SELECTED ANNUAL REPORTS

OF THE

PALOMAR OBSERVATORY

1990

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Enclosed are Selected Annual Reports from observers using the telescopes of the Palomar Observatory in 1990. For convenience, the reports are divided into four subject categories.

1. Galaxies and Quasars
2. Stars and Interstellar Medium
3. Solar System
4. Instrumentation

GALAXIES AND QUASARS

Formation of Solar-Type Stars

Principal Investigator: Charles Beichman
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Co-Investigators: S. Terebey
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T. N. Gautier
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Subject Heading: The Milky Way Galaxy

Formation of Solar Type Stars

Stars like our own Sun form out of the collapse of the small clouds of hydrogen gas and dust that float in the space between the stars. While we cannot travel back in time to see formation of the Sun and our solar system four and a half billion years ago, we can look out to regions of space only a few hundred light years away and find analogs to our own sun that are only a few tens of thousands of years old. Questions to be asked include: What triggers the collapse of a cloud into a star? What roles do rotation and magnetic fields play during collapse? Are stars surrounded by enough material to form planetary systems?

Infrared Observations of Star Formation

The infrared is the premier wavelength at which to study the formation of stars. Protostars are wrapped in a cocoon of gas and dust that makes them invisible to optical telescopes; only infrared and radio waves can escape the surrounding material. The all-sky survey made by the Infrared Astronomical Satellite (IRAS) in 1983 identified thousands of young stars through their long wavelength radiation. We have used the IRAS catalog to find suitable objects for ground-based follow-up observations.

The study of star formation has been accelerated by the introduction in the past few years of revolutionary new arrays of infrared detectors. Instead of building up maps by scanning the entire telescope over a small region, new cameras permit astronomers to make images in a few seconds, thousands of time more quickly than with a single detector. By comparing the infrared images with radio maps that trace the gas out of which the star is forming, it is possible to study the relation between the star, the material immediately around it, and the powerful stellar winds that have been found to accompany protostars.

Specific Observations from Palomar

Last year we used the near-infrared camera to survey the circumstellar environments of young low-mass stars on scales of roughly $500 - 10,000$ *AU* (Terebey et al. 1990a,b,c). The 20 sources we examined are members of the class known as IRAS-Dense cores; highly obscured objects that are found near the peaks of dense gas emission (Benson and Myers 1989; Beichman *et al.* 1986). These low-luminosity infrared sources embedded in dense cloud cores are protostars, i.e. stars deriving part or all of their luminosity from accretion. We have used the morphology of the gas-rich circumstellar environment around the young stars to investigate the importance of the different protostellar phenomena: winds, infall, disks, and stellar multiplicity.

A wealth of structure is seen in the camera images. We detect nebulosity around 55 percent of the stars. Comparison with the maps from the Owens Valley Interferometer shows that the extended infrared emission is clearly related to the outflow structure seen in carbon monoxide (CO), indicating that most of these sources are in the early wind-clearing phase of their evolution. The infrared nebulosity appears to be scattered stellar light that is outlining an outflow cavity. The observed multiplicity provides information on the origin of binary stars. Close to 15 percent of the sample are multiple on the scale of 20 arcsec or 3000 *AU*. This suggests that fragmentation of the surrounding dense cloud cores is important before or during gravitational collapse.

In a separate project we completed thesis observations for Karl Stapelfeldt by imaging Herbig-Haro objects, which are patches of optical nebulosity associated with young stars. We observed HH7-11, HH12 and HH34 in a large number of continuum and emission lines (Stapelfeldt *et al.* 1990). Emission from molecular hydrogen at 1 to 2 μm traces gas that has been compressed and shocked by the wind from the young star. Emission from ionized iron, denoted [FeII], at 1.6 μm traces gas that has been shocked so violently that the gas has been ionized. One of the major findings of this work was the fact that [FeII] at 1.64 μm is bright and can be used as a probe of ionized gas. This is important since the normal tracers of ionized gas like ionized sulfur [SII] and Hα are highly obscured by dust in these regions. In HH7-11 and HH 12 H_2 emission peaks are usually accompanied by [FeII] emission, except in three places where the ionized peaks are found 2-5" upstream of the H_2 peaks. The geometry suggests that in these locations the H_2 peak defines the region where the flow of gas from the star hits the ambient molecular cloud.

The major advance in the development of our camera was the replacement of the 128x128 HIRIS array with a 256x256 chip of the same design. The new chip results in a pixel size of 0.5", compared to 0.7" for the old chip, and is well-matched to the typical seeing at Palomar. At the same time, the field of view has increased to 2' on a side. In 1991 we intend to replace the present 256x256 chip with a 128x128 device with far better noise characteristics.

References

Benson, P. and Myers, P. 1989, *Ap.J.(Supp)*, **71**, 89.

Beichman, C. A., Myers, P. C., Emerson, J. P., Harris, S., Mathieu, R., Benson, P. J., and Jennings, R. E. 1986, *Ap. J.*, **307**, 337.

Stapelfeldt, K., Scoville, N.Z., Beichman, C.A., Hester,J.J, and Gautier, T. N. III 1990, *Ap. J.*, in press..

Terebey, S., Beichman, C. A., Gautier, T. N., and Hester, J. J. 1990a , *Ap. J. Letters*, **362**, L63.

Terebey, S., Beichman, C. A., Gautier, T. N., and Hester, J. J., Myers, P. C., and Vogel, S. N. 1990b, to appear in the conference proceedings of the ASP, *Astropysics with Infrared Arrays*, Tucson Az, Feb 1990, eds. R. Elston and C. Pilachowski..

Terebey, S., Beichman, C. A., Gautier, T. N., and Hester, J. J., Myers, P. C., and Vogel, S. N. 1990c, to appear in the conference proceedings of IAU Symposium 147, *Fragmentation of Molecular Clouds and Star Formation*, Grenoble France, June 1990, eds. F. Boulanger and E. Falgarone..

The Tidal Radii of the M31 Globular Clusters

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Co-Investigator: Ken Freeman
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Subject Heading: Galaxies and Quasars

M31 is known to have an extensive system of globular clusters distributed in a spherical halo around the disk of the galaxy. At the distance of M31 (700 kpc), these clusters are resolved, but just barely. We have used frames taken with the Four Shooter at the Cassegrain focus of the 200-inch Hale telescope during a period of excellent seeing in 1984 to study the spatial surface brightness distribution of the images of the clusters.

The surface brightness profile for a globular cluster can be characterized by two parameters, the core radius, which measures the concentration of the cluster towards its center, and the tidal radius, which describes the limit in the cluster size imposed by the tidal field of the host galaxy. The exact value of the tidal radius depends on the mass-to-light ratio within the cluster and on the eccentricity of the cluster's orbit within the potential field of the galaxy, which can be taken as spherical to first order.

We have measured the tidal radii of 30 globular clusters in M31 located in fields extending out along the minor axis of the galaxy. We have used these measurements to explore the simularity between the galactic globular cluster sample and that of M31. Although the uncertainty of each individual measurement is large, the results for the sample as a whole have significant statistical value. Basically we find that the mean tidal radii over two ranges in galactocentric radius are just what would be expected if the galactic globular cluster system were placed in the potential field of the somewhat more massive galaxy M31. Thus the mass-to-light ratios within the M31 globular clusters, as well as their mean orbital eccentricity, are within a factor of two of those characteristic of the galactic globular clusters.

A Study of the Possible Proto-Starburst Galaxy VII Zw 31

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Co-Investigators: R. de Carvalho, D.J. Thompson

Subject Heading: Galaxies and Quasars

VII Zw 31 was first identified as a blue, compact galaxy by Zwicky. Subsequent studies showed it to have an extremely high far infrared luminosity, and that it has the highest luminosity in an emission line of the CO molecule (Sage and Solomon 1987). These are, respectively, indicators of the dust and gas content of the galaxy. They would suggest that as much as half of the dynamical mass of VII Zw 31 is in the form of molecular gas and dust, while in comparison, only some 1 percent of the mass of the Milky Way is in this form. This led Sage and Solomon to suggest the interpretation of VII Zw 31 as a young galaxy (a proto-disk at a low redshift) that had yet to convert the majority of its gas into stars. We undertook some follow-up observations of VII Zw 31 at optical wavelengths, to better determine the nature of the object (Djorgovski *et al.* 1990).

Image processing reveals the presence of distorted isophotes, and a prominent central dust lane. The spectrum of VII Zw 31 shows the bright emission lines typical of galaxies undergoing rapid star formation, it also has absorption features which indicate the presence of older stars. The evidence suggests that VII Zw 31 is not simply a young galaxy, but an older galaxy that has been rejuvenated by a recent merger. Nevertheless, its large molecular gas content indicates that the major starburst is yet to begin. This object may represent an early evolutionary stage of the ultraluminous *IRAS* galaxies: in other words, a proto-starburst.

References:

Djorgovski, S., de Carvalho, R., and Thompson, D. J. 1990, *A.J.*, **99**, 5.

Sage, L., and Solomon, P. 1987, *Ap.J. (Letters)*, **321**, L103.

Infrared Imaging and Photometry of Distant Radio Galaxies

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California Institute of Technology

Co-Investigators: N. Weir, K. Matthews, J. Graham, T. Soifer

Subject Heading: Galaxies and Quasars

The most distant complete samples of galaxies are those of powerful radio sources. We are conducting a near-IR imaging/photometric study (with some subsidiary optical observations) of powerful 3CR radio galaxies. The sample covers a range in redshift, and includes some of the most distant galaxies known, up to $z \simeq 3.2$, and a few candidates for forming (or at least very young) radio galaxies.

One of the principal scientific goals of this study is understanding of the relation between the powerful radio sources and their host galaxies, and in particular the alignment effects and the puzzlingly small scatter in the K-band Hubble diagram. The explanation of these phenomena can lead to a better understanding of the origin and maintenance of nuclear activity in high-redshift radio galaxies.

Studies of radio galaxies at large redshifts have shown that the evolutionary effects in the visible bands dominate over the cosmological differences by several magnitudes at those large look-back times. The data in the visual range probe the rest-frame ultraviolet, dominated by the young stars whose short lifetimes reflect and amplify any changes in the star formation rate, the fluctuations in their relative numbers, or the intrinsic extinction differences in the host galaxies. Infrared data probe the region of the spectrum dominated by the red giants ($\sim 1\mu$m in the rest frame), where the evolutionary effects and their uncertainties should be much smaller.

Still, the origin of the large luminosity in distant, powerful radio galaxies is not yet fully understood. An important effect is the correlation between the orientations of optical isophotes and radio-lobe axes. These alignments suggest that there is a fundamental, possibly symbiotic relation between radio sources and their host galaxies, but the cause of the phenomenon is still unknown. Perhaps the simplest explanation is that near-jet turbulence, lobe backflows, or galaxy winds from central accretion disks can somehow stimulate star formation along the radio ejection axes. Infrared imaging provides a crucial test for this hypothesis. If the optical "lobes" consist only of young stars, they should be absent or at least heavily suppressed in a rest-frame $\sim 1\mu$m band. Alternatively, if the observed shapes of these galaxies are the same in the observed visual (rest-frame ultraviolet) and the observed infrared (rest-frame visible/red) bands, meaning that older stars are present, then this hypothesis would be in serious difficulty.

The nature of the infrared continuum thus holds the key for the understanding of the alignment effects and in deciding which physical mechanisms are causing the observed starbursts and the strong evolutionary effects in these distant galaxies. These, in turn, can help us understand the possible selection effects and the interpretation of the infrared Hubble diagrams.

IR imaging by us and other groups (e.g., Eisenhardt *et al.*) shows that the shapes of the "aligned" 3CR galaxies are roughly the same in the optical and IR, and that the alignments persist at longer wavelengths. This is contrary to the simplest predictions of the jet-caused star formation models. The situation is really even more complex, as shown by the example of 3C 368, a prototypical "aligned" galaxy (Djorgovski *et al.* 1990). There is a prominent, unresolved core in our K-band images, coincident with the radio core, which is probably a "hidden" quasar responsible for the radio source, the polarized light, and probably also much of the collimated line emission. Perhaps even more surprizingly, the second-brightest IR component in 3C 368 is essentially absent in the optical images, again suggesting that some dust is present. There are good alignments with the radio axis in both optical and IR regimes, even though the bright optical and IR components do not always coincide. Another puzzle is that the K-band Hubble diagrams for powerful radio galaxies show a remarkably small scatter, despite numerous reasons why they shouldn't: different components participate in alignments, there may be some contribution from active nuclei, and some extinction by dust. For the same reasons, age-dating of stellar populations in distant radio galaxies using integrated broad-band magnitudes is very dubious, if only because different image components have wildly different colors. None of the simple models so far can explain all of the data. The alignment effects and the small scatter of the IR Hubble diagram thus remain as challenges for theory.

In the past couple of years several high-redshift radio galaxies have been discovered, with optical and spectroscopic properties suggestive of primeval galaxies or protocluster cores. Infrared imaging can be used to search for the evolved (older) stars in these systems, and thus provides a crucial test of their nature and their evolutionary state. If there are no older stars detected, the case for the primeval galaxy (or the protocluster) interpretation would be considerably strengthened. The preliminary results suggest that there *are* infrared cores in these objects, which may be 1 – 2 Gyr old, and which may represent accretion centers of the protogalactic material. Further studies of these systems may provide important insights in the timing and the processes of galaxy formation.

Finally, infrared imaging can provide a crucial test for some of the "grand unified schemes" for AGNs, and in particular the unification of quasars and powerful radio galaxies proposed by P. Barthel (a Caltech postdoc at the time). Perhaps the best nearby example is the prototypical powerful radio galaxy Cyg A = 3C 405. Our images reveal a quasi-stellar IR nucleus, coincident with the radio core (Weir *et al.* 1990, Djorgovski *et al.* 1991). This is the first direct evidence for hidden quasars in powerful radio galaxies. This discovery explains the unusual properties of the object, and gives considerable support to Barthel's hypothesis. From our IR photometry, we were able for the first time to estimate the extinction to such a "hidden quasar" (through a circumnuclear torus?), $A_V \simeq 50 \pm 20$ mag. The extinction-corrected luminosity of the object is typical for the PG quasars in the same redshift range. Direct evidence for such "hidden quasars" can also help us to interpret the spectroscopic and polarimetric data on high-z galaxies, and it must be taken into account when trying to age-date the stellar populations in them.

References:

Djorgovski, S., Weir, N., Matthews, K., and Graham, J. 1990, in Elston, R. (ed.), *Astrophysics With Infrared Arrays*, *A.S.P. Conf. Ser.* in press.

Djorgovski, S., Weir, N., Matthews, K., and Graham, J. 1991, submitted to the *Astrophys. J. Letters.*

Weir, N., Djorgovski, S., Matthews, K., and Graham, J. 1990, in Elston, R. (ed.), *Astrophysics With Infrared Arrays*, *A.S.P. Conf. Ser.* in press.

A Search For Primeval Galaxies

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

One needs some physical signature of forming galaxies. Several powerful radio galaxies have been found at large redshifts, whose properties can be interpreted as those of giant elliptical galaxies in the process of formation. Strong Lyα emission is commonly detected from them, and they show a morphology suggestive of strongly dissipative merging and starbursts. These objects are very interesting, but it would be very important to find their radio-quiet, field counterparts. We are certainly observing some evolutionary and formative processes of distant radio galaxies; but the ultimate goal is to observe *normal* galaxies at the epoch when most of their stars form.

The timing of the epoch of galaxy formation is also an essential bit of information. The interesting redshift range to explore is $z \sim 2 - 5$ (quasars are now known to $z \simeq 4.7$), and it places the Lyα line in the visible range (approx. 4000 – 8000 Å), the optimal region for the CCD observations. Most searches for primeval galaxies to date have covered only a narrow range in redshift, typically near $z = 5$ or 10. New theoretical and observational results suggest that one should explore *a wide range of redshifts*, starting as low as $z \sim 2$, or so, looking for objects which are faint in the continuum, but Lyα-luminous.

An ideal instrument for this type of experiment is a low-resolution, scanning Fabry-Perot imager. A special, low-resolution Fabry-Perot imaging interferometer was designed and built for this purpose. The experiment consists of deep imaging of selected fields in a series of adjacent narrow bands, with a spectroscopic follow-up of all objects which show a probable line emission excess in one or more bands. In this search-and-discovery mode, the Fabry-Perot is stepped in wavelength an amount equal to the instrumental FWHM between exposures. A three-dimensional data cube (two spatial dimensions plus radial velocity, or redshift) is built up by successive exposures. The experiment emphasizes spatial information in deep exposures over a range of redshifts. The flexibility of the scanning instrument can be utilized by avoiding the strong emission-line features of the night sky (which determines the redshift intervals), and thus achieving a better S/N at faint light levels. The field of the instrument is about 6 arcmin, and the velocity resolution about 1000 km/s in the restframe for Lyα at any redshift.

