not be spatially coincident, as they will reflect different dynamical stages in the evolution of the galaxy: collapse, late infall, spiral density waves, interactions, mergers. Thus the precise measurement of faint galaxy spatial moments at two widely separated bands (e.g. B, I, and eventually K) will furnish a powerful new test of evolutionary models. For example, the simple presence or absence of color-dependent centroid shifts will immediately discriminate between several models for the purported excess of faint blue galaxies. Detailed modelling of moments and their color shifts using the large galaxy sample that will be obtained in a single LRIS field will place strong constraints on surviving models.

We have obtained preliminary data on the Palomar 60 inch and on the Keck telescope in support of our study of the spatial moments of faint galaxies.

We have obtained a preliminary sample of local "calibration" galaxies on the 60 inch. We have measured significant centroid, second moment, and higher moment shifts between B and I. Some statistics are plotted in Figure 1. Note that the B-band and I-band centers of light display shifts in the range $0.02 < \delta_{B-I}/\theta_I < 0.10$, with the expected correlation with later morphological type. We are proposing to obtain a much larger sample at the 60 inch including a selection of representative mergers and interacting galaxies.

We have analyzed serendipitous data obtained by S. Kulkarni on LRIS with 0.6-0.9 " seeing (with I. Smail and L. Yan). This data was taken in single exposures, up to 2 ksec. We examined one field in R and V to determine the limits on this measurement with LRIS. After calibrating out instrument chromatic aberrations, the 1 ksec exposures give a relationship between the relative error of the centroid shift: $\log [\sigma(\delta_{V-R}/\theta_V)] = 0.2[V-30.0]$. This threshold is limited by systematics (such as uncorrected pixel-to-pixel color variations of ~0.3%), as $\log [\sigma(\delta_{V-R}/\theta_V)] = 0.2[V-32]$ is expected from Poisson sky noise alone. (cf. Figure 2, showing $\sigma(\delta_{V-R}/\theta_V)$ vs. V). Figure 3 shows some objects which had excess δ_{V-R}/θ_V. A very preliminary examination of these indicates that these galaxies may be bluer and morphologically more complex than the "typical" galaxy.

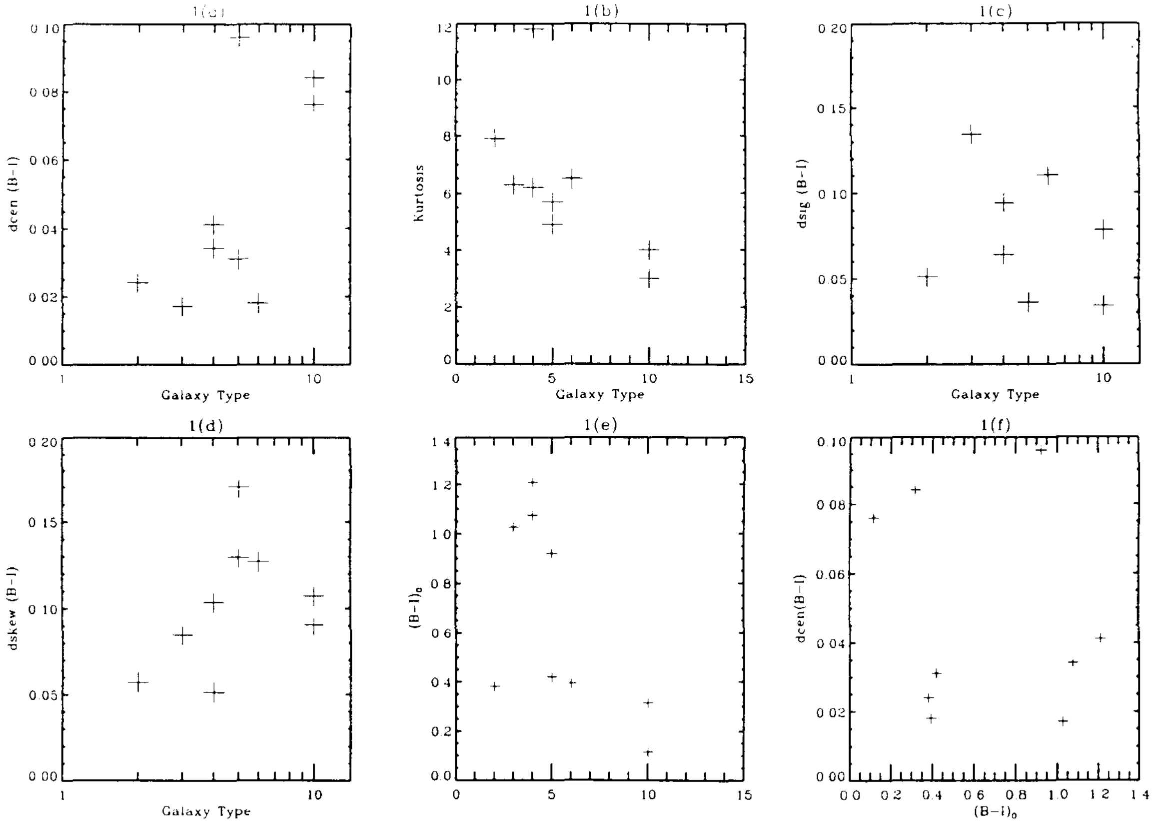


Figure 1: Some statistics from the preliminary galaxy moments calibration. (a) The B/I center of light shift normalized by the rms radius of the galaxy, vs. morphological type. (b) Kurtosis vs. morphological type. (c) Normalized 2nd moment shift vs. morphological type; (d) Skew vs. type; (e) Color vs. type; (f) Normalized centroid shift vs. color.

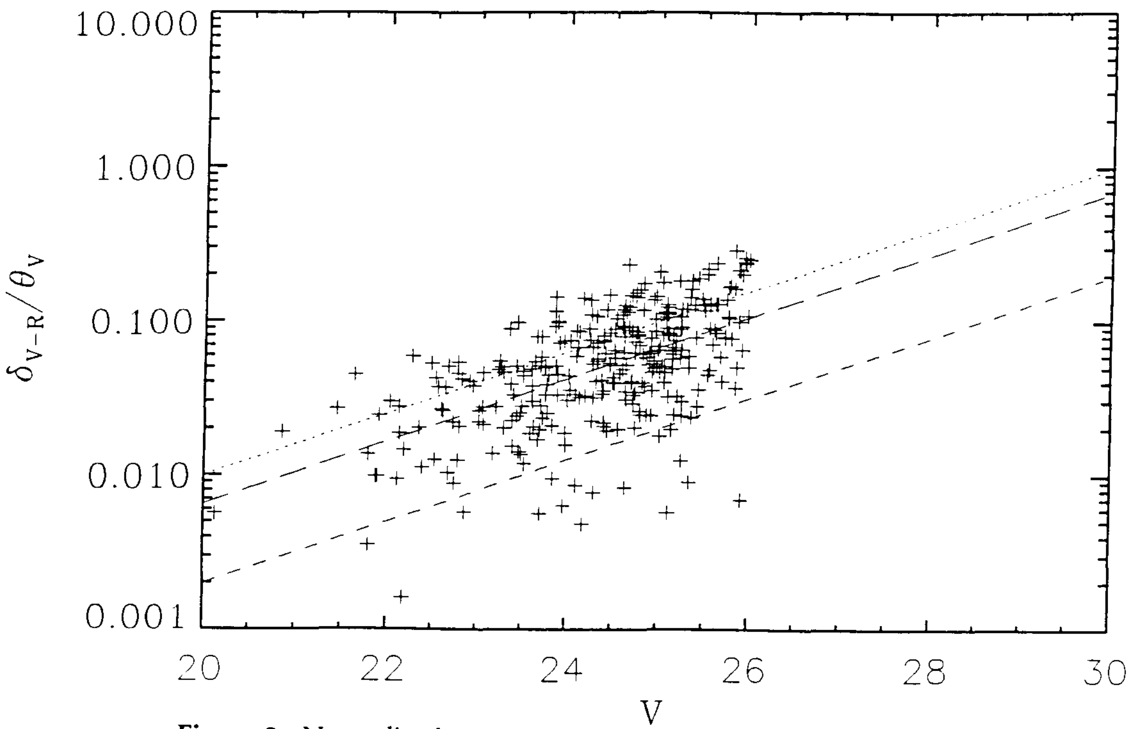


Figure 2: Normalized V/R centroid shift vs. V magnitude, for serendipidous deep field PSR1640+2224. Deviations from sky noise should follow 0.2V law, and do based on least squares fit, shown in dotted line, since galaxy surface brightness is approximately constant. Dotted line shows observed dependence, solid line shows 1σ predicted from pure Poisson fluctuations in sky noise, and dashed shows goal of proposed observation.