We started a search for emission-line objects (ostensibly, young and forming galaxies) by looking for the Lyα emission in several redshift intervals with widths $\Delta z \simeq 0.2 - 0.3$, in the range $z \sim 2.8 - 4.95$. Deep, narrow-band images are obtained, and any emission-line candidates are then followed by slit spectroscopy.

To date, we have surveyed 3 fields (0.02 deg^2) in the redshift range 4.42 – 4.61, and 5 fields (0.05 deg^2) in the redshift range 4.74 – 4.90, down to the limit of $AB_\nu \sim 23^m$. This is comparable to the best limits obtained to date in other similar experiments. No obvious primeval galaxy candidates were found so far, but our search is just begining. We have detected some faint emission line objects, but they are probably foreground emission-line galaxies. An example of a data cube is shown in Figure 1.

Our deep field survey will also provide data for studies of the evolution of the luminosity function of quasars and Seyfert galaxies at faint levels, and yield many foreground emission-line galaxies, in addition to any possible primeval galaxy candidates. The inventory of the resulting "data cube" would essentially produce a complete sample of faint starburst or active galaxies and quasars, at a depth exceeding most or all other surveys for such objects. Another exciting possibility is the detection of Lyα forest clouds, appearing in emission (model computations suggest that this is marginally possible).

Reference:

Djorgovski, S., Trauger, J., Thompson, D., de Carvalho, R., Stapelfeldt, K., and Weir, N. 1989, *Bull. Am. Astron. Soc.* **21**, 1172.

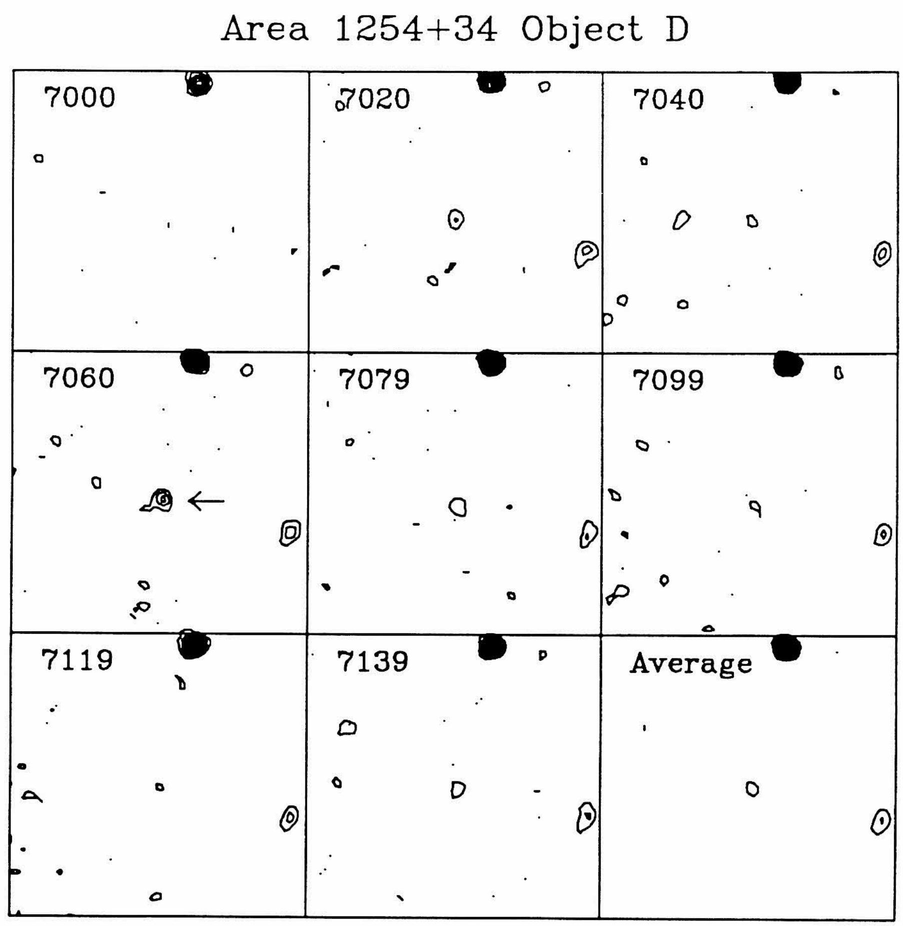
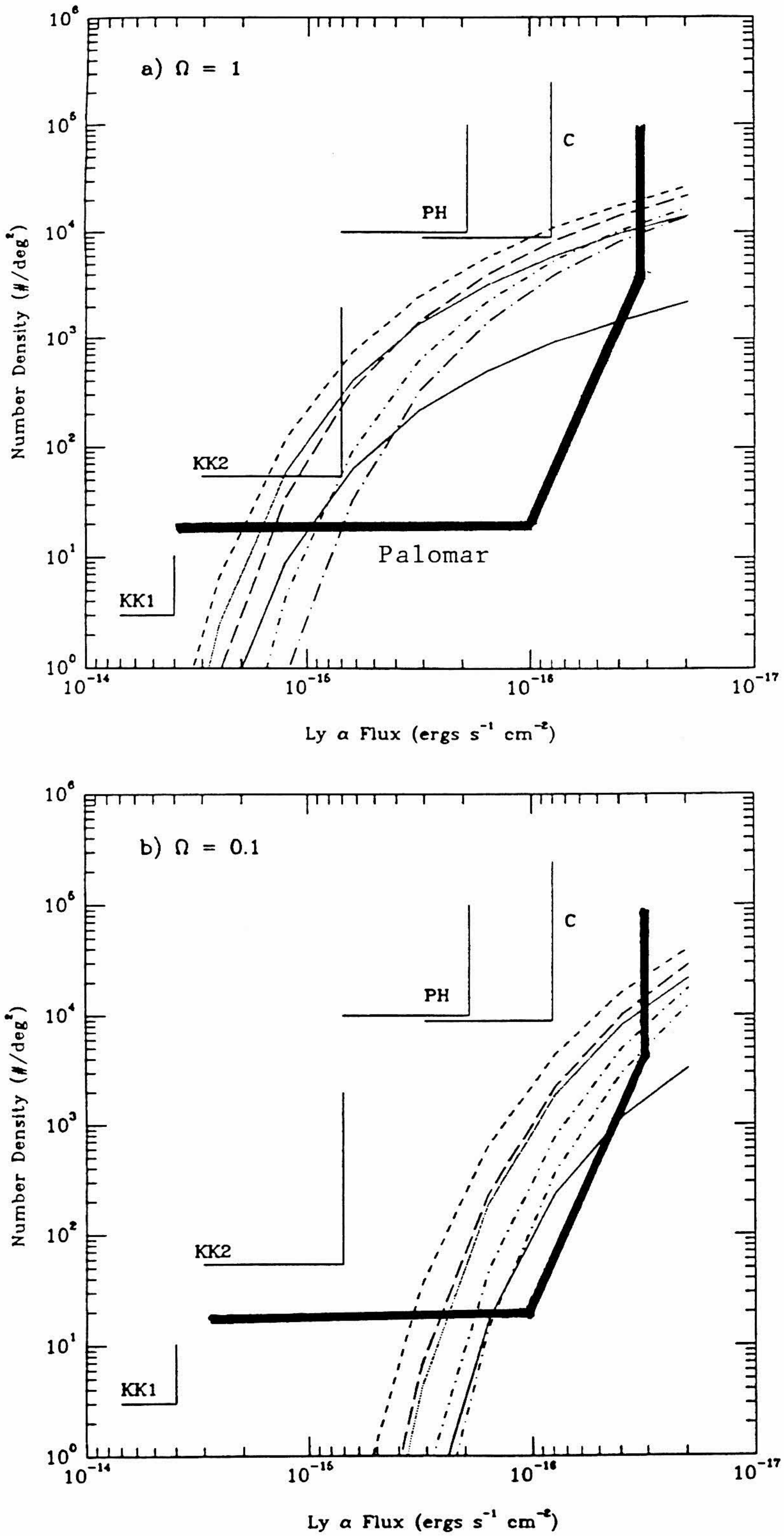


Figure 1: An example of a datacube extracted from the Fabry-Perot data. Object D in the field 1254 + 34 is one of the emission-line objects identified in an initial search of the Fabry-Perot images. A long-slit spectrum of taken with the 4-Shooter shows it to be an emission-line galaxy at $z = 0.407$.

Curves: CDM models
Thin right angles: Previous Limits

Thick line: This Survey



From: Baron & White (1987)
Ap.J. 322, 585.

FIG. 5.—(*a*) Same as Fig. 4*a* for Lyα searches. We have assumed 5% of the total flux to come out in Lyα and an observed band of 6000–9000 Å. We plot limits from the following searches: KK1—Koo and Kron 1980, photographic data; KK2—Koo and Kron 1980, CCD data; PH—Pritchet and Hartwick 1987; C—Cowie 1987. (*b*) Same as (*a*) for $\Omega = 0.1$.

Figure 2: Number-density / Lyα flux diagrams, showing the limits from the most sensitive past or ongoing primeval galaxy searches, and the predictions from the CDM-based theoretical models from Baron & White (1987). The thick lines indicate the estimated sensitivity of our survey to date.

Identification and Spectroscopy of B3 Radio Sources

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Subject Heading: Galaxies and Quasars

Optical follow-up of radio-selected objects is an old and profitable astronomical venture, which to this day can lead to discoveries of interesting new objects and phenomena. We are conducting a program of optical identifications of steep-spectrum sources from the B3VLA radio survey, and a study of selected interesting sources. We selected a rigorously defined, statistically complete subsample of 120 steep-spectrum ($\alpha_{408} \leq -1.0$), small angular size ($\leq$ 10 arcsec), $S_{408} \geq 0.2$ Jy sources, which we believe contains a large fraction of extremely distant galaxies.

The purpose of this investigation is to form a sample of moderate-power radio galaxies at cosmologically interesting redshifts, for the studies of galaxy evolution and radio source counts. We probe the flux range where the deviations of radio source counts from the euclidean geometry are the largest. Scientific goals of this survey include the comparisons of galaxies with a wide range of radio power at similar redshifts, a search for extremely distant clusters of galaxies, steep-spectrum quasars, and other unusual types of objects. Our sample will span a factor of a hundred in the radio flux, and containin hopefully objects both more normal and more extreme than those in the 3CR and similar samples.

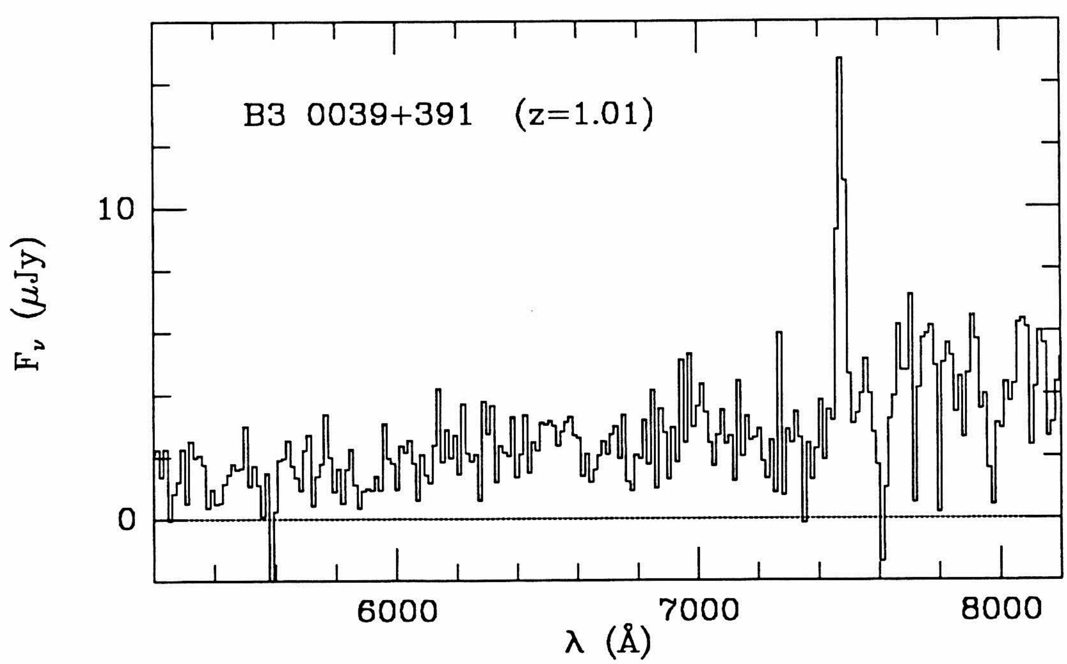

Figure 1: The spectrum of B3 0039+391, a 22^m galaxy, obtained with the 4-Shooter 1990. Note the strong [O II] 3727 line, giving the redshift of 1.01.

A few high-z galaxies have been already identified. Some sources (e.g., B3 1232+397B at $z = 3.22$, as measured by Eales *et al.*; Figure 2) show a clumpy, extended, low surface brightness morphology, which is reminiscent of the primeval galaxy candidates 3C 326.1, 3C 257, and 4C 41.17. We also have 4 or 5 candidates for high-z clusters; two striking examples include rich clusters around B3 1216+402 (probably at $z > 0.5$) and B3 0903+428 ($z \simeq 0.9$ measured by P. McCarthy).

Reference:

Djorgovski, S., Thompson, D., Vigotti, M., and Grueff, G. 1990, *P.A.S.P.* **102**, 113.

B3 1232+397B (z = 3.22) r+i P200 4S

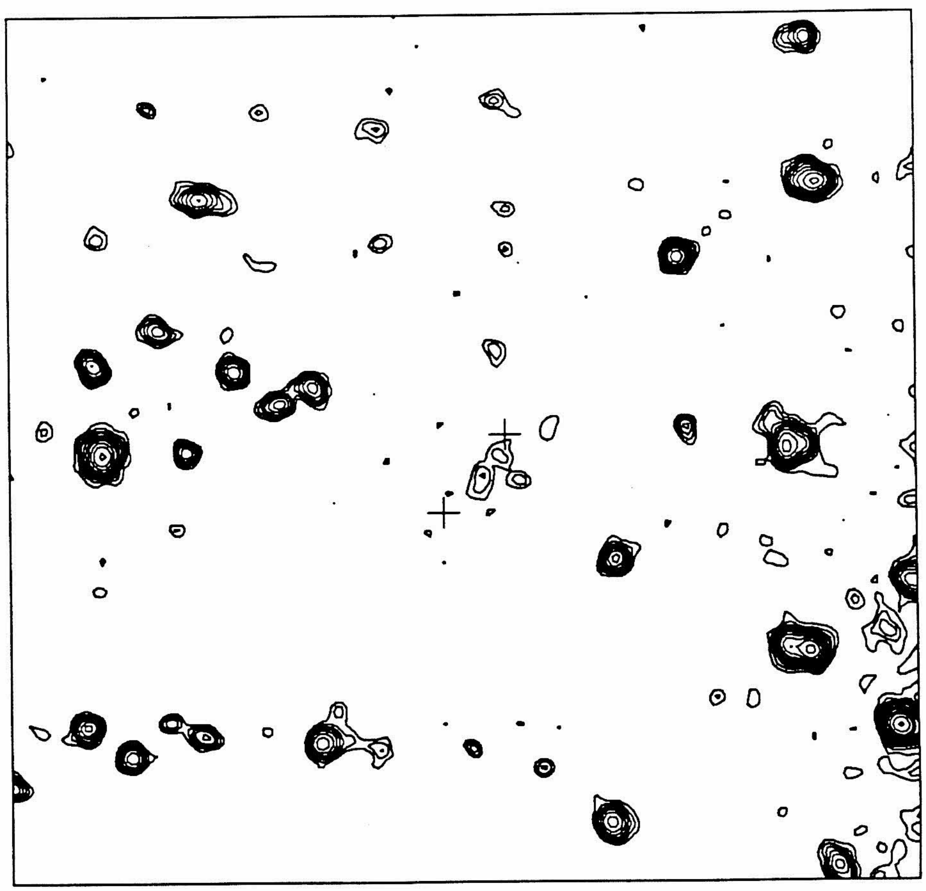

Figure 2: The field of B3 1232+397B, an $r \sim 23^m$ galaxy, from the images obtained with the 4-Shooter in March 1990. The field shown is 67 arcsec square, with N to the top, E to the left. The crosses mark the positions of the radio lobes. The clumpy, low surface brightness morphology is reminiscent of the primeval galaxy candidates 3C 326.1, 3C 257, and 4C 41.17. We have two other faint optical IDs with very similar properties, which still await spectroscopy.

Deep Surveys with the Four-Shooter

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J. G. Hoessel
University of Wisconsin

D. P. Schneider
Institute for Advanced Study

M. Postman
Space Telescope Science Institute

Subject Heading: Galaxies and Quasars

In the past observing year, the fourth year of the deep 4-shooter survey for clusters of galaxies using drift-scan techniques, we have begun to obtain redshifts for the clusters found in the survey. We hope to use most of our time in the next few years to continue this work, the survey itself having been completed last year except for a few scans in the very deep strips which we discuss more later.

The survey was designed to find and allow the construction of a uniform sample of clusters of galaxies between redshifts of about 0.5 and 1.0, or a range of ages because of the look-back time between 0.54 and 0.35 the current age of the universe (if OMEGA is about unity). It has been made in two colors, approximately the visual and infrared bands of the Johnson system. The four-shooter camera is used in a slow-scan mode for this survey, in which the CCD chips are read out continuously as the telescope is moved across the sky in such a fashion that the equivalent exposure time is about 5 minutes. The field of the instrument is about 8.5 minutes of arc square, and a 90-minute scan covers just over a degree in length. Eight of these scans are combined to cover a square field a degree on a side in each of six survey fields spread around the sky.

The data from the survey is now almost completely analyzed. The analysis consists of a classification of each image into stars and galaxies, and for sufficiently bright galaxies some information about galaxy type is also recovered. The galaxies are compiled into a catalog, which includes positions, brightnesses, and type information. From this catalog clusters are found, making use of the fact that clusters represent a density enhancement in both the plane of the sky and in brightnesses. The numbers of field galaxies rise smoothly as one goes fainter, while the number of cluster galaxies at a given distance first rises much faster and then much more slowly than the field population, giving rise to a pronounced "bump" in the number-brightness relation. We make use of both of these characteristics by means of a "matched filter" technique to find clusters. This has proven remarkably successful.

Late last spring we had our first spectroscopic run on this program; we have another later this fall. The data are not yet completely reduced, but two of the clusters we looked at have redshifts of 0.80 and 1.10 (the latter based on only one galaxy, so is somewhat uncertain). Thus the program appears to be producing objects in the desired distance range; the selection technique ensures that the sample is uniform, and similar selection techniques can be used in numerical models to test various cluster-formation scenarios and theories of large-scale structure.

The primary interest in this program is twofold--first, to study galaxies at large redshifts and see how they differ from their cousins at the present epoch, and second to study the structure of the clusters themselves. The galaxy evolution program has already borne rich fruit, clusters at redshifts of about a half, the close end of the distance range for this survey and an epoch at which the universe was about half its present age, containing galaxies really quite different from the population we see today. The hallmarks of these differences are various kinds of activity, including vigorous star formation and energetic nuclear (Seyfert) activity, both probably indicative of much higher gas content than in present-day large galaxies. The indications are that at greater distances a much larger proportion of the cluster population is active, and if this trend continues smoothly by the time redshifts of about 1 are reached most of the galaxies will be active. The clusters themselves are of interest because all dynamical calculations of cluster formation indicate that most clusters form between the upper and lower redshift limits of this survey, and so we should see a smooth increase of the spatial number density as we look at nearer objects. This study clearly requires very good understanding of the selection effects, and probably requires comparison with models which have been processed in the same way as the observations, but this data set will be the first which is capable of addressing this question.

References

J. E. Gunn and J.B. Oke, "Spectrophotometry of Faint Cluster Galaxies and the Hubble Diagram: An Approach to Cosmology," Ap.J., 195, 255, 1975.

J. E. Gunn, J. G. Hoessel, and J. B. Oke, "A Systematic Survey for Distant Galaxy Clusters," Ap.J. 306, 30, 1986.

J. E. Gunn, "Distant Clusters as Cosmological Laboratories", in "Clusters of Galaxies", STScI Symposium 4, eds Oegerle, Fitchett, and Danly, Cambridge, 1989, p341.

Galaxy Evolution and Large Scale Structure in the Far Infrared

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Co-Investigators: Carol Lonsdale & Perry Hacking
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In recent years it has become possible to examine the nature and distribution of galaxies at considerable distances from the Milky Way. Mounting evidence suggests that there is a population of galaxies at distances of order 1000Mpc which appears to be different from that found nearby. There may be a higher density of galaxies of a given luminosity at these distances or galaxies may be of higher average luminosity than those nearby, the exact nature of the differences are not clear. It is of great interest to understand these differences, and one of the tools we have to hand is the IRAS sky survey. This survey contains many thousands of infrared-active galaxies and we have been using it for some time to determine the nature of the galaxy population at large distances and its distribution on large scales. In order to do this we must have confidence in the identity of the sources we think to be galaxies, *viz.* we must ensure that they are not stars or cirrus patches in our galaxy!

Our observing time on the 60" telescope was to determine just this - the reliability of the galaxy selections from the faint infrared sources in the IRAS sky survey. We took CCD images of candidate galaxies too faint to be identified on the Palomar Sky Survey plates in order to determine their identity and magnitude. Candidate galaxies which were brighter than the plate-limit were examined on digitised versions of the plates produced by the Automatic Plate Scanner at Cambridge in England. This proposal was part of a larger program to determine what evolution is occurring amongst the more distant IRAS galaxies and what their distribution reveals about the character of the Universe on large scales.

In the past year we have observed about 80 candidate IRAS galaxies sufficiently faint to be below the limit of the Palomar Sky Survey plates. This brings the total observed so far to about 200. We have only completed the first part of the data analysis but the preliminary results are encouraging. We estimate that $\lesssim 5\%$ of the sources on the two plates for which we have completed the preliminary analysis are cirrus sources within the Milky Way. This percentage depends on position over the sky and further analysis will explore the cirrus contamination over other regions of the sky.

Radio galaxies at high-redshift

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Subject heading: Galaxies and Quasars

Recently several groups of researchers have been successful in discovering galaxies at high redshift. These systems are interesting for a variety of reasons. On the one hand, because we are seeing them as they were when the universe was very young (perhaps only 10% of its current age), they can place severe constraints on the evolutionary and dynamical processes required to form galaxies In addition, the detection of galaxies at very high redshift is of cosmological importance, in tying down the epoch of galaxy formation and the formation of large scale structures in the universe.

One of the most fruitful approaches to finding galaxies at high redshift has been to use samples of objects selected on the basis of their *radio* properties. Although radio surveys are useful in identifying faint sources over the whole sky, their utility in searching for distant galaxies arises from the empirical correlations between radio spectral index, size, compactness and luminosity, that have been determined observationally. These enable us to predict a source's intrinsic luminosity from its apparent properties and thus evaluate, on the basis of its observed flux density, whether is likely to be distant or not.

We have just begun a program to search for high-redshift radio galaxies both in order to place limits on the epoch of galaxy formation, and to investigate the redshift distribution of distant radiogalaxies. This uses samples selected on the basis of their radio properties, as explained above, together with the technique of "blind spectroscopy". In this method, optical spectra are obtained at the position of the radio source before deep optical imaging has been performed. Typically the optical counterparts of the radio objects are extremely faint (R $>$ 21) and so are not easily visible on survey plates. However the equivalent widths of the emission lines from these galaxies are usually extremely high ($>$ 100Å) so that spectroscopy is often more efficient than broadband imaging for detecting these galaxies.

Last year we used the Hale 5m telescope and the Double Spectrograph to examine a sample of 15 deep optically unidentified 7C radio sources. These data have not been fully reduced yet, but a preliminary analysis of a small number of the spectra has revealed redshifts that are high ($>$ 1) but not greatly so, suggesting that indeed we may be seeing a redshift cutoff for this sample at around $z = 2$. Despite the fact that these observations have not yet uncovered any very distant galaxies, they have already allowed us to improve the selection criteria that we use to identify the best high redshift candidates. The detection of optical line emission in these galaxies is confirmation that our observing strategy is a sensible for finding these distant objects, and we intend to continue our searches, with improved selection criteria, in the future.

The Halo of NGC 3079

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Subject Headings: Galaxies and Quasars
Interstellar Medium

NGC 3079 is an edge-on spiral galaxy showing a disturbed morphology and a thick warped disk of neutral hydrogen. Lobes of radio emission emanating from the nucleus, significant X-ray emission, and a far-infrared excess all attest to the presence of an energetically active nucleus at the heart of the galaxy. A wind issuing forth from NGC 3079 appears to be stripping material from a nearby companion galaxy NGC 3073, which shows a tail of neutral hydrogen pointing away from NGC 3079.

Using a reimaging CCD camera on the 1.5-meter telescope at Palomar Observatory we obtained images of NGC 3079 in the light of emission from hydrogen (Hα), doubly ionized oxygen ([O III]), and singly ionized sulfur ([S II]), as well as several line-free continuum wavelengths. The Hα image, after subtraction of starlight, is shown in the accompanying figure. The most striking feature of this image is the presence of a roughly X-shaped halo of emission extending up to $\sim$ 50,000 light years from the nucleus of the galaxy. This emission bounds the region of bright radio emission, which suggests that the gas in the halo of the galaxy is helping to confine the energetic plasma flowing out from the nucleus. This X is also visible in emission from [O III], which indicates that the material is directly illuminated by the intense and "hard" radiation field of the nucleus. This shows that if we were positioned above NGC 3079 rather than off to the side we would have an unobscurred view of the nuclear activity.

There are is also ubiquitous diffuse and filamentary emission above and below the bright portion of the disk which traces the presence of low density material that is being ionized and excited by ultraviolet light from hot stars in the plane of the galaxy. As a result of the less direct and "softer" radiation field, this emission can be seen in [S II] as well as Hα, but is not visible in [O III].

The effect of the nuclear activity on its surroundings can also be seen in a large (2100 light year diameter) loop of emission near the center of the galaxy. The strength of the [O III] emission from the loop sets it apart from most bubbles and shells in the interstellar medium. The strong [S II] and [O III] emission from this loop could be accounted for either by shocks driven by the "wind" from the nucleus, or by photoionization by the "power law" nuclear spectrum.

All in all, the current observations taken with what was already known about this galaxy show it to be a fascinating object in many respects, with much to teach us both about the warm ionized gaseous medium surrounding many disk galaxies, and about the effect of an active galactic nucleus on its surroundings.


Evolution of Low Redshift Emission Line Galaxies

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Subject Heading: Galaxies and Quasars

As a byproduct of the 4-Shooter transit surveys of Schmidt, Schneider and Gunn (hereinafter SSG), which are designed to locate high redshift quasars, a number of lower redshift emission line galaxies have been detected (SSG, 1986a,b). Due to the nature of the candidate selection process used by SSG, this sample of galaxies is well defined in a statistical sense, and can be compared to other well defined samples of galaxies to measure how these objects evolve with time. This project compares the properties of the emission line galaxies discovered by SSG to a nearby sub-sample chosen from the Harvard-Smithsonian Center for Astrophysics (CfA) northern sky redshift survey (Huchra, et. al. 1983). This nearby sample, which currently consists of 107 galaxies chosen from Burg (1987) and Edelson (1987), based on an equivalent width (the ratio of flux in the emission line to flux in the underlying continuum) greater than 25Å in the strongest line of doubly ionized oxygen, represent the objects which will be observed using the 60" Echelle in a low resolution, long slit grating mode (g-mode).

The modifications to the original P60 Echelle Spectrograph which have enabled the g-mode were part of the original design of the instrument (see McCarthy, 1988), but were not implemented until there was sufficient interest expressed to utilize this mode for observing the CfA galaxies for this project. The advantages of this mode over the regular echelle (or e-) mode are that the g-mode allows observations of extended objects such as galaxies since it has a long (6 arc minute) slit while the e-mode is better suited for point-like objects like stars. In addition, with the lower spectral resolution of the g-mode, it becomes possible to observe fainter objects in a reasonable amount of time. The existing P60 Spectrograph, which also has a long slit, is less desirable for this project because the CCD used with this Spectrograph is of poorer quality than the CCD used with the Echelle, and the Echelle in g-mode is three times more efficient at collecting light than the Spectrograph.

The observations of the CfA sample consist of 600-1200 second exposures along both the major and minor axes of each galaxy, covering the spectrum from 4350Å (blue) to 7200Å (red), which includes all of the important emission lines that will be studied in this project. A two dimensional model of each galaxy's light distribution is being developed so that the proper transformations can be made between this nearby sample and the more distant sample. Through the proper analysis of the two samples, a comparison of how the luminosity function of emission line galaxies (number of galaxies of a given luminosity per unit volume) has evolved between the epochs observed by SSG and the epochs covered by the CfA sample, will be carried out. From this analysis, a statement shall be made as to the extent to which evolution has played a role for emission line galaxies between the two epochs.

During the 12 nights of observing on the 60" this past year, most of the galaxies have been observed along one or both of their axes. In addition, testing has continued of the new g-mode of the Echelle Spectrograph, showing that it is superior to the existing P60 Spectrograph. A user's manual for the echelle in g-mode is being written to assist other observers in getting the maximum efficiency from the instrument.

Bibliography

Burg, R., 1987, Ph. D. thesis, Massachusetts Institute of Technology
Edelson, R., 1987, Ph. D. thesis, California Institute of Technology
Huchra, J., Davis, M., Latham, D., and Tonry, J., 1983, Ap. J. Suppl., **52**, 89
McCarthy, J. K., 1988, Ph. D. thesis, California Institute of Technology
Schmidt, M., Schneider, D. P., and Gunn, J. E., 1986a, Ap. J., **306**, 411
_______. 1986b, Ap. J., **310**, 518

Correlation of Near-Infrared, Radio, and Optical Images of Merging Galaxies

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Subject Heading: Galaxies and Quasars

Understanding the complex processes associated with galaxy interactions and mergers is a subject which has drawn increasing attention by many astronomers in recent years. This upsurge in interest has been primarily fueled by three major findings. Probably the most influential of these was the discovery that the optical counterparts of the most luminous galaxies observed in the far-infrared (10–100 μm) by the Infrared Astronomical Satellite (IRAS) are morphologically peculiar galaxies disturbed by galaxy interactions and mergers (see review by Schweizer 1986). Equally important were findings which indicate that the fraction of strongly interacting galaxies increases with higher far-infrared luminosity, and a population of ultraluminous galaxies exists with far-infrared luminosities as high as classical quasars. These systems all show evidence for strong collisions and mergers between gas-rich spiral galaxies, indicating that galaxy mergers are likely to be responsible for the formation and evolution of quasars (Sanders *et al.* 1988). A connection between galaxy interactions and less luminous active nuclei known as Seyfert galaxies has also been established in recent years (e.g., Kennicutt *et al.* 1987).

Much of the work accomplished in the past observing year involves analysis of near-infrared images obtained using the Palomar Cassegrain infrared camera. Along with a number of other infrared luminous galaxies, images of the merging system Mrk 463 have been analyzed at 1.2 – 3.7 μm. These images reveal the embedded stellar populations that are obscured by dust at optical wavelengths, and they provide valuable data for comparison with structures observed in radio continuum images obtained with the National Radio Astronomy Observatory's Very Large Array (VLA). At the estimated distance of Mrk 463 (200 million parsecs), 1 arcsecond on the sky projects to 1000 parsecs (1 kpc). Recent work at radio wavelengths with the VLA includes the discovery of extended structures which are apparently radio lobes extending 3-17 kpc from the eastern nucleus (Mrk 463E) aligned along the same north-south axis as previously known small-scale (0.05–1.5 kpc) radio structure (Figure 1). We have found that the shape of the radio spectrum of Mrk 463E is steep, typical for a Seyfert nucleus. The western nucleus (Mrk 463W) has also been detected at 20 cm and 6 cm for the first time, but it has only 1% of the luminosity of Mrk 463E and reveals a relatively flat spectral shape typical of a starburst nucleus.