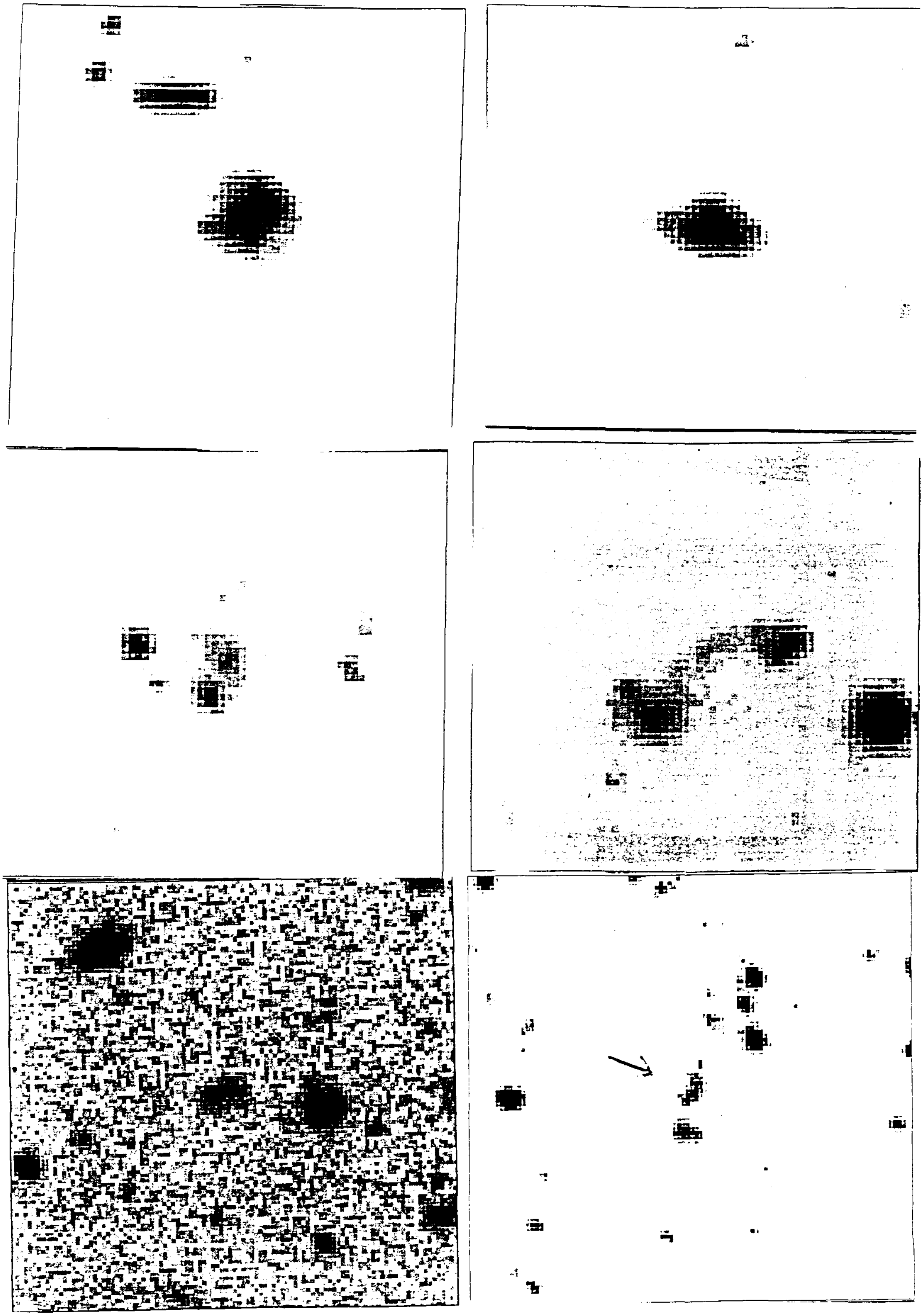


Figure 3: Examples of galaxies showing significant centroid shifts above the fitted 0.2V dependence. R-V colors for the four objects are (a) 0.4, (b) 0.8, (c) 0.3 (d) 0.4, (e) 0.1. (d) may be a lensed arclet. (f) -0.10 (g) -0.15.

Imaging and Spectroscopic Studies of Gaseous Galactic Halos

Principal Investigator: Christopher Martin
Division of Physics, Mathematics, and Astronomy
California Institute of Technology

Co-Investigators:

Dr. Peter Friedman
Columbia University

Dr. Stuart Vogel
University of Maryland

Subject Heading: Galaxies and Quasars, Interstellar Medium

The existence and nature of gas in the halos of spiral galaxies remains an elusive problem, despite considerable observational and theoretical effort. Since the pioneering hydrostatic hot halo model of Spitzer (1956),theoretical interest has turned to dynamical halos, such as the galactic fountain model (Shapiro and Field 1976), which are fueled by the individual and collective action of disk supernovae. Galactic halo gas may play an important role in the evolution of galaxies, particularly in the enrichment history. Understanding of halo gas may be a critical component of any explanation of QSO metal line absorbers.

Optical emission from galactic halos may be produced by a variety of processes: recombination and/or collisional excitation in warm or hot ionized gas, resonance line scattering and fluorescence of disk starlight from ionized or neutral gas, and scattering by halo dust of disk starlight. Photoionized gas at 10^4K should produce Hβ 4861,[OIII] 4959,5007, and [OII] 3727 emission. Collisionally ionized gas at 10^5 K, such as that found in the Milky Way (Martin and Bowyer 1990), would also produce [OIII] emission, as well as HeII 4686 and [Ne III] 3869 (among others). Silk and Sunyaev (197) pointed out that halo and exterior disk gas in galaxies without internal sources of collisional- and photoionization will still be ionized by the metagalactic UV radiation field, producing an inverse HII region.

Most observational evidence relates to the Milky Way halo. Observational efforts have tried to connect the phenomenology of the Milky Way halo gas with external galaxy halos. Observations of UV absorption (Savage and deBoer 1978: Davidson 1991) and UV emission (Martin and Bowyer 1990) in the Milky Way support the existence of collisionally-ionized gas in the halo, consistent with a low galactic fountain model and a halo scale height of ~2-4 kpc. The observation of HI chimneys and recent modelling of the collective action of supernovae in OB associations has contributed compelling evidence for the injection of cool and hot gas into the halo. ROSAT observations of a number of edge-on spiral galaxies have revealed million degree gas with scale heights of several kiloparsecs and with highly non-uniform morphology.

We have performed CCD narrow-band imaging on the Palomar 60 inch telescope of two nearby edge-on galaxies, NGC4565 and NGC891. We have detected [OIII] 5007 in the halo of both galaxies. In NGC891, the intensity is 0.2-0.5R, with a z-scale height for emission of 1-1.5 kpc, a factor of 1.5-2 greater than the Hα scale height which we also measure (cf. Figure 1). In NGC4565, where no Hα has been detected, we detect weak [OIII] in the halo in several locations, again with a 1-1.5 kpc emission scale height, and with an intensity of 0.1R. In both cases, since [OIII] is produced by collisional excitation, this implies that the [OIII] gas scale height is 2-3 kpc.

We have also performed deep spectroscopic measurement of the halo of NGC4565. We detect no Hα, to a limit of 0.15R (3 sigma), but we do detect [SII] up to 2 kpc off the disk. The implication is that the Hα and [OIII] gas phases may be unrelated. The [OIII] phase may be produced by cooling instabilities in a galactic fountain in both galaxies. The measured scale height is similar to that measured using absorption lines of high ionization species (CIV, NV) in the Milky Way, and the intensities compare reasonably with the CIV 1550 emission line intensity observed in the Milky Way halo.

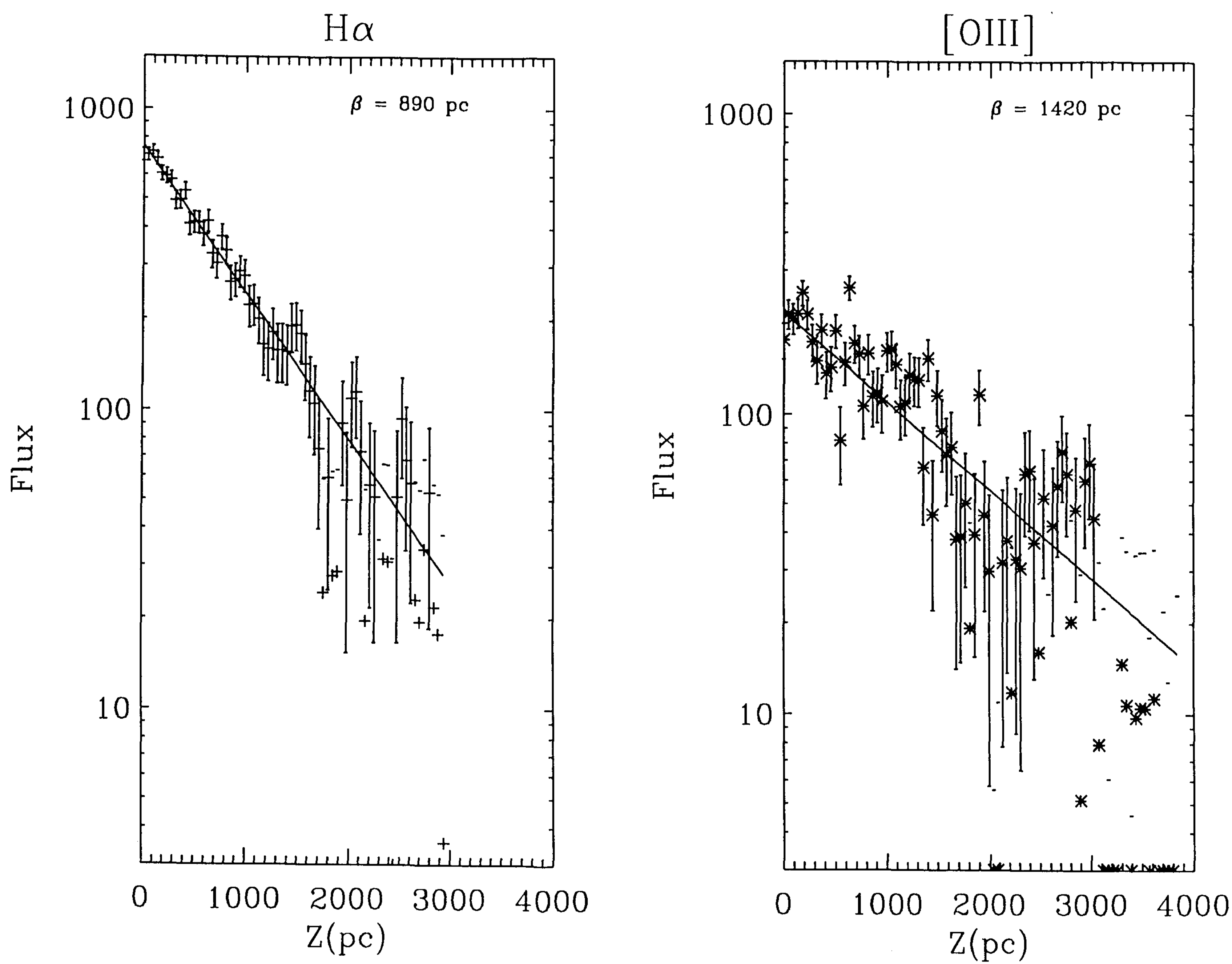


Figure 1: Emission from gas in the halo of NGC891. (a) Hydrogen line emission (Hα). (b) Oxygen ([OIII]) emission. The latter has a significantly higher scale height.