The vast difference between the radio properties of the two nuclei appeared to be in contradiction with optical images and spectra which indicated that both nuclei have comparable luminosities and similar high-ionization Seyfert 2 spectra (relatively narrow emission lines of hydrogen). Near-infrared images obtained at Palomar Observatory provided data that clarify the physical processes responsible for this dichotomy. The data show the dominance of Mrk 463E with increasing wavelength which demonstrates that excessive dust obscuration obscures the intrinsically luminous optical emission and actually makes it appear fainter than Mrk 463W in optical blue light (Figure 2). Comparison of luminosity profiles at 1.2 μm, 2.2 μm, and 3.7 μm to an unresolved point source at 2.2 μm (labeled "PSF" in Figure 3)

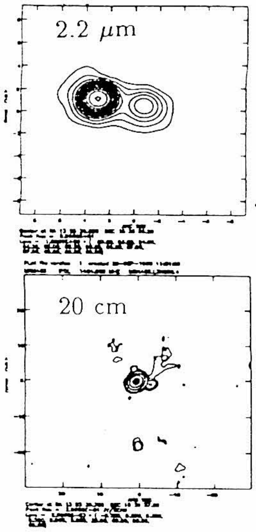

Fig. 1

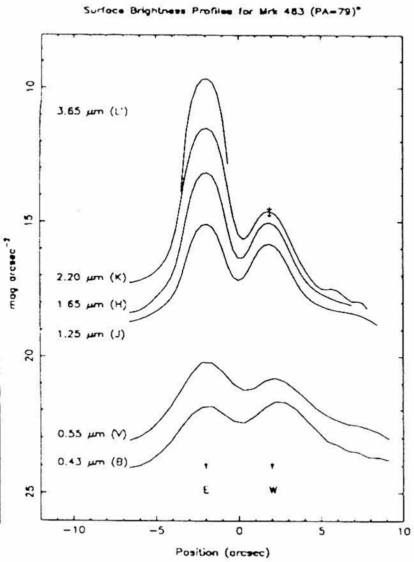

Fig. 2

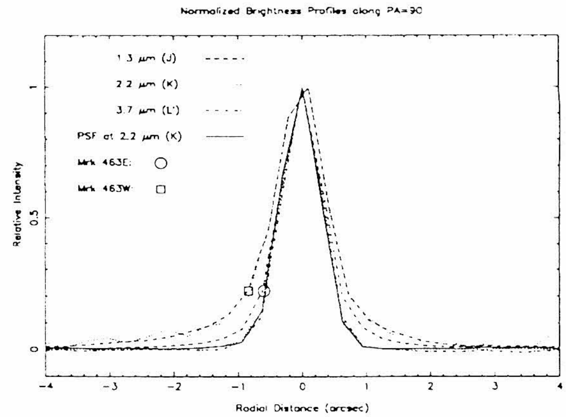

Fig. 3

demonstrates the presence of hot dust emission in an unresolved compact core surrounded by extended stellar emission in Mrk 463E (Figure 3). Highly extended 1.2 μm and 2.2 μm emission associated with Mrk 463W indicates the near-infrared emission from this source is likely due to star light and a relatively weak dust component. The extended infrared emission associated with Mrk 463W and its low radio power and relatively flat spectral shape imply it does not harbor a luminous compact active nucleus. Thus, these new data indicate that while both nuclei exhibit similar Seyfert 2 optical spectra, the intrinsic nature of the dust enshrouded nuclei are substantially different. We argue that the compact dust emission observed at 3.7 μm and the presence of radio lobes extending 0.05 – 17 kpc along the north-south axis are consistent with observations in polarized optical light which suggest a dust torus enshrouds a Seyfert 1 nucleus (very broad hydrogen emission lines) in Mrk 463E (Miller and Goodrich 1990). The luminous compact core and weak extended lobes imply that Mrk 463 represents the genesis of a radio quasar. The fact that one of the two merging galaxies clearly dominates the radio and infrared emission in this source has significant implications in regard to the role of tidal interactions and binary black holes in the evolution of active galaxies (Mazzarella *et al.* 1990).

References

Kennicutt, R. C., Keel, W. C., van der Hulst, J. M., Hummel, E., and Roettiger, K. A. 1987, *A. J.*, **93**, 1011.

Mazzarella, J. M., Gaume, R. A., Soifer, B. T., Graham, J. R., Neugebauer, G., and Matthews, K. 1990, *Bull. A. A. S.*, **22**, 808; *Ap. J.* paper in preparation.

Miller, J. S., and Goodrich, R. W. 1990, *Ap. J.*, **355**, 456.

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.

Schweizer, F. 1986, *Science*, **231**, 227.

THE STELLAR POPULATION OF LOCAL GROUP GALAXIES

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Subject heading: Galaxies and Quasars

The aim of this program is to understand more about the stellar content of galaxies in the Local Group, the kinematics of the stars in these galaxies, and the age distribution of the stars. Through the study of stellar populations we also learn much about the evolution of stars. Observations in 1990 concentrated on M31, the Andromeda galaxy, and its immediate neighbors.

1. THE BULGE OF M31

Although nearly 100 times more distant than the bulge of the Milky Way, the bulge of M31 can be resolved into individual stars, as was first shown by Baade in 1945. Recently, this resolution has been pushed very close to the nucleus to locations where spectroscopy shows the integrated light to be metal rich. Because the integrated optical and infrared light is similar to that of more distant bulges and elliptical galaxies, study of the stellar populations in the bulges of the Milky Way and M31 may provide insight into the ages and metallicities of stars in metal rich galaxy populations. In 1989 we obtained spectra of a few of the most luminous giants 3′ from the M31 nucleus, finding that, as in the bulge of the Milky Way the majority are late M giants.

In the current year Mould and Rich report infrared photometry for a sample of almost a thousand luminous giants in the bulge of M31, 500 to 1000 parsecs from the nucleus. The infrared camera at the cassegrain focus of the 5-m reflector was used to obtain images in the infrared J and K bands. The color-magnitude diagram constructed from a set of 9 contiguous camera fields shows a well defined giant branch that covers approximately the same color range as the giants in the Milky Way bulge. However, in contrast to the bulge fields, the giant branch tip is a magnitude brighter, and there are a number of very red stars. The central result of this work is that the M31 bulge luminosity function lacks the sharp cutoff at $M_{bol} = -4.2$ seen in the Milky Way bulge fields. There are substantial numbers of stars to $M_{bol} = -5.0$.

The Milky Way is not without possible counterparts to these bulge stars. Miras with 800 day periods and $M_{bol} \approx -5$ are present in the Milky Way bulge. OH/IR stars found in large numbers in the Milky Way bulge are also this luminous. There are a number of possible ways in which the present luminosity function may be understood.

One possibility is that our viewing geometry includes a substantial contribution from the disk of M31. In the Milky Way, the line of sight leaves the disk rapidly and traverses the spheroid cleanly. We can assess the possible contribution of the disk by examining Steven Kent's "small bulge" model of M31. In this decomposition the disk contributes approximately 30% of the total surface brightness 4′ from the nucleus along the minor axis. The classical decomposition of Gerard de Vaucouleurs has a central plateau in the disk profile. The corresponding disk surface brightness fraction is 16% in this "large bulge" model.

Is it possible that the extended asymptotic giant branch (AGB) from $M_{bol} = -4$ to -5.5 belongs entirely to the disk component of this field ? If star formation occurred in the central disk of M31 over the period from 1 billion to 10 billion years ago, one would certainly expect an extension to the AGB just as we see in Magellanic Cloud clusters of intermediate age. We can construct a toy model of the stellar population responsible for the extended AGB in this field by computing a weighted sum of the light from the star clusters in this age range. The fraction of the stars observed to have $M_{bol} < -4$ which could be supplied by a disk is between 17% and 56%. The identification of all these stars with the disk component is implausible, but cannot yet be not ruled out, given the considerable uncertainties.

A second possibility is that these stars are really members of an old bulge population, whose AGB extends to high luminosity due to super-metal-rich chemical composition. Credibility is lent to this possibility by extrapolation of the correlation found between the luminosity of Miras in globular clusters and the metallicity of the cluster. It is possible for stars with five times the solar metal content to be 12 billion years old but have turnoff masses $0.3M_\odot$ higher than metal poor stars. If that 0.3 $M_\odot$ is not removed by mass loss, it would be available for prolonging the life and extending the luminosity of such stars on the AGB. Neglecting any disk contamination of the present field, we might expect a total of 660 Miras, if *all* currently evolving bulge stars reach $M_{bol} = -5.5$.

A third possibility which deserves consideration is that of a young component to the bulge of M31. Such stars could be as young as 2 billion years.

Finally, the AGB stars may be "blue straggler" progeny; mergers of a pair of low mass main sequence stars could produce a single star of $1.5M_\odot$ capable of ascending the AGB to lofty heights. However, the percentage of blue stragglers on the M31 bulge main sequence would have to be unusually high (30%) to explain the present observations.

It is, of course, entirely possible that all of these factors do contribute to the observed AGB luminosity function. That there is disk contamination of this field is clearly true. Some fraction of the bulge population is likely to be super-metal-rich, given the strong absorption line spectrum of the nucleus of M31. Blue stragglers and young stars may also may also have been accumulated in a merger event. Further large scale surveys in the infrared, will constrain the importance of the role that these stars play in the M31 bulge population.

2. LONG PERIOD VARIABLE STARS IN M31

From 1988 through 1990 a survey of M31 for LPVs was conducted. This is being carried out at the Palomar 1.5-m telescope with the reimaging CCD camera and can be expected to yield a rich harvest of highly evolved stars. Over the period July through December one can scan 1.4 square degrees in M31 per night. Data are taken at a wavelength of 0.8μ during bright time. Data will be collected for a further year, and then analyzed for variability and periodicity.

3. THE ANDROMEDA DWARF GALAXIES

In 1972 Sidney van den Bergh discovered three faint companion galaxies to M31 on Palomar Schmidt plates; they are believed to be dwarf galaxies similar to the relatively nearby Fornax and Sculptor dwarf galaxies. These dwarf spheroidal companions of the Milky Way have an interesting dual character. On the one hand, galaxies such as Ursa Minor have color magnitude diagrams almost indistinguishable from those of globular clusters. On the other, there are systems like Carina in which there is a considerable population of intermediate age. The other five dwarf spheroidals are a blend of these characteristics – some more like Ursa Minor, others more like Carina.

There are so few of these objects to study, and yet their importance at the faint end of the elliptical galaxy luminosity function is so great, that it seems desirable to turn to our neighbor in the Local Group, M31, to learn more about this class.

Mould and Nemec are conducting a systematic search for short and intermediate period (0.3 day to 10 day) variable stars in the And I, II & III dwarf galaxies using 4-Shooter CCD frames. If these galaxies are at the same distance as M31, then they expect to identify an interesting mixture of different variable stars, such as are currently being found in the Fornax dwarf galaxy. If anomalous Cepheid variable stars, like those found in all the nearby dwarf galaxies, can be identified, the period-luminosity relationship for these objects will be used to determine distances accurate to $\sim \pm 5\%$. The color-magnitude diagram of Andromeda II shows a giant branch characteristic of Galactic globular clusters. The physical dimensions and luminosity are similar to those of the dwarf spheroidal in Sculptor.

4. THE DYNAMICS OF DWARF ELLIPTICAL GALAXIES

The Local Group contains two types of dwarf elliptical galaxies. M32 is a *compact* dwarf, and is thought to be an extreme member of the family of classical elliptical galaxies. NGC 205 and NGC 185 are examples of *diffuse* dwarfs. These systems have about the same total absolute magnitude as M32, but they are considerably fainter, and have surface brightness profiles that do not follow the de Vaucouleurs' law, but are more nearly exponential. It is thought that these systems form a separate morphological and physical class.

Our understanding of *giant* elliptical galaxies improved dramatically when it became possible to measure their internal kinematics. It is now generally believed that these galaxies have anisotropic velocity distributions, and are likely to have slowly rotating triaxial figures. Furthermore, it has recently become evident that many of the giant ellipticals may have distinct components in their nuclei.

It has also been established that rotational support becomes significant in elliptical galaxies of smaller total luminosity. Spectroscopic studies of the integrated light—with observations along many position angles—have confirmed that one of the smallest, M32, is indeed a classical elliptical, and appears fully supported by rotation. These observations have furthermore revealed the presence of a central dark object, which may well be a black hole. But little kinematic information is available for the diffuse dwarfs.

With a distance of 720 kpc and $M_B = -15.7$, NGC 205 is the brightest dE in the Local Group, but still a difficult spectroscopic object outside the nucleus. Mould, de Zeeuw and Held observed NGC 205 with the Double Spectrograph attached to the 5-m Hale telescope. With a 600 line grating and Texas Instruments CCD detector our blue spectra covered the wavelength range 3600–4430Å with a scale of 1.1Å/pixel. Due to the low surface brightness, observations were feasible out to at most an arcmin, so that they cover only the central regions of the galaxy.

Our main result that the maximum rotational velocity along the major axis of NGC 205 out to $1'$ is less than 25 km s^{-1} contradicts earlier claims—based on photographic spectra—that the rotation curve rises linearly to about 90 km s^{-1} at $90''$ from the nucleus We measure a velocity dispersion of 60 km s^{-1} over the central $1'$ with no significant rotation. The upper limit on rotation about either axis of 25 km s^{-1} implies an anisotropic velocity distribution.

We deduce $M/L_B = 7$ in solar units. The mass-to-light ratio of NGC 205 is not significantly different from that seen in pure old stellar populations such as globular star clusters. It is also consistent with the general trend, in which low luminosity dwarfs have higher values of M/L, and values larger than 10 are reserved for the very smallest dwarf spheroidals.

We have also recently observed the next faintest dE in the Local Group, NGC185, employing twice the resolution indicated above. These results are under analysis.

Imaging Fuzz Around Active Galactic Nuclei

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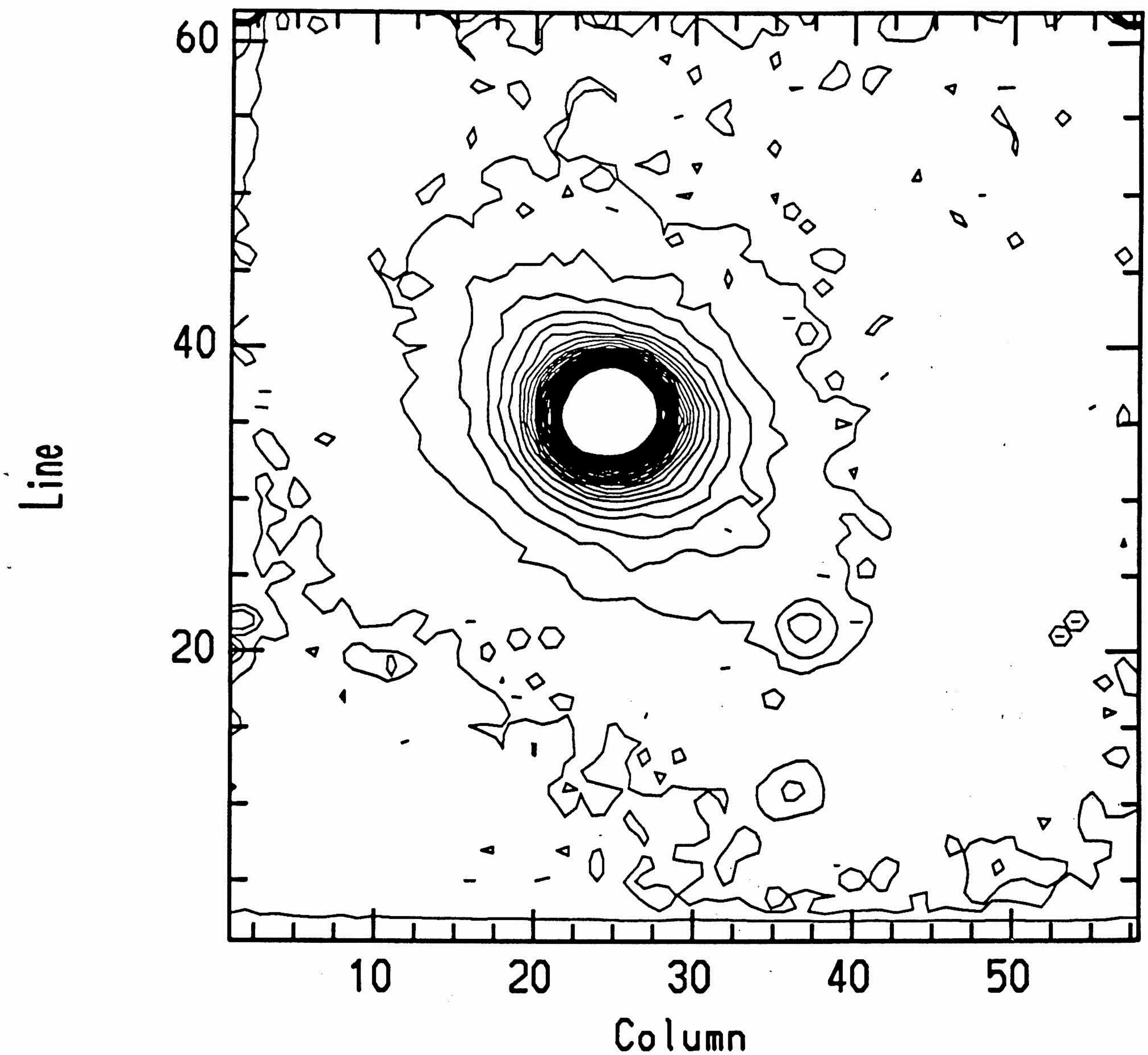
It is now generally accepted that quasars, once thought to be exclusively point like objects, all are embedded in galaxies. In fact, all active galactic nuclei are now thought to be associated with "fuzz" or surrounding galactic material. The relationship between the active nuclei and the galaxies which surround them is, however, uncertain and is one of the outstanding problems related to quasars and other extragalactic objects with highly active nuclei. The nature of the galaxies themselves, for example their morphological type, is also still debated. Even more uncertain is the evolutionary role of these galaxies. Did the nuclei condense from the galaxies or did the galaxies evolve from outflow from the nuclei? Several trails have recently indicated that galaxy collisions play a crucial part in the formation of quasars, and a critical question is to see if the "fuzz" exhibits the distortions which accompany such collisions.