Molecular Hydrogen Fluorescence in a Dissociating Molecular Cloud IC63

Principal Investigator: Christopher Martin
Division of Physics, Mathematics, and Astronomy
California Institute of Technology

Co-Investigators:

Dr. Tom Jarrett
Dr. Chas Beichman
IPAC

Subject Heading: Interstellar Medium

UV fluorescence of the Lyman and Werner bands is an observable byproduct o f the photodestruction of molecular hydrogen. It has been detected in the diffuse ISM by Martin, Hurwitz and Bowyer (1990), in Burnam's nebula (Brown etal 1981) and in the nebula IC63 (Witt etal 1989). In the latter case, the cometary nebula is clearly being destroyed by the nearby B-star γCas. The copious emission of Lyman band emission implies a fairly high density UV fluorescence pumps excited vibration levels in H_2, and the low decay rates lead to a significant population of H_2^*, which can have an important impact on the chemistry and energetics of the dissociation region.

We have searched for the radiative decay lines from the UV pumped vibrational states in H_2 in this nearby (D=190 pc) nebula using the Prime Focus IR Camera. With 1 arcsecond resolution, we can resolve structure in the photodissociation region of IC63 to $3X10^{15}$ cm. At a density of 10^5 cm^{-3}, this permits a column density resolution of $3X10^{20}$ cm^{-2}, or in terms of visible extinction $\Delta A_V \sim 0.14$. Photodissociation region models such as Tielens and Hollenbach (1985) predict significant structural variations on A_V scales of a few tenths of a magnitude.

We used the 200 inch PFIRC with narrow band filters at H_2 S(1) (1-0) and H_2 S(1) (2-1). The nebula displays copious H_2 emission, and the ratio of the (2-1)/(1-0) lines is 0.6, precisely the prediction for a fluorescent cascade through the vibrational levels (cf. Figure 1). The intensity observed implies that the NIR emission arises from a deeper, and more extensive layer of the dissociating cloud, since the Far UV emission arises from a layer with A(1600Å) ~ 1, and A(1600Å)/A(2.2 mm) ~ 11. We are developing a simple model to fit the combined far UV and NIR data.

We have also observed the edge-on galaxy NGC891 in the H_2 S(1) lines, and analysis is in progress. We hope to observe diffuse H_2 emission from the dissociating molecular gas throughout this galaxy. We plan to observe other nearby galaxies in future runs to survey the diffuse fluorescent emission and thereby study the dynamic equilibrium between the atomic and molecular phases in the global galactic interstellar medium.

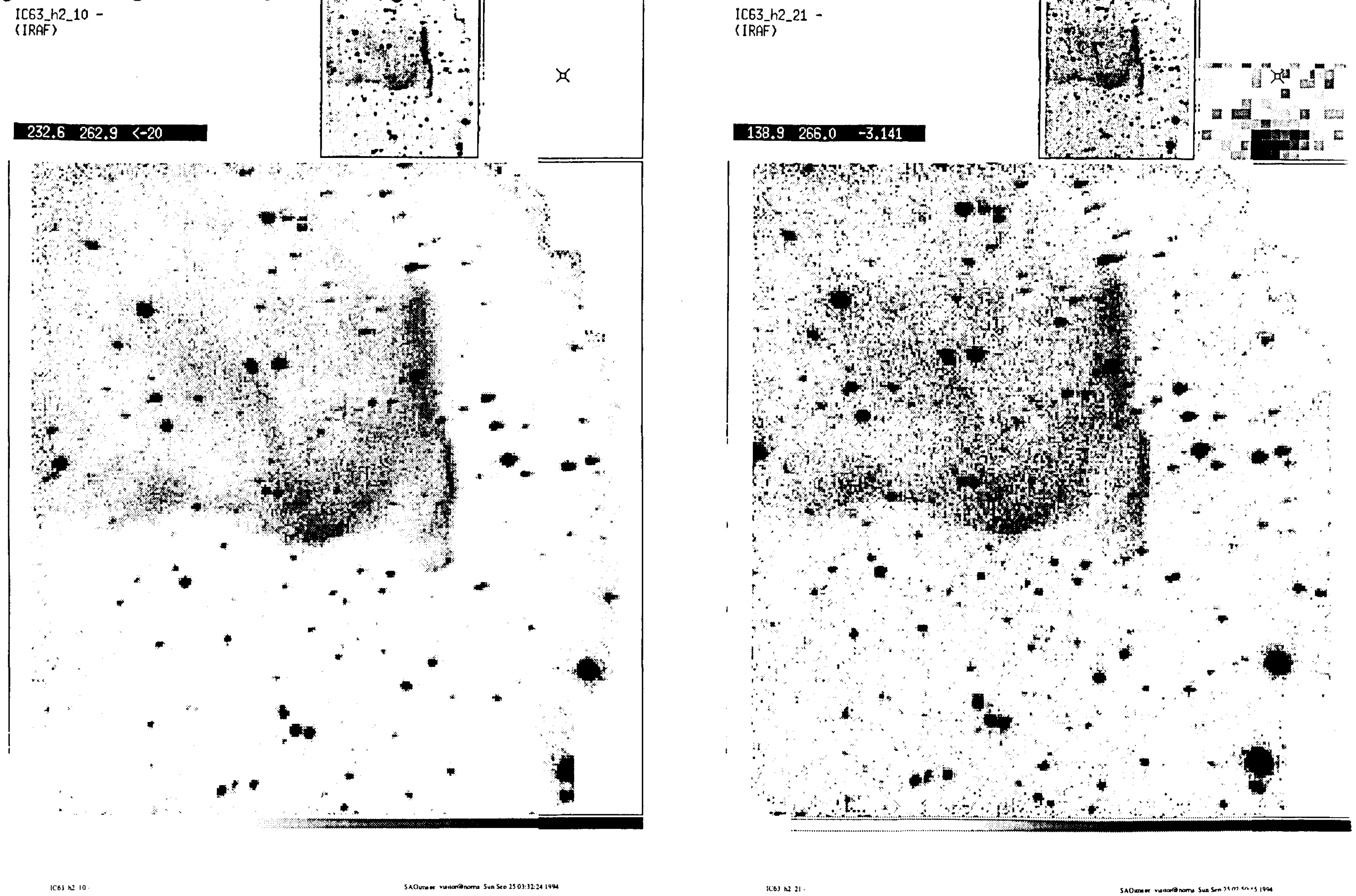


Figure 1: Narrow band PFIRC images of IC63 at (a) H_2 S(1) (1-0) and (b) H_2 S(1) (2-1). The nebula displays copious H_2 emission, and the ratio of the (2-1)/(1-0) lines is 0.6, precisely the prediction for a fluorescent cascade through the vibrational levels.

Long Slit GRISM Spectra of the Ultraluminous Galaxy Arp 220

G. Neugebauer, L. Armus, K. Matthews, B. T. Soifer
California Institute of Technology
Palomar Observatory

Subject heading: Galaxies and Quasars

The visually complex galaxy Arp 220 was shown by the Infrared Astronomical Satellite (IRAS) to emit 99% of its luminosity in the infrared. In fact, Arp 220 turns out to be prototypical of a new class of galaxies, the ultraluminous infrared galaxies, galaxies as luminous as quasars. More recently, near infrared observations have shown that the nucleus actually consists of two nuclei separated by 0.9" and that Arp 220 is most likely the result of a nuclear merger. Many studies of this system have been carried out in attempts to understand it in some detail, but the source of its high infrared luminosity is still in debate. The two main theories have involved either an active galactic nucleus (a massive black hole) or large star-bursts in the nucleus.

As reported in the Annual Reports last year, a near-infrared imaging study of Arp 220 has revealed that Arp 220 is a strong source of nuclear and circum-nuclear forbidden iron [FeII] and Pa-β emission in the near infrared. Imaging in the two lines has indicated that the [FeII] and Pa-β emission are both extended over the central 2-3", but with different morphologies. The [FeII] is more extended in the north-south direction than the Pa-β line. Nearly 75% of the detected [FeII] emission is spatially resolved. The Pa-β line is strongly peaked at the position of the western infrared nucleus, with a fainter "spur" in the direction of the eastern nucleus, while the [FeII] emission-line shows a weak peak at the western nucleus along with diffuse emission extending to the east, but with little indication of a secondary maximum at the eastern nucleus.

Last year, as well as taking images of the nuclei through narrow band filters, the complementary technique of long slit GRISM spectrometry was applied to the problem by aligning the slit of the GRISM along the axis joining the two nuclei. The seeing at Palomar was sufficiently good to isolate the two nuclei and thus to map out the line strengths in detail across the nuclei. The figure shows the total nuclear spectra in two wavelength intervals and how the lines change as a function of position.

The [FeII] and Pa-β line fluxes have morphologies in Arp 220 that are similar to those seen in active galactic nuclei and are larger than what is measured in galaxies powered mainly by nuclear star-bursts. Their ratios have led us to suggest that the extended [FeII] emission is generated as a result of fast shocks being driven into the circumnuclear gas. These shocks are produced in a powerful outflow - a super wind (Heckman, et al., 1987, *A J*, **93,** 276) from the star-burst in the nucleus.

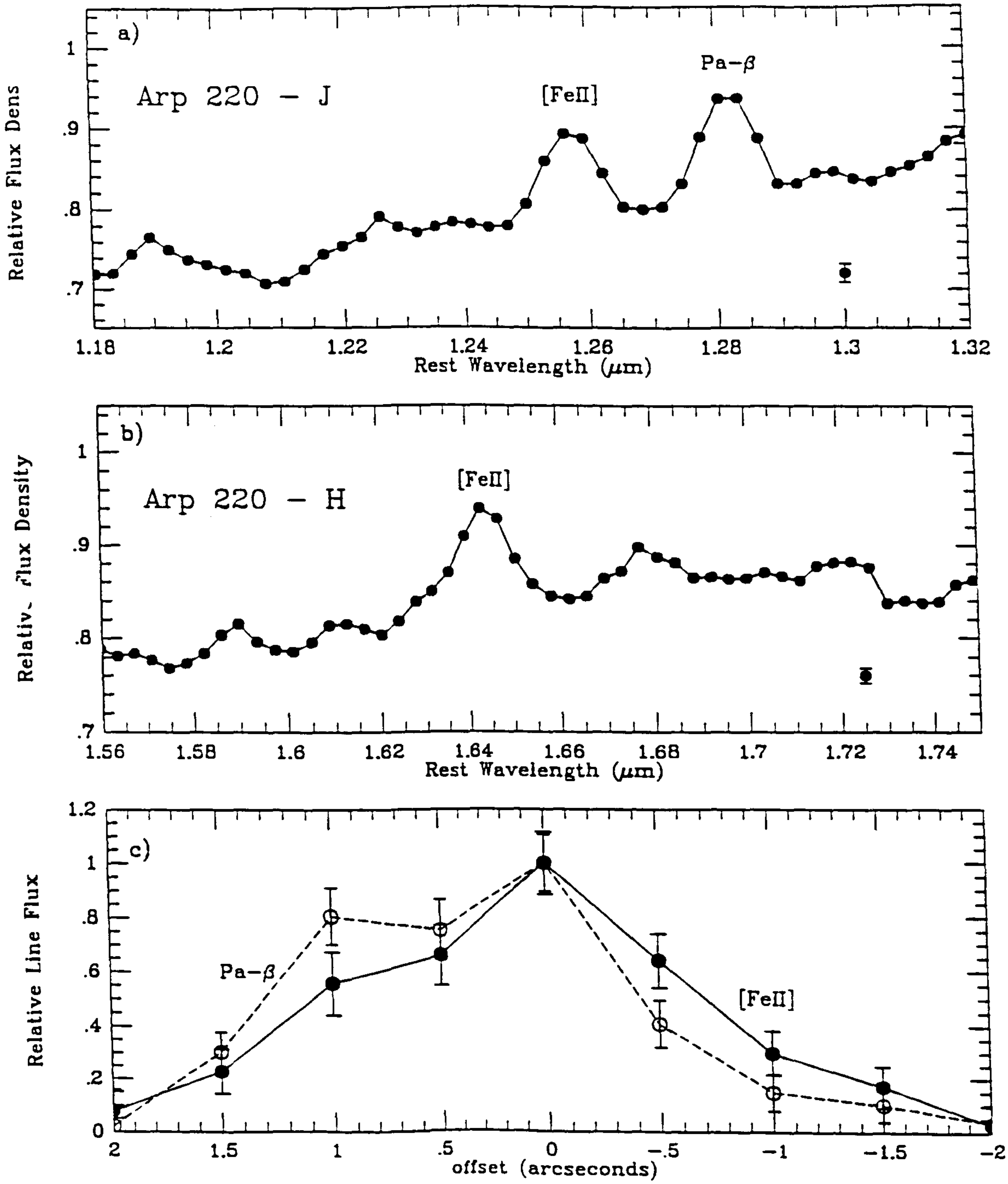


Figure Caption

Figures (a) and (b) show spectra of the central portion of Arp 220, extracted from an east west oriented slit encompassing both eastern and western infrared nuclei. The [FeII] and Pa-β lines are prominent at 1.644 μm and 1.257 μm. Figure (c) shows the [FeII] 1.257 μm and Pa-β lines as a function of position along the 0.8" wide slit normalized to 1.0 at the position of the western infrared nucleus. Note that the [FeII] and Pa-β lines have different spatial profiles, the former showing a sharper drop to the east and a shallower drop to the west than the latter.

Palomar Report

A. C. S. Readhead

Redshifts for the Caltech-Jodrell Integrated Sample

This program aims to find redshifts for a large complete sample of active galaxies which are being studied extensively at radio wavelengths. Altogether there are 347 objects in the sample, and redshifts have been obtained either at Palomar or through the literature of 251 of these. The program is the most intensive radio study that has been carried out thus far on active glaxies. In particular, Very Long Baseline Interferometry (VLBI) observations, with angular resolution of approximately one thousandth of a second of arc, have been obtained for most of the objects. This has led to two important discoveries:

1) A class of objects in which the radio structure is symmetric on the scale of 1pc – 100 pc — which we have named "Compact Symmetric Objects" (CSO's) has been discovered. These objects are either remarkably young and short-lived (typically $\sim$ 3000 years); or they must occur in extremely dense, massive neutral clouds in galactic nuclei. Typical masses are $10^{10}\,M_{\odot}$ in a cloud of radius < 200 pc.

2) It has been found that the small nuclear radio structure in these objects is preferentially aligned either parallel to the large-scale radio structure, or orthogonal to the large-scale structure. This was a very unexpected result, which might, possibly, indicate the presence of a binary black hole in these active galaxies.

In addition to these discoveries, these surveys are being used for two cosmological studies:

(i) the angular diameter-redshift relationship; and

(ii) the proper motion-redshift relationship.

Each of these programs aims at measuring the deceleration parameter, and hence the mean density, of the universe. The Palomar redshifts are essentail for all aspects of this work.

The Norris Survey of the Coronae Borealis Supercluster

Principal Investigators: Wallace L.W. Sargent and Todd A. Small
Palomar Observatory
California Institute of Technology

Subject Heading: Galaxies and Quasars

G.O. Abell (1958), from his survey of galaxy clusters on plates from the Palomar Sky Survey, was the first to observe and note the existence of clusters of clusters of galaxies. These clusters of clusters of galaxies, since dubbed "superclusters," are the largest identified structures in the universe. Superclusters are typically several hundred million light-years across in their longest dimension and have not yet reached equilibrium with their surroundings. In fact, superclusters are likely to still be expanding with the universe, albeit at a decelerated rate. The fundamental interest in superclusters derives from the fact that they are not yet in equilibrium, or, in other words, that the timescale for significant dynamical changes is as large as the age of the universe. This implies that imprints of how superclusters formed have not yet been erased by dynamical evolution. In particular, one hopes that studies of superclusters may yield information on the nature of density fluctuations in the early universe and may offer clues about the physical processes at work during the epoch of galaxy formation (Oort 1983).

We are carrying out a redshift survey of the Coronae Borealis supercluster, which is one of the most striking examples of superclustering in the sky, using the Norris Spectrograph on the 200-inch Hale telescope. The Norris Spectrograph is a sophisticated multifiber instrument that can record the spectra of up to 176 galaxies in one exposure. The survey consists of 36 fields distributed in a 6×6 rectangular grid over a $5° \times 5°$ region which contains seven rich galaxy clusters all at the same distance. We hope ultimately to measure appoximately 2500 redshifts, a number sufficient to allow a determination of the mean galaxy density in our survey region to around 5%.

The principal goal of the survey is to study the shape and extent of the Coronae Borealis supercluster. Although the region containing the seven Abell clusters is only 130 million light-years in diameter, there is circumstantial evidence that Corona Borealis extends for at least 700 million light-years in the two directions on the sky (Bahcall 1992). The evidence consists of structures seen at the same distance as Corona Borealis in other deep redshift surveys that were pointed up to 45° away from Corona Borealis. In constrast, preliminary results from our survey suggest that the depth of Corona Borealis is only 130 million light-years. Corona Borealis thus appears to be a flattened pancake. Although it is certainly not practical to survey the whole 700 million light-year by 700 million light-year region (which corresponds to 730 square degrees on the sky), we will be able to delineate accurately the structure of the Coronae Borealis supercluster out to a radius of 130 million light-years.