Imaging of the "fuzz" around quasars is difficult in visible light because the nucleus is many times brighter than the galaxy and the "seeing" due to the Earth's atmosphere smears the nuclear light into the galaxy. Imaging in the near infrared, which is now possible with the advent of infrared arrays, is potentially advantageous for examining "fuzz" in the proximity of the nucleus since the galaxy is relatively brighter at the near infrared wavelengths and the "seeing" degradation is smaller in the infrared. As an example, the figure shows the galaxy surrounding BL Lac, a strong prototypical active galactic nucleus. The image was obtained with the Cassegrain infrared camera at the 200-inch Telescope and is, as far as we know, the first image of the galaxy surrounding that nucleus. Aside from the "point-like" sources at the end of the galaxy - probably stars in the local Galaxy - the galaxy seems smooth and not disturbed or exceptional. About a half dozen other quasars have also been imaged in the near infrared. A preliminary analysis indicates that all look like normal elliptical galaxies which are not significantly disturbed. It is too early to draw vast conclusions from this preliminary look; it is hoped to make these images the start of a substantial, quantitative and systematic investigation.

A contour map of the 1.3 micron emission from BL Lac is shown. The ordinate lies along a north-south line and consists of 62 lines each 0.31 arc-seconds high. The abscissa is east-west and represents 58 columns also each 0.31 arc-seconds wide. Thus the image consists of 3,596 square pixels. The galactic nucleus, BL Lac itself, is highly active, highly variable and is point-like. The intensity of the pixels in the lowest contour is about 1.5% of the peak nuclear value.



Redshifts and Evolution of Galaxies in Distant Clusters

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Subject Heading: Galaxies and Quasars

As part of a continuing program to study the evolution of distant clusters of galaxies two related programs are under way. The first of these is being carried out by Oke and is a detailed study of 8 distant clusters all of which are at the same age; they have redshifts very close to 0.5. The overall aim is to study the stellar content of the member galaxies and in particular to determine if the galaxies have young recently formed stars or only very old stars born soon after the galaxies themselves formed. Two kinds of observations are required. First, CCD photometry is carried out to characterize the overall distribution of energy in the spectrum over as large a wavelength interval as possible. These observations when analysed are used to determine whether a galaxy has only old stars in it or young stars as well. The young stars are detected in the ultraviolet measurements since these stars are hot and radiate strongly in the ultraviolet. Slit spectra are also obtained for a sample of up to a dozen galaxies in each cluster. The spectra are used to measure the redshifts which indicate whether a given galaxy is a member of the cluster or a foreground or background interloper. The strength of spectral features also gives information about the young and old stars in the cluster.

The above program is nearing completion with virtually all of the CCD photometric observations completed and also a substantial part of the spectroscopy already done. During the last year most of the effort has gone into continuing the spectroscopic work and also reducing the spectra. During the few available night during the last year 37 spectra of faint galaxies in clusters were obtained which when added to the 100 previously obtained spectra yield redshifts for about 100 objects in the eight clusters being studied. As expected, a few of the observed objects turn out to be very faint stars or non-member galaxies.

A second program being carried out by Gunn, Hoessel, and Oke is the study of clusters of galaxies in the Gunn, Hoessel, Oke Catalog of Clusters of Galaxies. One part of the program is to obtain redshifts for clusters in the catalog since only 135 of the 418 catalog clusters have redshifts. All of the spectra have been reduced and redshifts for nearly 50 additional clusters have been determined. These have redshifts ranging from 0.3 to 0.8. The clusters with the highest redshifts will be studied in detail for evolutionary effects since they are substantially farther away than the 8 clusters discussed above which are being studied by Oke.

Dynamics of Spiral Galaxies in Different Environments

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Subject Heading: Galaxies and Quasars

One of the fundamental problems of observational extragalactic astronomy is to determine the distribution of mass in the universe. Individual spiral galaxies serve as valuable probes in this endeavor. The motions within an individual galaxy reveal the total amount of matter, both luminous and dark, whose gravitational forces induce those motions. In a popular sense, we "weigh" a galaxy by observing how rapidly the stars fall to (i.e., orbit) the center. Over the past decade, our research has been directed at learning how stellar orbits in a galaxy differ as a function of the Hubble type, the size, and the local environment of the galaxy. Following our early work on the rotation properties of isolated field galaxies, we have now completed observations of galaxies in two different types of neighborhoods: those located in small, compact groups of four to eight galaxies, and those located in a large, relatively young cluster, the Virgo cluster. Our current observations extend the study to a third environment, that of the crowded cores of distant populous clusters. If the dark halos known to be associated with field galaxies have been disturbed or have not been permitted to form in the denser environments, then this altered distribution of matter will be reflected in the orbital motions which we study.

We have used the 200-inch double spectrograph to obtain long-slit spectra of galaxies in the compact groups identified by Hickson (1982). Theses are relatively isolated groups of 4 to 8 members, with a galaxy surface density as high as that in the cores of the rich clusters. The galaxies are faint and the observing times consequently long; a typical integration time is 70 minutes. The analysis of this valuable material, combined with images from the Kitt Peak 36-inch telescope, is now completed and in press (Rubin et al. 1990, 1991). Some of the galaxies are tidally interacting and distorted; some appear morphologically normal. Observed velocity patterns range from too peculiar to form rotation curves (1/3 of spiral sample), to abnormal (1/3), to normal (1/3); peculiar rotation curves are only loosely coupled with peculiar morphology.

From the analysis, we infer that some spirals located in dense groups contain less dark matter than equivalent isolated spirals. Such reduced dark mass might indicate a disruption or ablation of the dark halo for galaxies located in regions of high galaxy density. If a normal spiral consists of 1/2 luminous, 1/2 dark matter interior to the optical image, then the mass of the dark matter halo for a spiral in a compact group must be diminished by about 50% to account for the rotational differences from the field spirals. This observation leads to an important conclusion. The total mass contained in spirals is not sufficient to keep the compact group together, yet evidence indicates that the groups are forming, rather than dispersing. This implies that there must be a component of dark matter which forms a common intergroup background, and is not clumped about individual spirals.

Our observations support a model in which the compact group galaxies have only recently accumulated from the lumpy general galaxy distribution, and in which tidal interactions are frequent and ongoing. As the universe ages, some galaxies will move into regions of density higher than average, gravitationally attract other galaxies, slow the general expansion of the universe, and ultimately halt the expansion in that region. If the galaxy density is high enough, compact groups will form, and finally merge to a single galaxy. The computer simulations of Barnes (1989) indicate that the galaxies within such groups will merge within a few orbital periods to form a relatively normal elliptical galaxy. Such may be the future history of the Milky Way-Andromeda galaxies, which are currently approaching each other in what is believed to be a first pass.

Last year we completed observations of rotation curves for spirals in the Virgo cluster, a more normal cluster environment. This material is presently being measured and analyzed. In the Virgo cluster, spirals near the cluster center have minimal neutral hydrogen disks which are truncated and asymmetrical, compared with normal non-cluster spirals, yet the denser molecular gas properties are normal. Such properties are indicative of complex gas/star interactions, stripping, or mergers. We hope that the galaxy dynamical properties will offer clues as to the past histories of the Virgo spirals.

We also initiated observations of spirals near the cores of clusters of different richnesses, fractional spiral populations, core densities, and X-ray luminosities. These galaxies are among the most distant we have observed, yet we derive rotation velocities of high accuracy. We anticipate that these programs will aid us in deriving the distribution of mass within the clusters, and ultimately to understand if the distribution of dark matter within the cluster follows the distribution of luminous matter. Such a conclusion would place important constraints on models of initial galaxy and cluster formation.

References

Barnes,J. 1989, *Nature* **338**, 123.
Hickson, P. 1982, *Ap.J.* **255**, 382.
Rubin, V., Hunter, D., and Ford, W. K. 1990, *Ap. J.* Oct. 10.
Rubin, V., Hunter, D., and Ford, W. K. 1991, *Ap. J. Suppl.* in press.

Progress on the Second Palomar Sky Survey

Principal Investigators:

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Subject Heading: Instrumentation

The second Palomar Sky Survey, comprising 894 6 × 6 degree fields covering the northern hemisphere, continues to be taken with the Oschin Schmidt telescope. We are acquiring plates in three passbands - blue (IIIaJ + GG385 filter), red (IIIaF + RG610) and infrared (IVN + RG9) - matching the surveys of the ESO and AAO southern Schmidt telescopes, and we have been accumulating J and F plates in a routine fashion over the past year. The only major modification to the processing system made within the last year is the installation of a light-tight drying cabinet in the IVN hypering laboratory. The infrared plates are hypersensitised in a bath of silver nitrate and ammonia, and it is essential that the plate is allowed to dry before being placed in the telescope. The addition of the drying cabinet will permit a second plate to be hypered while the first is still drying, improving the efficiency of plate-taking.

We have also experimented with a new type of coating on the plate-holder mandrels, replacing the neoprene covering with a teflon coating. The mandrels are figured to deform the photographic plates to conform to the spherical focal plane of the Schmidt. Using teflon has several advantages: first, it is easier to figure than the neoprene sheeting used on the original plate holders; second, the non-stick properties are an advantage with the IVN plates, whose backing can become slightly sticky after hypering; and, finally, the teflon-coated mandrel appears to reduce the incidence of small (several millimetre diameter) diffuse spots (possibly static discharge marks) that have occurred on some of the IIIa-emulsion plates.

During the course of the year (from 1st October, 1989) we have accumulated a further 292 plates that are of acceptable quality for the survey, including 128 IIIaJ plates, 133 IIIaF plates and 31 IVN plates. Of these, 94 are graded A-quality plates. We now have acceptable plates for approximately 38 % of the IIIaJ survey and 32 % of the IIIaF survey, although the IVN survey, which got underway at a later date, is only 3 % complete.

Recently, a formal agreement was signed between Palomar Observatory and the European Southern Observatory covering the reproduction of film and glass copies of the Sky Survey plates. The copies will be made at the ESO Photolabs in Garching-bei-Munchen and distributed as the Palomar Observatory - European Southern Observatory Photographic Atlas of the Northern Sky. The first shipment of 90 plates for copying was made in early October of 1990.

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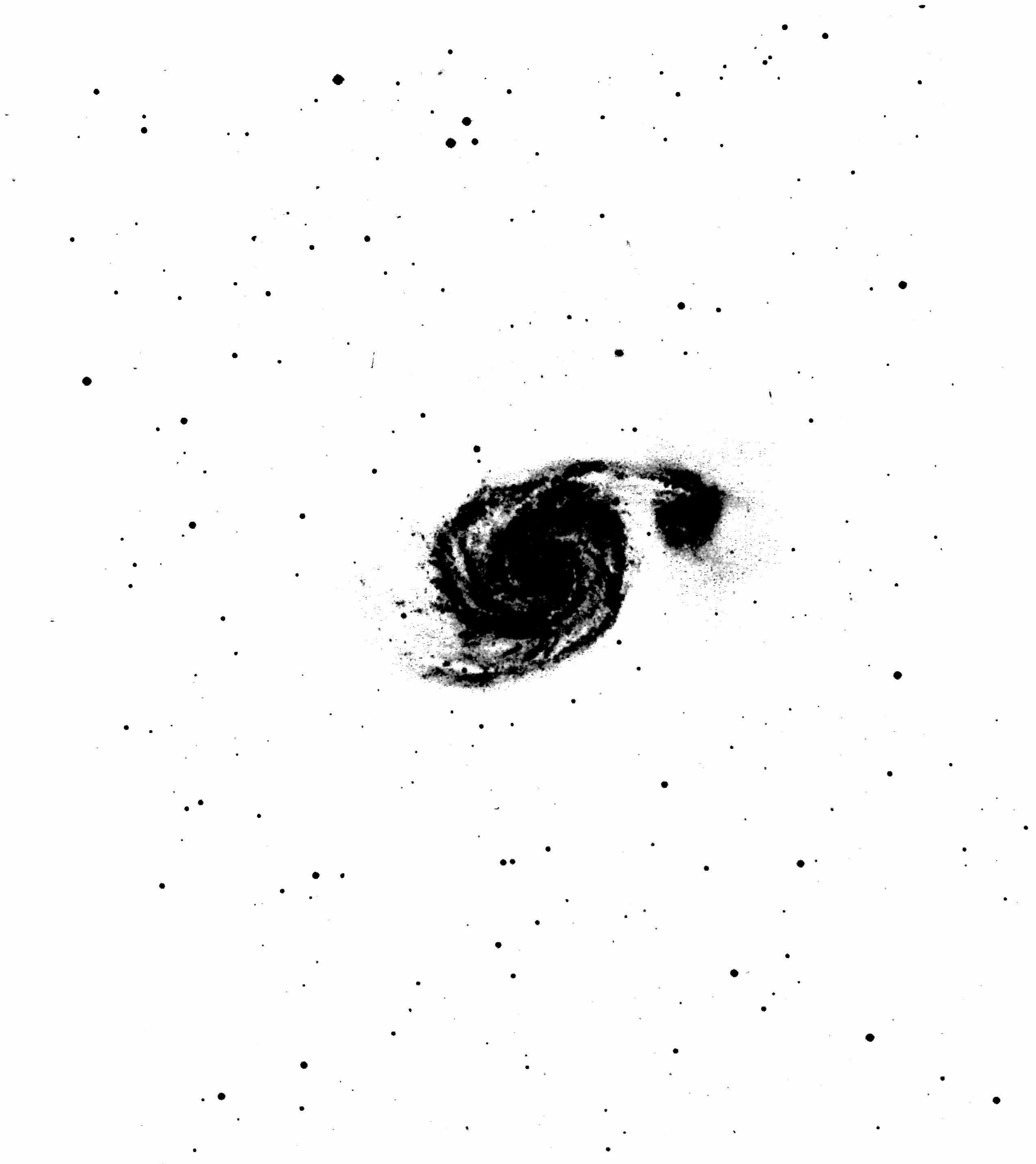
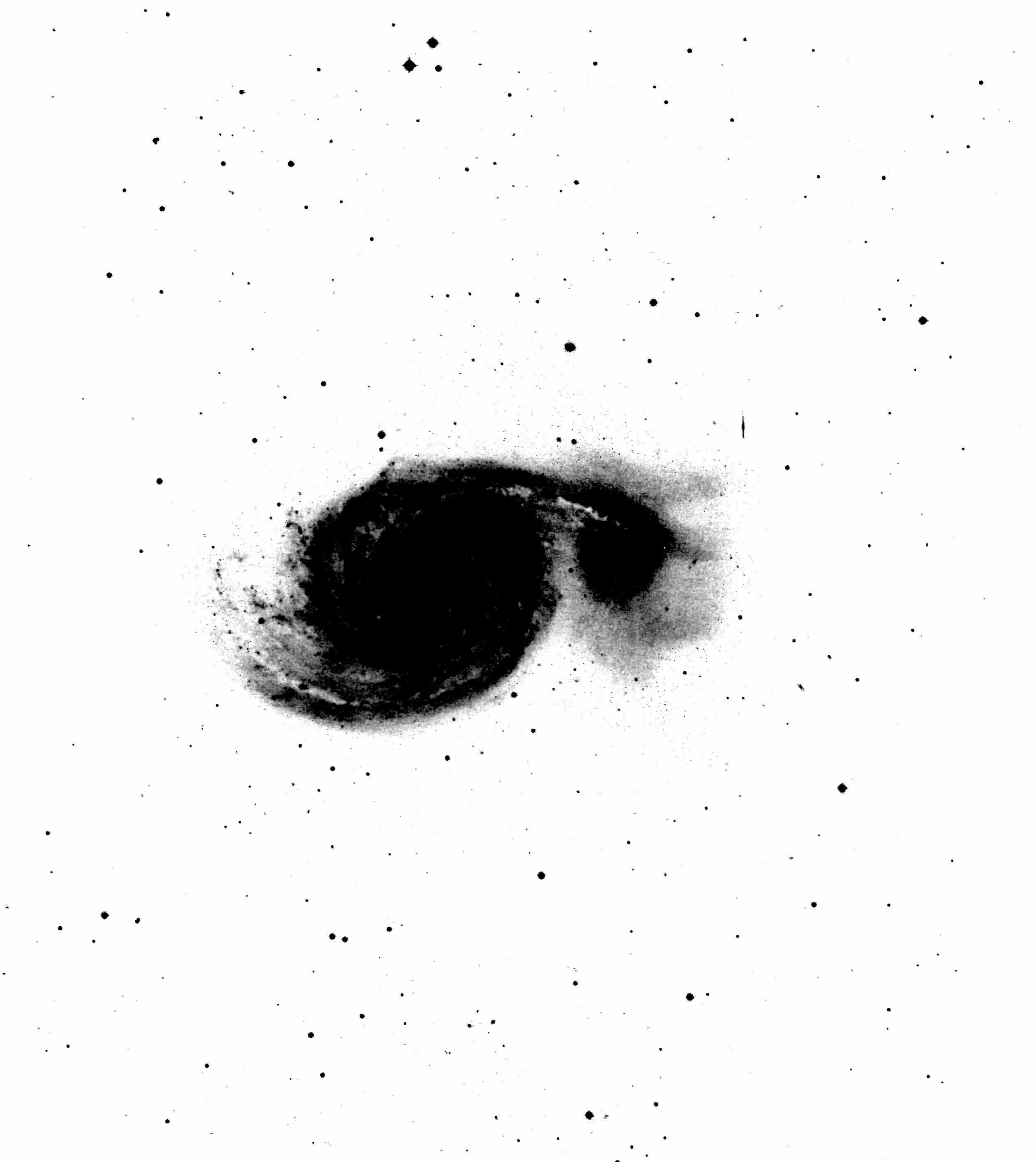
* In addition to the above named people, the POSS II team consists of E. Emery and H. Petrie (Palomar Engineering), and R. Thicksten, M. Sweet, C. Brewer, D. Mendenhall, J. Mueller, and J. Phinney (Sky Survey Operations).

Several scientific projects are being undertaken with plate material from the Sky Survey, utilizing both accepted plates and plates that have been rejected for cosmetic defects (aircraft trails, etc.). Tinney (graduate student), with Reid and Mould, has started a major survey for low luminosity stars in the galactic disk. Since these objects, with luminosities of $10^{-3} - 10^{-5} L_{\odot}$, have low temperatures ($T_e < 3000K$), they have very red colours and can be identified by combining photodensitometer scans of IIIaF and IVN plates. To date, R and I plates in five fields have been scanned using the COSMOS measuring machine at the Royal Observatory, Edinburgh, and follow-up infrared (JHK) observations of the candidate low-luminosity stars have been obtained with the 200-inch telescope. The preliminary results, described elsewhere in this report, show that these techniques are successful in identifying stars with luminosities comparable to the faintest detected in other surveys.

Picard (graduate student) and Mould are using IIIaF plates of 18 fields to search for high redshift ($z > 0.4$) clusters of galaxies. Again, the plates have been scanned with the COSMOS measuring machine, the stars and galaxies separately identified, and the galaxy distribution function constructed. The results, described in more detail elsewhere in this volume, can be used both to probe the cluster-cluster correlation function and to study galaxy evolution at earlier epochs. Sky survey plate material is also being used to complement a deep ROSAT survey of the northern ecliptic pole. Finally, the Sky Survey observers have discovered one comet, eight notable asteroids and seven supernovae in 1990. Several of these supernovae were confirmed spectroscopically on the same night with the Hale 200-inch telescope.





Quasar Absorption Lines

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Subject Heading: Galaxies and Quasars

Quasar absorption lines provide the only practical means of directly studying the evolution of the interstellar gas in galaxies since the time when galaxies and quasars first formed. The absorption lines provide a sensitive measure of the physical state of the gas, including the relative abundances of the common elements, of intervening galaxies, even dwarfs. Two large observing programs were completed during the year. The first was a study of the spectra of 102 bright QSOs designed to yield the behavior of Mg II absorption over the redshift range $0.2 \leq z_{abs} \leq 2.2$. Earlier work (Sargent, Boksenberg and Steidel, Ap. J. Suppl., 68, 539, 1988) had shown that the incidence of C IV absorption *decreases* with increasing redshift over the range $1.2 \leq z_{abs} \leq 3.5$ accessible to ground–based observations; this was interpreted as a direct sign of the build–up of heavy elements over time in early galactic halos (Steidel, Sargent and Boksenberg, Ap. J. Letters, 333, L4, 1988). All the 102 spectra have been reduced and 120 Mg II absorption redshifts have been identified, most of them newly discovered. The incidence of Mg II absorption appears to increase over the above observed range, at a rate which is consistent with no cosmological evolution in the properties of the absorbing galaxies. Work is in progress to reconcile this result with the remarkably different behavior of C IV. With Steidel, a picture of the evolution of the gaseous content of early galactic halos was developed in which halos are initially composed of discrete, tenuous clouds with sizes and masses similar to those of dwarf galaxies and which are ionized by the metagalactic quasar UV radiation. In this picture star formation in galactic disks continues as long as the primitive halo clouds supply fresh gas to the disk via collisions. In further work on QSO absorption lines, spectra were obtained of 44 QSOs with $z_{em} \geq 2.75$ in order to find examples of "Lyman Limit" absorption systems. The new sample covers the winter region of the sky which was not included in the recent survey for such systems carried out by Sargent, Steidel and Boksenberg (Ap. J. Suppl. 69, 703, 1989). In the combined sample we have found 62 Lyman limit systems which can be used both for detailed composition studies and to measure the cosmological evolution of a particular well–defined class of absorbers. The data are all reduced and preliminary analysis has shown (in agreement with previous work) that there is no evidence for evolution in the interstellar hydrogen over the observed range of redshift and cosmic time.

The quasar Q0248+4302 (m_V = 17.65 magn., z_{em} = 1.313) lies 14.7" away on the plane of the sky from an anonymous galaxy, G0248+4302 (m_V = 16.1 magn., cz = 15,300 km s^{-1}). Low resolution ($\sim$ 5Å) spectra of Q0248+4302 covering the wavelength range $\lambda\lambda$3150–7000 and obtained in the aforementioned survey of Mg II absorption, revealed exceptionally strong interstellar Ca II and Na I absorption lines at the redshift of the galaxy. While the line of sight to the QSO intersects the galaxy at a projected galactocentric radius ($\sim 11h^{-1}$ kpc) which is consistent with previous detections of Ca II and Na I absorption in the spectra of QSOs near foreground galaxies on the plane of the sky, the line equivalent widths are ~ 2 times larger than for the strongest case previously known.

CCD images obtained on the Palomar 60–inch telescope of the field of Q0248+4302 in the B, g and i bands reveal that G0248+4302 is a close pair of interacting galaxies and that the absorption takes place in a sinuous tidal tail which extends out to at least $60h^{-1}$ kpc and which happens to lie in the direction of Q0248+4302. The exceptional strength of the interstellar absorption lines probably results from the large velocity range in the tidal material.

Mg II, Mg I, Fe II and Ca II absorption lines are found in the spectrum of Q0248+4302 at $z_{abs} = 0.3940$. There is a concentration of faint galaxies around the QSO which could be part of a cluster at $z \sim 0.4$. A faint galaxy, plausibly at this redshift, lies between the QSO and the galaxy on the plane of the sky.

The QSO pair Q2345+007A, B, whose components are separated by 6" on the plane of the sky has been considered for several years to be an example of a "gravitational" lens although the object, presumably a galaxy, responsible for the lensing has never been identified. Sargent and Steidel (A. J. 99, 1693, 1990) obtained spectra with very S/N of both components over the wavelength range 5127–8967 Å. A cross–correlation analysis of the spectra leads to a redshift difference between the two objects of 44 ± 40 km s^{-1}. The Mg II $\lambda\lambda$2796, 2803 doublet is identified in absorption for the previously identified system at $z_{abs} = 1.491$ in both objects; in addition, 5 lines of Fe II at this redshift are identified in the spectrum of Q2345+007 B. The continua of Q2345+007 A and B have the same spectral shape to within about 2%, but there are significant differences in the emission line spectra, most notably that the ratio C III] λ1909/ Mg II λ2799 is larger by a factor of ~ 1.5 in Q2345+007 B as compared to Q2345+007 A. The ratio of the continua is $(A/B)_{cont} = 3.72 \pm 0.02$ over the observed wavelength range, whereas the emission line intensities vary from $(A/B)_{em} = 2.6$ for C III] to $(A/B)_{em} = 4.0$ for Mg II. Thus, under the gravitational lens hypothesis, one must invoke microlensing and/or differential amplification of the continuum and broad line emitting regions to explain the observations. In view of the new data, we favor the interpretation that the objects are not a gravitational lens, in which case the inferred characteristic physical size of the Lyman α clouds at $z \sim 2$ must be revised upward by a factor of 4–18, to ~ 100 kpc. We show that the resulting picture of bloated photoionized clouds is consistent with recent estimates of the metagalactic ionizing flux.

In an effort to further elucidate the properties of candidate gravitational lenses, new spectra of high quality were obtained of Q2345+007A,B and of a second pair, Q1634+267A,B., two quasar pairs which may be gravitationally lensed. These spectra will be used to compare the emission lines and continuum shapes in the respective pairs of images.

During work on the identification of the galaxies responsible for the Mg II absorption discovered in various earlier surveys, Steidel and Sargent accidentally found the second known example of a Lyman alpha–emitting extended cloud next to a high redshift QSO. The object in question is Q1548+0917 ($z_{em} = 2.749$). Only Lyman Alpha emission was detected and there is a possibility that this 23rd magn. object (which is about 100kpc in diameter) may be a primordial cloud. Further observations are planned for 1991.

High Redshift Quasar Surveys

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Subject Heading: Galaxies and Quasars

Quasars are the most energetic and luminous objects in the universe. Even though they are not much bigger than our solar system (small by astronomical standards), they outshine even the biggest galaxies containing tens of billions of stars. Observations of nearby quasars show that they are located at the centers of galaxies; they probably derive their luminosity from processes associated with the accretion of matter from the host galaxy into a black hole with a mass of a hundred million suns. Some quasars are as much as 1000 times more luminous than the galaxy in which they reside. Thanks to their extraordinary brightness, quasars can be detected to far greater distances than galaxies.

Finding quasars among the millions of stars in the sky, that make up our own Milky Way galaxy, is not easy. Quasars of moderate redshifts exhibit blue colors, which help in their selection among the galactic stars which are mostly red. Extensive surveys for such quasars, conducted at various observatories (including Palomar) over the last 15 years, have shown that their numbers at given luminosity increase dramatically with redshift. For quasars of average luminosity, the space density at redshift 2 is a hundredfold of that in our neighborhood, at redshift zero.

Quasars with redshifts larger than 2 are not bluer than galactic stars; they can be found by recording low-dispersion spectra (rather than direct images) and by selecting objects that show emission lines in these spectra. Schmidt, Schneider (Institute for Advanced Study, Princeton), and Gunn (Princeton University) are engaged in a major program to take a census of quasars of large redshift. Their survey is carried out with the 200-inch telescope in stationary position; tens of thousands of spectra of celestial objects are recorded in a night as a long strip of sky moves across the telescope field. All objects that show emission lines are then observed individually to select the quasars among them and to obtain their redshifts.

The survey has produced hundreds of quasars with redshifts ranging from less than 1 to over 4. Of particular interest are the 86 quasars found with redshifts between 2.75 and 4.75. At these redshifts, the light from an object takes 13 – 14 billion years to reach us. We assume here that the Big Bang, which started the universe, happened 15 billion years ago. Therefore, we see these objects as they were at a time 1 – 2 billion years after the Big Bang.

From a preliminary analysis of the 86 quasars, Schmidt *et al.* find that the space density of quasars is declining with increasing redshift. This behavior is opposite to that for quasars at smaller redshift. They conclude that the number of quasars went through a maximum at a redshift of about 2. Translated into cosmic times, quasar numbers rose sharply in the period of 1 – 2 billion years after the Big Bang, peaked at about 3 billion years, and ever since declined to the present epoch of 15 billion years. If quasars represent an early phase in the birth of galaxies, then galaxies may have formed in the period of 1 – 3 billion years after the Big Bang. Direct observations of galaxies (which are much less luminous than quasars) at these large distances are not possible at present.

The current survey can detect quasars with redshifts up to 4.8. Since Schmidt *et al.* found a quasar with a redshift of 4.73 last year, they are convinced that quasars with redshifts larger than 4.8 must exist. They have started a new survey based on imaging through four red filters. Comparison of the image strengths on the four images will allow the selection of objects that may be quasars with a redshift in the range 4.0 – 5.6. Spectroscopic observations of the candidate objects will tell whether or not they are high redshift quasars.

Near Infrared Imaging of Infrared Bright Galaxies

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Co-Investigators: J.R. Graham, K. Matthews, G. Neugebauer,
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Division of Physics, Mathematics and Astronomy

Subject Heading: Galaxies and Quasars

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

On the basis of these studies we have been able to assess the importance of infrared emission in the energy budget of galaxies in the local universe, and to identify the major mechanisms for powering the infrared luminosity in galaxies. We have also identified, on the basis of these studies, a new class of extragalactic emitter, ultraluminous infrared galaxies; galaxies with luminosities as great as quasars but where nearly all this luminosity is emitted in the infrared. We have suggested that these ultraluminous galaxies are in fact dust enshrouded quasars that are newly formed, and that will eventually shed their enveloping gas and dust and be revealed as visible quasars.

The studies we have completed to date on the infrared bright galaxies discovered by IRAS have been based on optical imaging and spectroscopy and infrared photometry. Because the nuclei of these galaxies have enormous masses of interstellar dust (and gas), the visible radiation that powers the luminosity is efficiently absorbed by the dust and is converted into far infrared radiation. Near infrared emission, on the other hand, can escape because the dust is a much poorer absorber of this radiation. Thus the near infrared emission in these galaxies can be used to probe deeply into the nuclei of these galaxies, into the environments of the power sources for the enormous luminosity. Previously we reported our results on the infrared imaging of the Ultraluminous galaxies from the IRAS Bright Galaxy sample, that showed half of these galaxies were double nuclei systems. From this we were able to limit the lifetime of the ultraluminous phase of infrared bright systems.

In the last year we have continued our imaging studies of many of the high luminosity infrared galaxies from the IRAS Bright Galaxy sample at wavelengths of 1.2 to 3.7 μm. This program has been made possible with the near infrared cameras used at the prime focus and Cassegrain focus of the Hale 5m telescope. The Cassegrain camera was constructed by K. Matthews of the infrared group in Physics, while the Prime focus camera was bult by Beichman, Gautier, and Hester of IPAC.

Most recently, we have pursued a careful analysis of the imaging data of the Ultraluminous galaxy Arp 220. These data are shown, in the form of "color images" in figure 1. The images show the systematic changes in the appearance of Arp 220 as a function of wavelength, with the galaxy becoming substantially more centrally condensed at increasing infrared wavelength. Plotted in figure 1 are contour plots of the ratios of the images of the central 18" of the galaxy obtained at 1.2, 1.6, and 2.2 μm. These plots show systematically increasing ratios of flux at 2.2 μm to flux at 1.6 μm, and of the flux at 1.6 μm to flux at 1.2 μm as the radius approaches the center of the galaxy.

Visibly Arp 220 shows the morphology of a merging galaxy with faint tidal tails extending to more than an arc minute (at the distance of Arp 220, 1" corresponds to 385 pc, so that the tidal tails are visible to a radius of ~20 Kpc), and a dust lane that is virtually opaque and obscures the nucleus of the galaxy. In the infrared, the nucleus is clearly visible, and the dust lane is barely visible. The systematically changing colors shown in figure 1 cannot be attributed to a uniform screen of obscuration in front of a normal stellar population, but rather shows clearly the drastic change of the character of the emission in this system at distances of <1 Kpc from the nucleus. The near infrared emission must be increasingly dominated by thermal emission from the hottest dust that is present in the galaxy, and that is heated by a combination of the many newly formed massive stars and the active nucleus present in the system. Another result that has emerged from the careful imaging of the core is that the double nucleus of this system, reported by Graham last year, show systematically different colors, and these nuclei can be identified as the separate peaks in the ratio of flux at 2.2 μm compared to 1.6 μm and 1.6 μm compared to 1.2 μm respectively. How this is related to diagnosing the active nucleus in the system is unclear at this time.