We have collected over 1050 redshifts in the Coronae Borealis field in three seasons. The rate at which accumulate redshifts more than doubled this spring with the addition of a large-format CCD with extraordinary quantum efficiency. With 9000 second exposures, we can reach $r \sim 21$ with a velocity resolution of 75 km s^{-1}. A close-up view of the distribution of galaxies in redshift-space around the Coronae Borealis supercluster is shown in a redshift-right ascension pie diagram (Figure I). The supercluster (redshift $z \approx 0.07$) and a background structure (redshift $z \approx 0.11$) over two billion light-years distant stand out in this figure. We have distinguished galaxies with emission lines from those with only absorption lines. Although we have not yet performed a detailed analysis, it appears to the eye that the emission-line galaxies are not as strongly clustered as the absorption-line galaxies and that the emission-line galaxies are very roughly distributed in shells surrounding the dense concentrations of absorption-line galaxies. Both of these observations, if they remain evident when all the data have been collected, will support the theory that the emission-line galaxies are gas-rich objects that are only now separating from the general expansion of the universe and falling into the cluster cores (Gunn and Gott 1972).

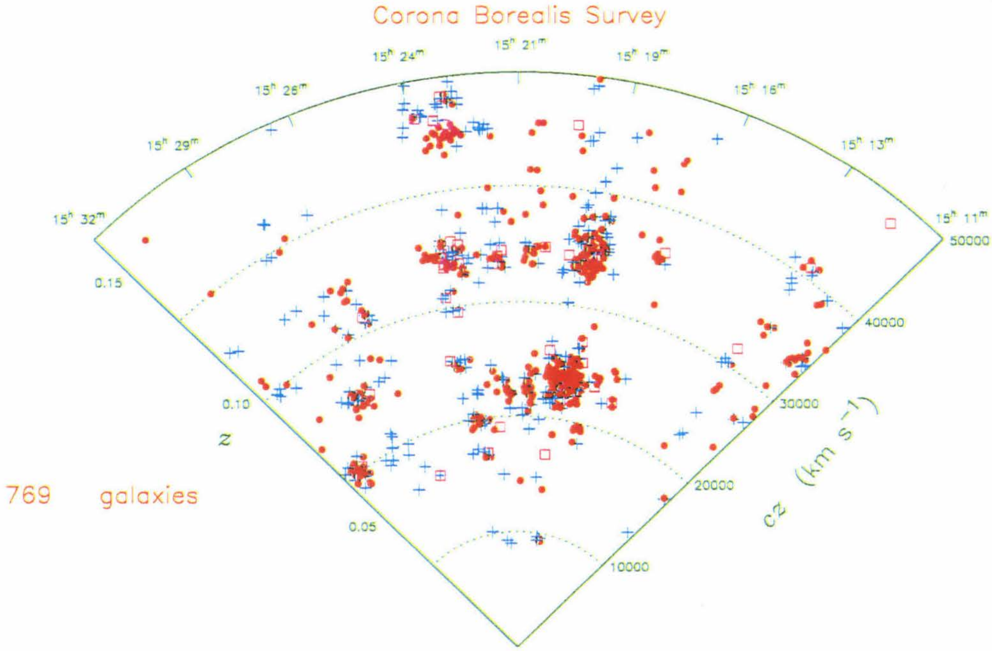


Figure I. Redshift-right ascension diagram for our nearby data. Galaxies with emission lines are marked with crosses, galaxies with absorption lines are marked with circles, and galaxies with E+A spectra are marked with squares. The regions between R.A. 15^h13^m and R.A. 15^h16^m and between R.A. 15^h24^m and R.A. 15^h26^m have not yet been surveyed.

Further support for the theory that emission-line galaxies are falling into the clusters is given by our detection of a population of galaxies, called "E+A" galaxies, within the cluster that are readily interpreted as the direct descendants of the infalling emission-line galaxies. "E+A" galaxies have hydrogen Balmer series absorption lines (an A-star spectrum) superposed on the spectrum of an old stellar spectrum (characteristic of an elliptical galaxy), indicating that the galaxy has had a burst of star formation in the previous billion years. The burst of star formation was perhaps induced when an infalling gas-rich galaxy crossed a spherical shock front in the intracluster medium (Evrard 1991). During the burst, the galaxy would have had strong emission lines, just like the emission-line galaxies detected in our survey.

References

Abell, G.O., 1958. *Ap. J. Supp.*, **3**, 211.

Bahcall, N.A., 1992. In: *Clusters and Superclusters of Galaxies*, p. 275, ed A. C. Fabian. Kluwer Academic Publishers, Dordrecht.

Evrard, A.E., 1991. *MNRAS*, **248**, 8p.

Gunn, J.E. and Gott, J.R., 1972. *Ap. J.*, **176**, 1.

Oort, J.H., 1983. *ARAA*, **21**, 373.

Rees, M.J., 1992. In: *Clusters and Superclusters of Galaxies*, p. 1, ed A. C. Fabian. Kluwer Academic Publishers, Dordrecht.

Zeldovich, Ya.B., 1970. *A&A*, **5**, 84.

THE EVOLUTION OF GALAXYIES AND THE GROWTH OF RICH CLUSTERS: DEEP IMAGING WITH COSMIC ON THE 200″

Investigators: Ian Smail, Roger Blandford (Caltech) & Alan Dressler (OCIW).

Subject Heading: Galaxies and Quasars

We have obtained very deep images of distant clusters of galaxies to study the evolution of both the galaxies within the clusters and the growth of the clusters themselves. These images were taken with a new high-efficiency CCD detector mounted on the COSMIC imaging spectrograph at the prime focus of the 5-m Hale. This new CCD detector is roughly a factor of two more efficient than the previous detector and has thus allowed us to obtain high quality data on very faint galaxies in relatively short exposure times. This new facility was provided at very short notice by Profs J. Westphal and J. McCarthy to whom we are indebted for their hard work.

We imaged a total of fourteen rich clusters which because of their great distances are observed as they were roughly three to seven billion years ago. The most distant clusters are thus seen at an epoch when the Universe was less than half its current age. These clusters will be used to study the evolution of galaxy populations within rich clusters. In nearby clusters a single type of galaxy dominates the central regions: spheroidal galaxies. These galaxies are clouds of stars supported by the random motions of the stars, rather than bulk rotation, as seen in Spiral galaxies such as the Milky Way. They are also characterised by old stellar populations which show extremely homogenous qualities, such as color. The homogeneity of the colors of the stellar populations between different spheroidal galaxies within a cluster has profound implications for the formation and age of these galaxies. Working from local rich cluster populations model constraints can be placed on both the epoch of formation of the spheroidal galaxies and the possible spread in this epoch between the galaxies. The current limits require that all the bright galaxies within a rich local cluster must have formed in less than a billion years, at least 9 billion years ago.

A much stronger result is possible if we can study the homogeneity of spheroidal galaxy colors in a distant rich cluster, viewed when the Universe was much younger than it is today. We have undertaken such observations of two clusters seen at a look-back time of 7 billion years using the 5-m Hale. These observations were taken in superb conditions during June '94, giving very deep exposures in $\sim$0.7 arcsec seeing. Preliminary analysis of one cluster has shown that the spheroidal cluster galaxies are still remarkably homogenous, the spread in their colors having increased by only a factor of $\sim$50% from that observed locally. This forces the epoch of spheroidal galaxy formation beyond 11 billion years, to within 1–2 billion years of the Big Bang. To take full advantage of this unique dataset we have obtained Hubble Space Telescope images of the central regions of our two clusters. These will allow us to morphologically classify the cluster galaxies and so remove peculiar galaxies from the sample. This should further reduce the scatter amongst the remaining normal spheroidal galaxies and place still stronger limits on their formation epoch.

The remaining twelve clusters imaged this Summer are part of a study of gravitational lensing by massive clusters of galaxies. The clusters are selected on the basis of their X-ray luminosity. These X-rays are emitted from very hot gas which is bound to the deep potential well of the cluster. Thus if a cluster has a high X-ray luminosity it is likely to be very massive. The deep potential wells of such clusters should act as efficient gravitational lenses – deflecting the paths of light-rays passing through them. The observational consequence of this is that the image of any object viewed through the cluster will appear highly distorted, appearing as giant, elongated arcs of light. In the most extreme case several images of a *single* background galaxy will be seen. The properties of the various images (positions, brightnesses, etc) can be used to construct detailed models of the distribution of mass in the lensing cluster and thus constrain the nature of the mysterious 'dark matter' which is thought to dominate the mass of the Universe. We elected to survey a large number of clusters searching for these rare, extreme multiply-image configurations. Furthermore, we noticed that distant galaxies tend to be bright in the near-ultraviolet. Thus we can reduce the contamination of our sample from galaxies in front of and within the clusters by selecting in the near-ultraviolet. The availabilty of a high efficiency CCD on the 5-m made this project feasible.

We are currently analysing the data we collected. In addition to the candidate multiply-imaged systems we have also discovered 3 new giant gravitational arcs. These are extremely distorted images of background galaxies and will be very useful in the modelling of the cluster lenses.

Evolution in the Clustering of Galaxies to $r = 26$

Principal Investigator: Jeremy Mould
Palomar Observatory, Caltech and Mount Stromlo and Siding Spring Observatories, ANU
Co-Investigators: Tereasa G. Brainerd, Theoretical Astrophysics, Caltech and
Ian Smail
Palomar Observatory, Caltech

Subject Heading: Galaxies and Quasars

One of the most challenging problems in astronomy today is to explain the growth of structure in the Universe over the period between redshift 1000 and the present epoch. At early epochs the Universe was structure free to considerable precision. It is of great interest to trace the present rich structure back in time.

Brainerd, Smail and Mould obtained results for the two-point angular correlation function of galaxies, $\omega(\theta)$, to a limiting magnitude of $r = 26$. Their catalogue was constructed from deep imaging using the COSMIC imaging spectrograph on the Hale 5-m. The final sample was 80% complete to $r = 26.2$ mag yielding ~6600 galaxies over a 90.1 sq. arcmin field. The analysis shows $\omega(\theta)$ for faint galaxies can be parameterized by a power law of the form $A_\omega \theta^{-0.8}$, in agreement with the angular clustering statistics of shallower catalogues. The derived amplitude, A_ω, for the catalogue is small, but non-zero. This is the deepest study that has been carried out of the excess probability $\omega(\theta)$ of finding galaxies associated with one another.

The investigators combined this measurement with the latest statistical constraints on faint galaxy redshifts from gravitational lensing studies, which imply that the bulk of the $r \lesssim 26$ field galaxies should be at redshifts $z \sim 1$. They showed the derived A_ω to be significantly lower than that predicted from the local bright, optically-selected galaxy correlation function using the lensing-determined redshift distribution and modest growth of galaxy clustering. However, this simplistic model does not include the variation in observed morphological mix as a function of redshift and apparent magnitude in the sample. At our faintest limits they reached sufficiently high redshifts that differential K-corrections (*i.e.* the effect of redshift in changing the observational bandpass) will result in the observed galaxy mix being dominated by star bursting dwarf and low surface brightness irregulars, rather than the early-type systems used to define the local bright galaxy correlation function. Adopting the correlation function measured locally for these low surface brightness galaxies and assuming modest clustering evolution, they obtained reasonable agreement between a simple model based on these ideas and observations. This model, therefore, supports the scenario where the high number density of faint galaxies is produced by normally clustered star forming dwarf galaxies at modest redshifts.

Dust in the Broad-Line Region of Active Galaxies

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

Subject Heading: Galaxies and Quasars

The class of active galaxies includes, at the most energetic end, the quasars, objects which are among the most powerful in the universe. It is thought that quasars, along with their less energetic cousins like Seyfert galaxies, are powered by a supermassive black hole in the center of an otherwise normal galaxy such as our own Milky Way. These black holes are millions to billions of times as massive as the Sun, and their intense gravitational field causes a wide range in bizarre, extreme behavior, including jets of relativistic particles, winds moving at tens of thousands of km/sec, and extremely harsh radiation fields. In recent years it has been a common assumption that the radiation in the centers of even weak, low-luminosity active galaxies has been enough to destroy any dust in the nuclei of the galaxies (specifically, in the "broad-line regions," roughly 1–10 parsecs from the black hole). Recent work has shown, however, that some types of Seyfert galaxies have undergone extreme brightening or fading which is consistent with the passage of dust clouds in front of the nuclei (Goodrich 1989, 1990). These studies have relied to a great extent on measuring the changes seen in optical spectra of the Seyfert galaxies and comparing them with the changes expected from a change in the amount of dust along the line of sight to the nucleus. Significantly, the time scale for these changes is short enough that they imply velocities of thousands or even tens of thousands of km/sec across our line of sight, just the range of velocities seen in the central broad-line regions of active galaxies. This indicates that dust has survived into the broad-line region, despite the current common wisdom. The energy sources in the nuclei of the Seyfert galaxies are inherently unstable, and cause variability of their own, but such variability has a different character than that caused by changes in dust.

In 1993/1994 the Palomar 60-inch was used, together with the spectrograph built by Jim McCarthy, to survey a class of objects called Seyfert 1.8 and 1.9 galaxies. These objects include some of the most highly variable Seyfert galaxies known, and provide an ideal source for studying variability. In my earlier thesis work I found three objects which showed variations consistent with changes in the amount of dust along our line of sight. Comparing the recent Palomar data with previous spectra from various workers, variability in two of the three objects studied earlier was confirmed. One of the objects, NGC 7603, has brightened another factor of two from its previous "high state" in 1984–1986. Significant variability in another four objects was seen. In two of the cases previous data are not good enough to test whether dust might have caused the variability, and in one of the other cases the variation seems to be due to intrinsic variability of the energy source, not from dust. Data from the fourth object are marginally consistent with a change in dust along the line of sight, but are not good enough to make this statement conclusive.

This second epoch of observations is the most extensive and uniform to date, and will form the basis for future work. The objects which have been seen to vary significantly can be observed more frequently, allowing tighter constraints on the time scale of the variability, hence on the tangential speed of the dust clouds if that is what causes the variability. Details of the study will be available with the February 10, 1995 issue of *The Astrophysical Journal* (Goodrich 1995).

Goodrich, R. W. 1989, ApJ, 340, 190.
Goodrich, R. W. 1990, ApJ, 355, 88.
Goodrich, R. W. 1995, ApJ, in press.

The Internal Kinematics of Sa Galaxies

co–PI's: M. Haynes, A. Broeils
Cornell University

co–I: K. Jore
Cornell University

Subject Heading: Galaxies and Quasars

By a variety of criteria, the Sa galaxies are a more heterogeneous group than their later spiral counterparts, the Sb's and Sc's (Haynes *et* al. 1990). First, relative to the later-type spirals, Sa's are found in higher density environments and are more likely to be active or interacting. Second, the distribution of various properties for Sa galaxies, like bulge-to-disk ratio, σ_{HI} and σ_{FIR}, are much broader; in particular the median values for these surface densities are significantly smaller than those for the later types (Roberts and Haynes, 1994). Unfortunately, the Sa galaxies as a class have been relatively understudied, because observers often choose to focus on more homogeneous classes and those more easily detectable in, for example, HI and Hα (e.g. Cayette *et* al. 1994).

We are investigating the detailed distribution and kinematics of stars and gas within a sample of non-interacting, inclined Local Supercluster Sa galaxies in order to determine the cause of the diverse properites of this class of galaxy. To determine the origin of the stars and gas, in the disk or the bulge, requires detailed kinematic information obtained along both major and minor axes in order to constrain the dynamical models. Ultimately we hope to interpret our findings in light of other information available for these galaxies: optical wide band imaging to determine the light distribution, narrow band imaging to find the location of the X-ray gas, HI, FIR, CO, X-ray and radio fluxes and a measurement of the local galaxy density.

In March 1994 we obtained high-dispersion, long-slit spectra with the red and blue cameras of the Double Spectrograph for 9 galaxies over three nights. H-α, [N II] , [S II], and [O III] lines were observed in order to trace the gaseous comopnents of the galaxy. Mg Ib absoption lines are used in order to trace the stellar component of the bulge and disk. The spectrum of one of our galaxies is extremely interesting since the stars in the inner regions of the galaxy, which are traced by the Mg Ib absorption lines, are rotating counter to the emission line rotation curve of the gas . An I-band image shows the galaxy to be very smooth with no evidence for a counter-rotating element from the visual structure of the galaxy. Counter-rotating stellar disks have been found in a few elliptical galaxies (Rubin, 1994) and the Sab galaxy NGC 7217 was found to have 30% of its stars rotating retrograde to the rest of the galaxy (Merrifield and Kuijken, 1994). Since there has been little study of the stellar dispersion profiles of early type spirals, it is not known if this is a common occurrence in Sa galaxies.

References

Cayette, V., Kotanyi, C., Balkowski, C., van Gorkom, J. 1994, A. J. **107**, 1003.
Haynes, M.P., Herter, T., Barton, A.S., Benensohn, J.S. 1990, A. J. **99**, 1740.
Merrifield, M.R. and Kuijken, K. 1994, Ap. J. **432**, 575.
Roberts, M.S., and Haynes, M.P. 1994, Ann. Rev. Astron. Ap. **32**, 115.
Rubin, V.C. 1994, A. J. **108**, 456.

Accurate Abundance Determinations of Suspected Young Galaxies

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

Co–Investigators: Liese E. van Zee, Adrick Broeils
Department of Astronomy, Cornell University
Co–Investigators: John J. Salzer
Department of Astronomy, Wesleyan 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.

In order to investigate the processes of galaxy and star formation, we have begun a detailed investigation of galaxies that are optically faint, HI–rich and dynamically–young. Prototypical "young" galaxies, such as I Zw 18 and HI 1225+01, are distinguished not only by low metal abundances but also by high values of M_H/L_B and large hydrogen envelopes which surround the compact optical galaxy. We have identified a sample of potentially young systems, distinguished by high M_H/L_B and large D_{HI}/D_{opt}, via Arecibo mapping observations of low luminosity galaxies. The high M_H/L_B systems tend to be of low optical surface brightness and show a variety of morphological structure; they are an extreme class of readily identifiable dwarf galaxies. The star formation process in high M_H/L_B objects appears to be inefficient since they are underluminous for their HI mass (van Zee *et al* 1994). We are currently in the process of determining dynamical and evolutionary ages for these systems.

In low abundance systems, the calculated heavy element abundances place upper limits on the number of star-formation episodes a system has undergone. Determination of accurate nebular abundances requires derivation of electron temperature and density to correctly interprete observed line intensities. The electron density is measured through the [SII] $\lambda\lambda 6617, 6731 \mathring{A}$ doublet. The electron temperature is determined from the ratio of [OIII] lines $(\lambda 4959 + \lambda 5007)/\lambda 4363$. One major problem with previous observations of low metallicity systems has been the difficulty of detecting the [OIII] $\lambda 4363$ line; several empirical relationships, based on ratios of stronger lines, have been developed (e.g. Stansińska *et al* 1981; Skillman 1989). However, with the additional light gathering power of the Palomar 5 meter telescope, we have been able to detect the faint lines with reasonable integration times and thus do not have to rely on this uncertain practice.