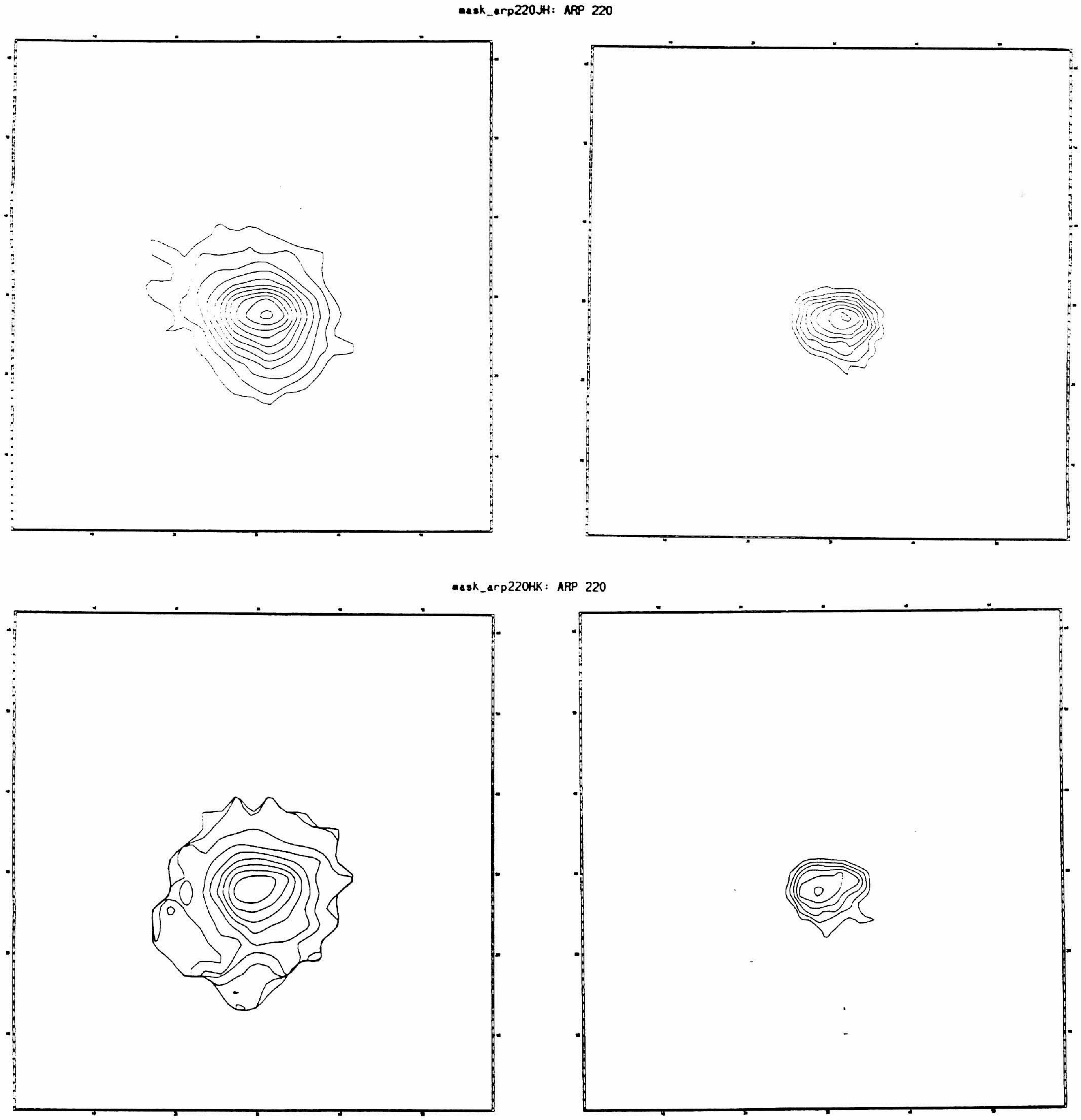

Figure 1. Contour plots of the 1.6 μm/1.2 μm [J-H] (top) and 2.2 μm/1.6 μm [H-K] (bottom) flux density ratios for Arp 220. The units are magnitudes, with the contour levels of 0.08 mag in all cases except the lower left where the contours are 0.1 mag. The peak is 1.56 mag in the [J-H] image, and 1.18 mag in the [H-K] image. The coordinates are pixels, with 1 pixel being 0.31". Note the strong peaking of the reddest colors at the nucleus of the system. The displacement of the peaks in [J-H] and [H-K] can be clearly seen in the right hand images.

High-Resolution Imaging of the Double QSO 2345+007

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Co-Investigator: S. G. Djorgovski

Subject Heading: Galaxies and Quasars

The quasar pair 2345+007 A,B has been a puzzle to scientists since its discovery nearly ten years ago. Initially, the two objects were thought to result from the gravitational lensing of a single, distant source, whose light rays were bent and split by the gravitational pull of an intervening galaxy or cluster thereof. Later results, however, suggested that the two images might actually result from physically distinct, but possibly interacting, quasars. Correctly explaining the nature of this QSO pair is of interest to astrophysicists for a variety of reasons, chief among them its implication for the sizes of the intergalactic hydrogen clouds found interspersed throughout the known universe. Unfortunately, most attempts to provide observational evidence favoring one or the other hypotheses have produced ambiguous or inconclusive results.

If 2345+007 is actually a lens, certain image geometries would be much more highly favored than others. High resolution imaging could therefore help provide important clues as to the true nature of this object. Using the Palomar 200" telescope we obtained very high signal-to-noise images of the 2345+007 field, with the intent of sharpening those images on the computer using what are called image restoration techniques. The intent of these methods is to help remove the blur introduced by the atmosphere and the telescope to obtain the highest possible spatial resolution inherent in the data. Figure 1 depicts one of these images as well as its restoration. In the latter, component B appears slightly extended roughly in the direction perpendicular to component A, while component A does not appear extended at all. To determine the validity of this result, we very carefully modeled the original data and conducted numerous Monte Carlo simulations where we created the data ourselves and restored it using the very same technique. The results suggest that with greater than 98% confidence, the apparent extension of component B is real. This result is corroborated by the restoration of a completely independent image taken with a different filter on the same night. As this particuar image geometry is not expected in current theories of gravitational lens optics, we interpret these results to support the binary quasar hypothesis.

Through a combination of state-of-the-art telescope design and instrumentation, and the application of sophisticated image processing tools such as the one demonstrated here, a true breakthrough in ground-based astronomical imaging is well within reach. It is conceivable that in many instances we will be able to achieve resolution in direct optical imaging approaching a tenth of an arcsecond, a full factor of ten better than what was considered good not more than a decade ago.

Reference:

"High-Resolution Imaging of the Double QSO 2345+007", Weir, N., and Djorgovski, S. 1991, *Astron. J.* in press (January issue).

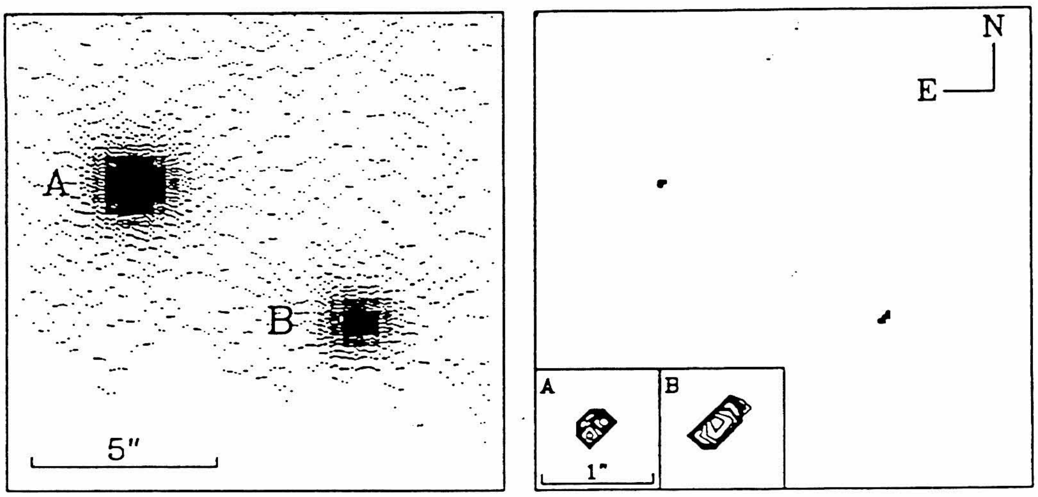

Figure 1: An image and restoration of the binary quasar/gravitational lens candidate QQ 2345+007, from a g band CCD image obtained at Palomar Observatory (from Weir and Djorgovski, 1991).

Properties of Mass-Ejecting Quasars

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Subject Heading: Galaxies and Quasars

Scientific Context

For about three decades it has been realized that the nuclei of many galaxies exhibit phenomena which cannot be explained by the collective effects of a large number of stars undergoing normal stellar evolution. Such nuclei are now referred to as "Active Galactic Nuclei" or "AGNs". This activity spans a huge range in power output and in character. Those objects at the upper end of the range of power which have extremely compact nuclei observable in visible light are the Quasars, or more properly Quasi-Stellar Objects. (QSOs)

The fundamental premise underlying nearly all theoretical attempts to understand Active Galactic Nuclei is that matter is being accreted onto a massive Black Hole at the center of the galaxy and in the process passes through a thin accretion disk. It is the overall task of those interested in AGNs to try to confirm and flesh out this picture so as to understand the formation and evolution of AGNs throughout the history of the Universe as well as to understand the huge diversity of the phenomena associated with AGNs.

The Long Term Program

In particular, considering only the very luminous and powerful Quasars, we have for several years been interested in understanding why there are such striking differences in two respects from Quasar to Quasar. **First**, among Quasars of given power in visible light, the range of energy output at **radio** wavelengths varies over a range of about 100,000. **Second**, about 1 in every 10 Quasars shows unambiguous evidence (based upon data taken with spectrographs) for ejection of gas at speeds typically 3-10 % of the speed of light, while the rest do not. As a result of our work and others, it has now become clear that these two features are not unrelated: Quasars which are powerful emitters of radiation at radio wavelengths are never among those which show the spectroscopic evidence of gas ejection.

During the last three observing years at Palomar our program has been to assemble spectroscopic data that will help to answer the following questions: i) Are the mass-ejecting quasars inherently different from all the other quasars, or, do nearly all quasars eject mass but in only 1 out of 10 cases do we happen to look in the appropriate direction to see this ejected matter? In either case, what is the mechanism that produces this ejection? ii) How stringent is the avoidance of the mass ejection phenomenon among the powerful radio sources and is this avoidance an intrinsic one, or could it likewise be understood in terms of preferential viewing directions for the powerful radio sources and mass ejectors which are mutually exclusive?

Results from the past observing year

During the past year we concluded a detailed comparison of the properties of the mass-ejecting and normal quasars. The results strongly support the view that all quasars which are not strong radio sources are **inherently** mass ejectors, but only 10 % of the time do we directly observe this ejection. The difference between the two kinds of objects is apparently primarily one of orientation. An unexpected and remarkable result was the discovery of structure in the pattern of velocities of the ejected material which strongly suggests that radiation pressure plays a significant role in the ejection of the gas.

We also concluded our study of the quasars which are strong radio sources. The result very strongly confirms the view that strong radio emission and ejection of gas of the kind described above are mutually exclusive. In contrast to the result above, however, it appears that this cannot be explained as an orientation effect. The strong radio sources in our sample contain large numbers of objects whose radio properties indicate that we are **not** viewing them at certain preferred angles.

We have now begun to undertake the next step in the investigation, namely to understand exactly where in the range of radio power the quasar switches off the ejection of gas and switches on powerful jets of radio emitting plasma, whether this switching occurs suddenly or gradually and whether the switching is best understood in terms of a real change in physical processes or whether we are viewing a mixture of two quite distinct populations of quasars.

STARS AND INTERSTELLAR MEDIUM

Studies of Young Stellar Objects and Their Circumstellar Disks

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Co-Investigator: Chris Koresko (Cornell Univerity)

Subject Heading: Stars

T Tauri stars are pre-main sequence objects of approximately Solar mass whose enigmatic properties puzzled astronomers since their discovery by Alfred Joy in 1945 (Bertout 1989). In this decade, it became apparent that most, if not all of these properties result from the action of circumstellar disks. Most of these disks have characteristics similar to those ascribed to the primitive Solar nebula, prior to the formation of the planets (Beckwith *et al.* 1990). By the time the stars reach the main sequence, only the most tenuous remnants of these disks remain (Backman and Gillett 1987), the material having gone into planets, been dissipated into space, or fallen onto the stars. T Tauri stars span the range of ages during which planet formation presumably takes place, and so there is great interest in understanding how the disk characteristics aid or inhibit the birth of planets around these nearby stars.

It is possible to reproduce the observed spectral energy distributions of these stars using very simple calculations with only a few ajustable parameters (*e.g.*, Adams, Lada, and Shu 1987). The infrared emission (wavelengths beyond about 2 μm) originates almost entirely within the disks, with the short wavelengths dominated by hot regions within a few tenths of an AU from each star. Infrared photometry therefore provides a diagnostic of the physical state of the inner disk, a region where the terrestrial planets are thought to have condensed in the young Solar system.

A subset of these stars have energy distribution suggestive of gaps in the inner disks. The signature of these gaps is strong far infrared and millimeter-wave emission (indicative of disk material a few AU from the star), weak emission at 5 and 10 μm (showing a deficit of matter within 1 AU), and strong emission shortward of 2 μm (from the stellar photosphere). In a sample of 86 stars, at least a dozen display this property. The implication is that the inner disks clear before the outer regions, possibly through accretion onto the star, possibly by tidal forces induced by a large body orbiting the star. Gaps should form naturally in the presence of orbiting bodies, such as small planets, and the observations described below aim to confirm their existence and understand what conditions give rise to their formation.

Beckwith and Koresko have undertaken a study of the photometric properties of these stars with an emphasis on disks with gap signatures. Using the Caltech infrared photometers and a Cornell visual photometer, they are deriving accurate spectral energy distributions between the B band and 10 μm for several dozen young stars. Since these stars are irregular variables with fluctuations sometimes occuring within a few days, it is important to have observations of the entire optical/infrared region for each star nearly simultaneously. The preliminary results confirm the diminished middle infrared flux from the gap candidates and give magnitudes for about a dozen new stars previously lacking photometry. Several of the stars in their sample are binaries with small separations. The infrared emission from these stars tests the hypothesis that companions can clear gaps in the circumstellar disks, perhaps even disrupting the disks entirely.

This work is part of a larger effort to understand planet-forming disks using Palomar for very high resolution images (Beckwith *et al.* 1989), the Owens Valley Millimeter Array to study the gas in the outer disks (Sargent and Beckwith 1987), and the Caltech Submillimeter Observatory to assess the particle properties (Beckwith and Sargent 1991).

REFERENCES

Adams, F. C., Lada, C. J., and Shu, F. H. 1987, *Ap. J.*, **312**, 788.

Backman, D. E. and Gillett, F. C. 1987, in *Cool Stars and Stellar Systems and the Sun*, ed. J. Linsky and R. E. Stencel (Berlin: Srpinger Verlag), p. 340.

Beckwith, S. and Sargent, A. I. 1991, in preparation.

Beckwith, S., Sargent, A. I., Chini, R., and Güsten, R. 1990, *Astron. J.*, **99**, 924.

Beckwith, S. V. W., Sargent, A. I., Koresko, C. D., and Weintraub, D. A. 1989, *Ap. J.*, **343**, 393.

Bertout, C. 1989, *Ann. Rev. Astr. Ap.*, **27**, 351.

Sargent, A. I. and Beckwith S. 1987, *Ap. J.*, **323**, 294.

SEARCH FOR INFRARED PULSATIONS FROM LIKELY SITES OF NEUTRON STARS

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Co-Investigators: Steven V. Beckwith (Cornell University)
Scott Lundgren (Cornell University)

Subject Heading: Stars

CONTEXT

In recent years, much work has centered on understanding the evolutionary links between ordinary stars and their various end products, especially neutron stars: X-ray pulsars driven by in-falling material from companion stars and radio pulsars self-driven by rotation. Both kinds of objects display periodic pulses caused by rotation of an X-ray or radio beam through the Earth's direction. The Galaxy is populated with neutron stars that are manifested in a veritable zoo of observable situations. Further progress requires that we discover more neutron stars at important *evolutionary stages* and that we find more to probe their galactic distribution. Ultimately we hope to understand the processes by which neutron stars transfer enormous amounts of energy to the interstellar medium, one by-product of which (through supernovae) is the formation of new stars and, hence, new civilizations. Pulsars are also excellent clocks, with the fastest objects rivaling even the best terrestrial time standards owing to the stability of their rotation. Other, less stable objects are not of interest as clocks, but provide the opportunity to study 'seismic' effects from neutron star interiors. As clocks, pulsars present themselves as engineering tools to be used in improving our knowledge of the solar system (e.g. the masses of planets and the orientation of the solar system), as detectors of gravitational radiation, and as probes of ionized plasma in the interstellar medium.

PALOMAR OBSERVATIONS

Work at Palomar is aimed at discovering new pulsars in the infrared and optical, and to analyze objects discovered by us and others through other ground-based and space observations. This work will be a comprehensive amalgam of hardware and software effort in the areas of detector and signal processing development, in addition to advances in our understanding of the astrophysics of neutron stars.

The class of pulsar we are most interested in consists of young, rotation driven objects, such as the pulsar in the Crab Nebula (~1000 years old) and the Vela pulsar (20,000 years). The means by which young objects deposit prodigious amounts of energy to the interstellar medium are unclear. The number of young objects in the Galaxy and their properties are also poorly known. However, with an estimated birthrate of almost one neutron star per century in the Galaxy, we expect there to be ~10 Crab-type and 200 Vela-type pulsars in the Galaxy. Infrared wavelengths are superior to both the optical and radio for very distant objects because visual extinction is severe at the short wavelengths while interstellar scattering quenches the radio pulsations.

1990 OBSERVATIONS

In the first half of 1990 we obtained fast sampled data at the 5 m telescope using an InSb detector at 2.2μ in the directions of Galactic supernova remnants, gamma ray burst sources, and the Galactic center. We developed a PC data acquisition system providing continuous sampling at 0.25 ms intervals for time periods as long as one hour. We have also developed Fourier analysis code at Cornell on a DECStation 3100. In our first run (May 1990), we obtained data that allowed us to develop analysis software that rejects instrumental interference (primarily harmonics of 60 Hz) and to calibrate our data. In one field, a putative supernova remnant of age less than 100 years, we found no evidence for a pulsar; this provides support for the view that the object is a misidentified planetary nebula. More importantly, in two of the directions near the Galactic center, we found significant pulsations: one with a period of 39.2 ms, the other with a 33.8 ms period. The flux density is consistent with that expected if the Crab pulsar were placed at a distance of 8.5 kpc, and its intrinsic lumimosity were increased by a factor of 5. We plan to verify these promising candidates, as well as many others, in future observations. Later this year (October 1990) we will obtain additional 2.2μ data in the directions of other supernova remnants, known short period pulsars, and a gamma ray burst source error box.