In 1994, we have obtained long slit spectra of four HII knots in three galaxies (UA357, U5716, and U11220) with the Double Spectrograph on the 5 m telescope at Palomar. These three galaxies were selected because they had some of the largest D_{HI}/D_{opt} ratios in our sample and $H\alpha$ imaging revealed several bright knots of star formation in each system. The oxygen abundances for two of these knots have not yet been calculated because the spectra are not of high enough quality to accurately determine the electron temperature. However, preliminary reduction of the data indicates that the derived oxygen abundances of UA357-1 and of U5716-1 are less than that observed in the Small Magellanic Cloud (SMC).

References:

Skillman, E.D. 1989, Astrophys. J. **347** 883.
Stansińska, G., Alloin, D., Collin-Souffrin, S., Joly, M. 1981, Astron. Ap. **93**, 362.
van Zee, L., Haynes, M.P., Giovanelli, R., 1994, submitted.

Star Formation Histories of Luminous Starburst Galaxies

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

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

Subject Heading: Galaxies and Quasars

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

We have been studying the star formation histories of 20 nearby interacting starburst galaxies to determine if starburst activity is indeed biased against the formation of low-mass stars and to determine how interactions affect the star formation. At radio wavelengths, spatially extended emission arises from star forming regions and supernova remnants and thus directly traces starburst activity. To select active nearby starburst galaxies, we therefore chose the twenty starburst galaxies from the *Uppsala General Catalogue of Galaxies* with the highest radio (6 cm) luminosities. We have have already imaged these galaxies and two "normal" comparison galaxies at 1.25, 1.65 and 2.2 μm at Palomar with the Prime Focus Infrared Camera. The images show that merging galaxies and galaxies with more widely separated nuclei have similar near-infrared colors and luminosities. We have also obtained 2.2 μm spectra of 18 sources at the Kitt Peak National Observatory. Together, the images and spectra constrain the amount of dust emission from each galaxy and the percentage of light emitted by young supergiants formed in the burst. We have found that 15 to 50% of the 2.2 μm light is produced by hot dust emission. Nearly all of the remaining near-infrared light is produced by young red supergiants. We have also obtained high-resolution optical spectra of 10 of the galaxies at Palomar with the Double Spectrograph. Rotation curves have been extracted from these spectra in order to estimate the underlying galaxy mass. The galaxy mass, supergiant population and far–infrared luminosity have been used to constrain stellar population models. We have shown that over half of the galaxies in the sample are biased towards high mass star formation. For every low mass star formed in these galaxies, the number of high mass stars formed is significantly higher than the number formed in our Galaxy. In May 1994, we obtained high spatial resolution 2.2 μm images of selected galaxies with the Cassegrain Camera. These images are being examined for the presence of previously unresolved multiple nuclei and star forming knots. Images of emission from the 2.17 μm Brackett γ recombination line of atomic hydrogen and the 2.12 μm molecular hydrogen line were also obtained for selected galaxies. The relative spatial distribution of the two types of emission will provide additional information concerning the current location of hot young stars and supernovae and thus further constrain the origin and future evolution of star formation within these galaxies.

This project has been the subject of D. Smith's recently completed PhD thesis. D. Smith presented a poster and a dissertation talk describing the project and images obtained at Palomar at the 182nd and 183rd meetings of the American Astronomical Society in June 1993 and January 1994, respectively. A paper discussing our results for UGC8387, a moderately luminous starburst, has been accepted for publication in the *Astrophysical Journal.* Results from D. Smith's dissertation will be presented at the 184th meeting of the American Astronomical Society in January 1995.

References

Rieke, G.H., Lebofsky, M.J., Thompson, R.I., Low, F.J., and Tokunaga, A.T., 1980, *Ap. J.*, **238**, 24.

Rieke, G.H., Loken, K., Rieke, M.J., and Tamblyn, P., 1993, *ApJ*, **412**, 99.

Soifer, B.T., Houck, J.R., and Neugebauer, G., 1987, *Ann. Rev. Astr. Ap.*, **25**, 187.

Telesco, C.M., Campins, H., Joy, M., Dietz, K., and Decher, R., 1991, *Ap. J.*, **369**, 135.

Brackett Line Spectroscopy of Spiral Galaxies

G.J. Stacey, H. Latvakoski
Department of Astronomy, Cornell University

C. Beichman, G. Helou, and T. Jarrett
IPAC, Caltech

Subject Headings: galaxy-wide star formation, ISM

Stars form in molecular clouds. Normal spiral galaxies form stars at a rate consistent with steady star production over the lifetime of the Universe. The Infrared Astronomical Satellite (IRAS) discovered a class of extremely infrared bright galaxies that are forming stars at nearly 100 times the rate for normal spirals. To understand what triggers these episodes of prodigious star formation in "starburst" galaxies, it is important to understand what causes star formation in normal spirals such as our own.

We have begun a program to study star formation in normal spiral galaxies via a large array of spectral probes. We aim to deduce how the global properties of galaxies such as morphology, environment, or gas content relate to star formation activity, and what affects the newly formed stars have on their nascent interstellar medium. Our studies include a variety of probes in the far-infrared ($\lambda > 30\mu m$) from both the Kuiper Airborne Observatory (KAO) and scheduled observations with the Infrared Space Observatory (ISO). These data have relatively modest spatial resolution (10"→100") and therefore give us a course view of the properties of the interstellar medium (ISM).

Recently, we have begun a program to image nearly normal spiral galaxies in the Brγ recombination line of hydrogen using the Prime Focus IR Camera on the Palomar 200" telescope. With the 200" telescope, our spatial resolution is much higher, ~1". The Brγ line traces the ionizing photons from young massive stars, so our high resolution images tell us the degree and location of high mass star formation in the galaxy. Infrared lines such as the Brγ line have a distinct advantage over their optical counterparts in that the infrared lines suffer relatively little extinction. This allows us to see deeply into the dust enshrouded cores of the molecular clouds where stars are formed.

We have spent the lion's share of our time imaging two galaxies in Brγ: NGC 6946 and NGC 891. NGC 6946 is a nearby grand design spiral galaxy viewed nearly face-on. We will compare our Brγ image with those obtained in the CO (1→0) line, the 21cm line, the 158μm [CII] line, and the far-infrared continuum. The combination of these probes will tell us where the star formation is occurring and what types of stars are being formed. Our data are not fully reduced at present, but preliminary analysis shows patchy star formation regions largely confined to the spiral arms. The patchiness has a size scale near the resolution limit of the telescope. There is enhanced emission at the galactic nucleus implying enhanced star formation activity there.

NGC 891 is an edge-on spiral galaxy believed to resemble our own in many respects. We have completely imaged this galaxy in Brγ and find the emission to be strictly confined to the galactic plane except near the nucleus where there may be some high latitude emission. The scale-height of the emission along the plane is consistent with that of the molecular gas, and about twice as large as that for the Milky-Way. To get to these high latitudes, the clouds need an extra source of kinetic energy that may be derived from supernova explosions. These results are consistent with a higher rate of star formation in NGC 891 than in the Milky Way.

INSTRUMENTATION

Construction of a Near Infrared Spectrometer for the Hale 200 inch Telescope

Larkin, J. E., Knop, R. A., Matthews, K., & Lin, S., Soifer, B. T.
Palomar Observatory, Caltech 320-47, Pasadena, CA 91125

Subject Heading: Instrumentation

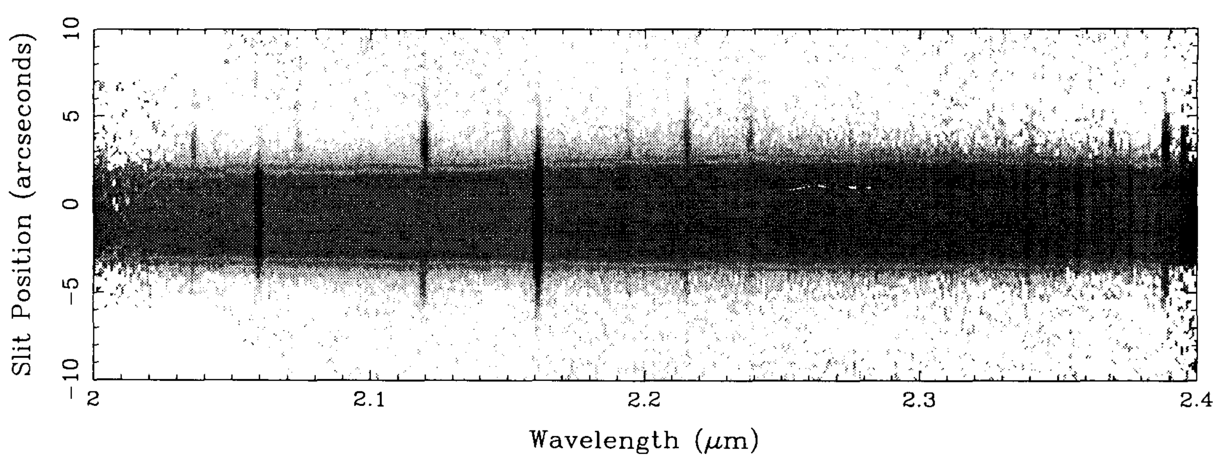
With the recent development of large format infrared arrays, infrared spectroscopy has become both practical and extremely productive. The near infrared part of the spectrum from 1.0 to 3.5 microns contains a wealth of atomic and molecular transitions of astrophysical importance which have only recently begun being investigated. Interstellar dust is also much more transparent to infrared radiation as compared to optical radiation, so obscured regions such as galactic centers and star forming regions can be probed more deeply with infrared line diagnostics. The infrared group at Caltech set out to construct an infrared spectrometer to take advantage of the high quality infrared cameras already available at Palomar and to improve our ability to investigate infrared emission processes. The spectrometer was designed to cover a wavelength range from 1.0 to 3.5 microns with resolutions of $\frac{\lambda}{\Delta\lambda} \sim 1000$ and 4000 for a 0.626 arcsecond slit width. In addition to its spectroscopic capability, the instrument can also take images, which are useful in their own right, and guarantee that the object of interest is positioned correctly.

The construction of the spectrograph has been a major component in the Ph.D. theses of James Larkin and Robert Knop, and both students are now involved in independent research projects utilizing the instrument. The great majority of the spectrometer's internal components were constructed by Larkin and Knop in the physics machine shop in the basement of the Downs Laboratory at Caltech. The outer cryogenic vessel, mirrors and gratings were procured from outside vendors. The internal components are cooled with liquid nitrogen in order to reduce infrared emission from the mirrors and other surfaces. The spectrograph was delivered to Palomar in April 1994 and performed wonderfully. Bad weather during this and the subsequent observing run in May prevented a full test until July 1994, where the instrument again performed very well.

Larkin's thesis involves using the spectrometer to study the central most regions of ~30 nearby galaxies known as LINERs (Low Ionization Nuclear Emission-line Region galaxies) which exhibit unusual, and unexplained spectral features. The hope is to probe more deeply into the heavily dust enshrouded centers than previous methods using visual spectroscopy and determine more fundamental properties of these galaxies and their sources of excitation. Knop is using the spectrometer to study the infrared line emission from the central regions of Seyfert Galaxies, which are galaxies that are known to contain a very energetic source in their nucleus. This project uses the length of the slit in the spectrometer to look for line emission which is spatially extended as well as for unresolved emission directly on the active source at the center. The goal is to probe these galaxies for the presence of circumnuclear starbursts (sites of rapid massive star formation) by comparing the emission observed in the Seyfert galaxies with the emission from galaxies known to have massive star formation in their center. In addition to these theses, the spectrometer has been used to study planetary nebulae (shell like structures thrown off by dying stars). Additional uses of the spectrometer will include the study of very distant galaxies and quasars, which are seen as they were when the universe was much younger and stars were just beginning to form.

Figure 1 shows a spectrum of the planetary nebula BD+30°+3639 to illustrate the capabilities of the instrument (See Shupe's annual report on planetary nebulae). The spectrum covers the entire K-band atmospheric window with a wavelength range from 2.0 to 2.4 microns. Wavelength increases towards the right of the figure, and position on our slit runs vertically. The broad horizontal stripe is due to thermal radiation from the main shell of material surrounding the remnant of the central star. Thin vertical stripes are individual emission lines due to energy transitions in various atomic and molecular species within the shell and surrounding material. The spectrum was taken with the medium resolution grating and shows more than 15 identifiable spectral lines.

We would like to thank Dave Shupe for providing his excellent data as an example of the spectrometer's capabilities. We would also like to thank the very professional staff of Palomar Observatory for their assistance with operating the spectrometer and telescope. Infrared astronomy at Caltech is supported by grants from NASA and the NSF. A paper is in preparation on the spectrometer and will be submitted soon.



A spectrum of the planetary nebula BD+30 to illustrate the capabilities of the instrument. The spectrum covers the entire K-band atmospheric window with a wavelength range from 2.0 to 2.4 microns. The broad horizontal stripe is thermal radiation from the main shell of material surrounding the remnant of the central star. Thin vertical stripes are individual emission lines due to energy transitions in various atomic and molecular species within the shell and surrounding material.

The Second Palomar Sky Survey

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

Subject Heading : Instrumentation

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

Each individual Schmidt plate covers an area of 6.5 × 6.5 degrees on the sky, although the unvignetted field (i.e. the region where the full 48-inch aperture in visible) is only 3^o in radius. To allow for sufficient overlap between adjacent fields, the POSS II plates are being taken on a grid of points with 5^o spacings. This divides the northern hemisphere into 894 fields - hence the full survey will comprise 2682 plates. During the past year (Oct 1, 1993 to Sep 30, 1994) we obtained 318 plates, of which 261 (or 82 %) are of sufficient quality to be included in the final survey. In total, we now have accepted plates for 699 fields in the blue (78 %), 740 in the red (83 %) and 402 (45 %) in the near-infrared. Based on the current progress, we expect to finish (at the 99 % level) the red and blue surveys by late 1996, while the entire project should be completed by the end of 1997.

POSS I was copied to paper and glass by the Caltech Graphic Arts facility, and has proved an invaluable tool for many astronomical projects worldwide. In an effort to make POSS II available on a similarly wide scale, Caltech has entered into an agreement with the European Southern Observatory whereby ESO Photolabs are copying the new survey onto film. So far more than 600 plates have been sent to ESO for copying, and some 450 film copies have been issued. In addition, an agreement has been reached with the Space Telescope Science Institute concerning the digitisation of the survey plates using the PDS machines at that institution. Some 430 plates have been sent to STScI and the Caltech side of the operations is being co-ordinated by Djorgovski. Finally, a team of astronomers (headed by D. Monet) at the U.S. Naval Observatory have completed work on developing a plate-scanning machine which is optimised for extremely accurate positional measurements. We have been obtaining a series of short-exposure (3 minute) unhypered IIIaJ plates in addition to the sky-limited exposures in each survey field, and in September, 1994 all of these plates were shipped to Flagstaff. The measurements from these plates will be used tie together the faint, radio-star astrometric reference frame and the brighter fundamental reference stars. Besides this purely positional work, the project will also compare astrometry from POSS I and POSS II plates to determine stellar proper motions. Scanning is well underway, and we anticipate shipping most of the POSS I plates to Flagstaff in late 1994.

[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

The Palomar Cassegrain Infrared Cameras

D.L. Shupe, K. Matthews, G. Neugebauer, B.T. Soifer, C. Fry, S. Lin, & D. Warden
Palomar Observatory, California Institute of Technology

Subject Heading: Instrumentation

From 1988 to 1993, the original Palomar Cassegrain infrared camera, designated D-78, proved to be a valuable and versatile component of the instrumentation available at the 200-inch Hale Telescope. In this form, the camera employed a 58×62 element detector array manufactured by Hughes Santa Barbara Research Center (SBRC). D-78 was used profitably in many investigations, ranging from stellar occultations of Saturn's rings, to low-resolution spectroscopy of the most distant infrared luminous galaxy known. At the time the camera was built, however, it was realized that detector technology would continue to improve. Therefore, the camera was designed to accommodate the next generation of infrared arrays as well. These plans came to fruition in 1994 in a two-step process.

The first step was the construction of a new Cassegrain camera, designated D-80. Nearly all of the optical and mechanical elements of this camera were low-cost spares obtained for D-78. For D-80, however, a 256×256 element array manufactured by Rockwell International was used. This device employs a mercury-cadmium-telluride detector material capable of sensing light with wavelengths between 1 and 2.5 micrometers, and was originally developed for the Near Infrared Camera and Multi-Object Spectrograph (NICMOS) to be installed on the Hubble Space Telescope later this decade. The new camera has several significant advantages over the original D-78, including covering almost four times the area on the sky, providing better sampling of stellar profiles, and most significantly, an order of magnitude improvement in noise over the 58×62 array. D-80 saw first light on the 200-inch telescope in December 1993, and has been in final form since February 1994. The camera has since been used by members of the infrared group and by other astronomers at Caltech, Cornell, and Carnegie, for a wide variety of projects including narrowband imaging and spectroscopy of galaxies (Armus *et al.* 1994) and studies of molecular hydrogen in planetary nebulae (see Shupe's Annual Report). The low noise of the system makes it particularly effective as the detector of the new infrared spectrometer (see Larkin's and Knop's Annual Reports)–D-80 has been used in this fashion for all of the spectroscopy runs thus far.

The success of D-80 made possible an upgrade of the detector in the original camera, D-78. A Hughes SBRC 256×256 element detector, based on indium-antimonide material, was installed. Funding for it was provided jointly by Palomar Observatory and a special grant from the National Science Foundation. This array is sensitive to wavelengths from 1 to 5 microns, and is the same device used in the Keck Near-Infrared Camera (NIRC). The upgrade similarly enlarged the field of view, improved the spatial sampling of objects, and provided better noise than the original camera. In addition, D-78 may be used in the 3 to 5 micron region, where the NICMOS detector in D-80 is not sensitive. The upgraded D-78 was completed in time for the impact of Comet Shoemaker/Levy-9 with Jupiter, for which the camera performed exceptionally (see the Annual Report relating to the impact observations).

Both cameras are now operating with very good sensitivity. The overall system efficiency, defined as the ratio of photoelectrons collected in the array to photons at the top of the atmosphere, is nearly 40% at 2.2 microns–almost a factor of two improvement over the original Palomar camera, and comparable to the efficiency of the NIRC on the Keck Telescope in Hawaii. Currently, it is common to employ both cameras on the 200-inch at once, with D-78 at the normal Cassegrain imaging station, and D-80 serving as the detector section of Larkin & Knop's infrared spectrometer.

Armus, L., Shupe, D.L., Matthews, K., & Soifer, B.T., "Near-Infrared [FeII] and P-β Imaging and Spectroscopy of Arp 220", accepted for publication in the *Astrophysical Journal.*