<u>Herbig-Haro Objects from Massive Pre-Main Sequence Stars</u>

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Subject Heading: Stars

Herbig-Haro (HH) objects, small blobs of high-velocity gas seen in the vicinities of young stars, have become signposts of star formation. A number of young, low mass stars, including the prototype star T Tauri, have been shown to be associated with HH objects and/or highly collimated "jets," which share many spectral properties in common with classical HH objects. For the most part these HH objects and jets have been found near low-mass young stars, the so-called T Tauri stars. Higher mass stars such as the Herbig Ae/Be stars appeared to show little if any of this type of activity. Recently, however, it has become clear that this is more a selection effect than anything else. Many Ae/Be stars are surrounded by fairly bright reflection nebulae, and these nebulae tend to obscure possible HH objects in the vicinity. Discovery of HH objects or jets around the Ae/Be stars V645 Cygni, Z CMa, LkHα 234, and an anonymous Ae star in Cygnus have shown that HH objects associated with more massive stars are generally more luminous, making study of their properties easier. Little work has been done on the possible differences between HH objects associated with low-mass stars and high-mass stars.

As part of an ongoing program to identify and study new Herbig-Haro objects and stellar jets, imaging of a large sample of Herbig Ae/Be stars was carried out on the 60-inch telescope at Palomar Observatory. In July, CCD images of the area around each star were obtained through continuum and [S II] passbands. A comparison of the two sets of images reveals the [S II]-bright regions in the nebulae, which are either HH objects or jets, or photoionized gas. Follow-up observations in the light of Hα distinguish between the photoionized gas and the shock-heated HH objects. Several HH objects or stellar jets were imaged, including the jet in LkHα 234. Observing time in December should allow completion of the imaging survey.

<u>The Remarkable H_2 Morphology of the Planetary Nebula NGC 7027</u>

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Subject Heading: Stars

Only a very few stars end their lives in a spectacular display like the star Sanduleak -69 202 which exploded in the Large Magellanic Cloud as a supernova in 1987. This star was massive (propably 10 times the mass of the sun), and therefore a fairly rare object. Stars of the mass of the sun end their evolution in a much more gentle, though no less interesting fashion. At present our sun is a so called main–sequence star, which means that it is buring hydrogen to helium through thermonuclear reactions in its core. However, when hydrogen is exhausted, and helium starts to burn to carbon, the sun will swell up in radius becoming a red giant star. During the red giant phase a remarkable event happens – the star starts to loose its envelope when a "stellar wind" starts to blow. At first this wind carries only a small amount of matter (even the sun has a solar wind which carries 10^{-14} solar masses per year). However, as helium exhaustion is approached the mass loss rate increases dramatically to $10^{-4} - 10^{-3}$ solar masses per year. This mass is lost in a relatively slow (10 $km\,s^{-1}$) wind which is cool, and is therefore an ideal place for the formation of molecules and dust. Clearly if this mass loss rate was sustained for $10^3 - 10^4$ years the star would be completely eroded. However, after a few tenths of a solar mass is lost to a circum-stellar cloud of gas and dust, the compact and still very hot (10^6 degree) core is uncovered. The upshot of this is that stars of solar mass, up to about eight times the mass of the sun never proceed to burn carbon to magnesium, and the uncovered core, now without any energy generation source, will cool over the next billion year. These cooling stellar remnants are known as white dwarf stars. The transition from red giant to white dwarf occurs rapidly on an astronomical time scale, and there are few objects known to be at this stage. However when the white dwarf core is first exposed it illuminates, and energises the cast off envelope, lighting it up to produce a spectacular nebula known as a planetary nebula. By understanding the structure and dynamics of planetary nebula we can hope to reconstruct the dramatic last stages of stellar evolution before a star dies and becomes a white dwarf.

Planetary nebula come in a wide variety of shapes. Many display a remarkable symmetry, which has lead to names such as the Helix Nebula and the Ring Nebula. These nebulae tend to be old, evolved nebulae, in which much of the information regarding their formation is now lost. Small young, nebulae from which one might hope to learn most about their formation, look amorphous. However, this is due in large part to the dust which is present in the nebula which absorbs optical light. Consequently the best wavelengths to observe these young objects is in the infrared where the effects of dust absorption are much reduced. Furthermore, in the infrared we can detect some of the molecules, such as molecular hydrogen (H_2), that are prevalent in the cold envelopes of nascent white dwarfs.

With these facts in mind we have begun a program to image young planetary nebulae at the 200-inch telescope with the new infrared camera. The first data obtained for this project is for a planetary known only as NGC 7027.

The data was obtained with narrow band filters which isolate emission in the light of ionized hydrogen at wavelength of 4.05 μm *, the "dust feature" at 3.3 μm which is due to a carbon–hydrogen bond resonance in dust grains, and the first vibrational transition of H_2 at 2.12 μm . The ionized hydrogen emission is smooth, elliptical in form, with the intensity peaked at two points opposite each other, equidistant from the center of the nebula. This map shows where light from the newly uncovered stellar core is ionizing the circumstellar envelope. This is a very different picture from that obtained at optical wavelength where dust absorption makes the nebula look very assymetric. A striking change of morphology is seen in the H_2 emission, and to a lesser extent in the dust feature (see Fig. 1). The H_2 emission is composed of two

* For comparison the wavelength of the yellow light from sodium street lights is 0.6 μm

components: 1) an incomplete elliptical ring of knots which bounds the ionized gas; 2) a remarkable thin shell which loops around the H II region with four–fold symmetry. The dust feature emission is similar to the emission from the ionized gas, but is displaced further from the center, extending at low surface brightness into four "ears" which fill in the bays delineated by the outermost loops of H_2 emission.

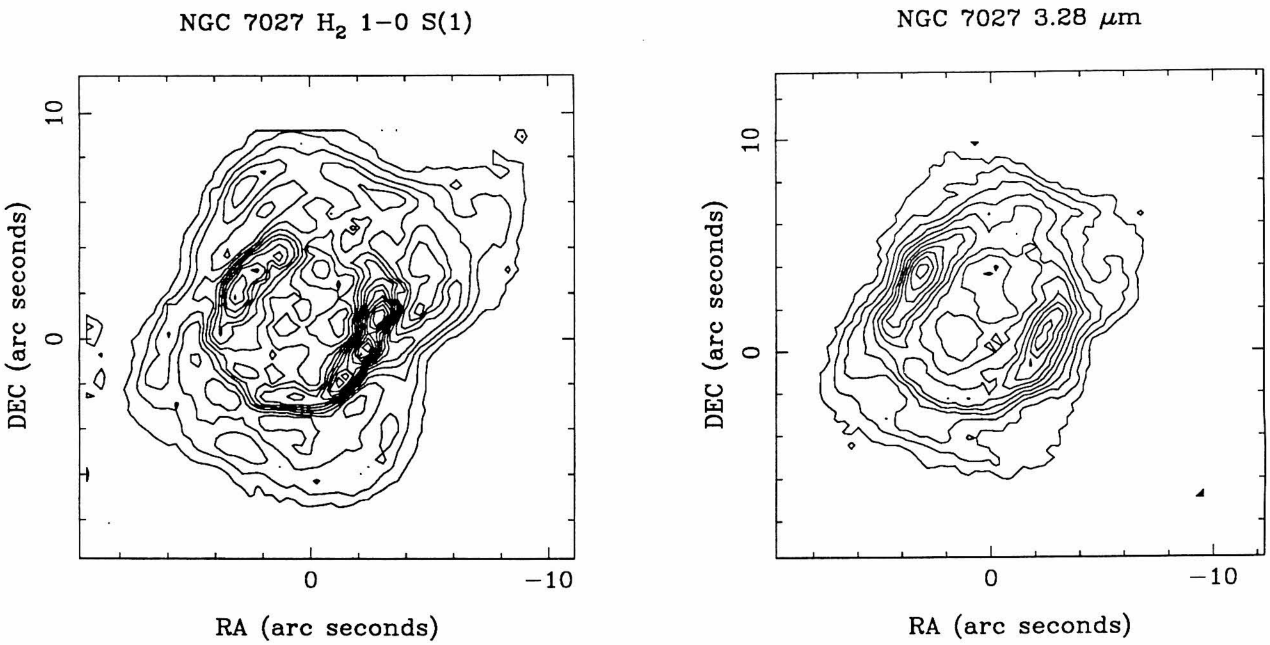

Figure 1

The left hand panel shows a contour plot of the infrared molecular hydrogen emission from the planetary nebula NGC 7027. The emission consists of two components – an elliptical ring which bounds the region of ionized gas, and a loop like structure with four–fold symmetry. The right hand panel shows emission from the dust emission band at 3.3 μm .

The remarkable H_2 morphology of NGC 7027 is not easy to understand, but the current model for the formation of planetaries forms a basis. According to this model the nebula is formed from the ejected envelope of a red giant star. Ionization of the molecular envelope starts when the stellar core in uncovered, and the shape of the nebula is from this point thought to be determined by the interaction of the slow wind that formed the envelope, with a fast hot wind from the central star. The high pressure of this hot wind drives a supersonic shock wave into the cool gas from the red giant envelope, and sweeps it up into a thin shell. As the nebula ages the swept up shell is ionized by the central star leading to the formation of a bright optical shell which is characteristic of many old planetaries. According to this model H_2 emission should be seen where the shock driven by the fast wind is propagating into the cold molecular envelope. However we see two regions of H_2 emission, one close to the edge of the ionized gas, and another which has propagated much further into the envelope. We therefore conclude that the red giant mass loss phase cannot have been the steady, gentle affair pictured in this model. Rather, to explain the outer loops of H_2 emission we must deduce that the mass loss rate changed abruptly at some earlier epoch, or even that an explosive event caused the outer shock. The symmetry of the H_2 loops is not well understood. However it is clear that the symmetry must be intrinsic to the molecular envelope, and suggests that the mass loss from the progenitor star must also have had four–fold symmetry.

SURVEYS FOR BROWN DWARFS

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Subject Heading: Stars

Brown dwarfs are objects in a sense midway between stars and planets in terms of their mass and internal energy generation properties. By definition, they do not have enough mass to sustain steady-state nuclear fusion in their cores, but they are considerably more massive than Jupiter – this corresponds to a mass in the range 1% to 8% of the mass of the Sun. When they are young, brown dwarfs are relatively warm and luminous as they convert their gravitational potential energy into heat. However, because they cannot sustain fusion in their core for very long, their fate is to cool and become fainter, until by the age of the Sun they emit only about one millionth the luminosity of the Sun. Predicted by astrophysical theory, no brown dwarfs have been yet definitely identified, although other groups of astronomers have listed at least eight possible brown dwarf companions to brighter stars.

The Pleiades is an ideal cluster to look for brown dwarf stars. As mentioned earlier – brown dwarf stars become fainter as they grow older. The Pleiades being relatively young (70 Million years) and nearby (490 light years) allows a greater chance of finding these stars.

After extensive photometric and spectroscopic analysis, one can conclude that intrinsically faintest and reddest objects found in a deep multicolor survey of the Pleiades reveals no stars that are cooler than certain known stars close to us. If these nearby stars are brown dwarfs, then so are several of the stars found in the Pleiades. The burden of proof is on demonstrating the nature of the heat source in the nearby cool stars.

Hamilton has also performed a spectroscopic analysis of brown dwarf candidates found by other investigators, which suggests that these are all hotter-than-expected stars which are enveloped in thick dust cloud. The apparent coolness attributed to these stars initially by the discoverers is due to an inability to correctly estimate the effects of the dust upon the light which reaches us.

Broadening of the Hydrogen Balmer Lines During Flares

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Subject Heading: Stars

Flares on M dwarf stars are characterized by greatly enhanced chromospheric emission as evidenced by the strong hydrogen Balmer lines and ionized calcium H and K lines. These emission lines are an important diagnostic of the atmospheric conditions in the flare emitting regions. In particular the broadening of the Balmer line wings, which has been unambiguously observed in many flares, may indicate that a hot dense chromosphere resulting in significant Stark broadening of the lines is present. On the other hand, the broadening in the line wings may be due to coherent mass motions into or out of the chromosphere. The ability to detect broadening in the line core is the key to distinguishing these effects and hence determining the true nature of the chromosphere during flares.

Our program is designed to address the line broadening question using high spectral resolution observations obtained with the echelle spectrograph on the Palomar 60" telescope, in conjunction with photometric observations using the 24" telescope at the Table Mountain Observatory in Wrightwood, California. By obtaining simultaneous photometric and spectroscopic observations we are able to calibrate our spectra and obtain the energy and duration of the flare, to compare with other previously observed flares. The echelle spectrograph allows us to take spectra with excellent spectral resolution over a large wavelength range which encompasses the entire Balmer series. In these spectra the Balmer and Ca II lines are resolved in the line core during quiescence; any broadening during flares is easily detectable.

We monitored several solar neighborhood flare stars on two nights in February 1990 and two nights in April 1990, and successfully obtained observations of three flares, including one very energetic event that lasted for more than an hour. Our preliminary finding is that the Balmer emission line cores did not show the broadening expected if the Stark effect was the principal broadening mechanism. These data are currently being prepared for publication.

Brown Dwarfs in the Taurus Cloud

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Co–Investigators: John Stauffer (NASA Ames Res. Center)
Donald Hamilton (Palomar Observatory)
William Forrest (University of Rochester)

Subject Heading: STARS

Theoretical estimates indicate that self-gravitating bodies below a mass of about 0.08 $M_\odot$ will never achieve a high enough central temperature to undergo stable nuclear burning. Such objects are referred to as brown dwarfs. It is of great interest to know if brown dwarfs do exist in the galaxy, and if so, how many there are and what are their masses. A large population of such objects, which are very difficult to detect, could contribute significantly to the mass of the galaxy. Current estimates of the dynamical mass in the solar neighborhood indicate about a factor of two greater mass than is directly observed.

The search for low mass objects has intensified in recent years with the development of significant improvements in both optical and infrared detector technology. The most common technique in the search for brown dwarfs is to look for companions to low-luminosity objects such as white dwarfs and late-type main sequence dwarfs. This allows accurate determination of a distance, and rough estimates of an age - important for distinguishing between brown dwarfs and very low-mass stars (VLM's). Several brown dwarf candidates such as Giclas 29-38B, GD 165B, and Gliese 569B (Zuckerman and Becklin 1988; Becklin and Zuckerman 1988; Forrest, Skrutskie, and Shure 1988), have been found. However, within the range of plausible ages, temperatures, and luminosities all three candidates could be VLM's rather than brown dwarfs. Furthermore, binary systems do not directly address the missing mass problem.

Since brown dwarfs have no internal heat source, they cool and dim with time (with lower mass brown dwarfs being cooler and fainter for any given age). Hence brown dwarfs will be easiest to detect when they are young. This has spawned another approach to search for brown dwarfs, namely to look in young, nearby, rich star clusters. Stauffer *et al.* (1989) have applied this technique to the the Pleiades cluster, searching a large area with the 4-Shooter attached to the Hale 5.08 m telescope. They found several brown dwarf candidates. Because the distance, age and metallicity of the Pleiades is well known, these objects are possibly the best yet brown dwarf candidates. They will provide particularly important constraints on theoretical brown dwarf models if they are confirmed to be Pleiades members. Interestingly, it does not appear that high mass brown dwarfs contribute significantly to the total mass of the cluster.

Using infrared imaging Forrest *et al.* (1989) have applied a similar technique to the Taurus cloud. Taurus is a younger complex than the Pleiades so that equivalent mass brown dwarfs should be correspondingly brighter. Searching small ($25''$) regions near 26 members of the association, Forrest *et al.* find 20 faint (K = 13–16 mag) stellar objects near 13 of them.

Nine of the objects are very red and also appear to be Taurus members. For an estimated age of 10^6 years, the observed luminosities give masses in the range 0.005-0.015 $M_\odot$ as derived from theoretical cooling curves. Four of the candidates have proper motions suggestive of membership in the Taurus cloud.

The objects found by Forrest *et al.* appear to be quite populous but as yet definitive determination of whether they are brown dwarfs or reddened stars requires spectroscopic studies. Several of the candidate stars have R magnitudes of order 19, and infrared colors corresponding approximately to mid to late M dwarfs. If these stars are not low mass members of Taurus, what are they? The area surveyed by Forrest *et al.* was too small for low mass, (nearby) field dwarfs to contribute significantly. The only plausible identification for the brown dwarf candidates is then that they are heavily reddened, relatively early (spectral type K or earlier), background stars.

We have obtained low resolution red spectra (5700-8600 Å) with the using the 4-Shooter spectrograph of 6 of the candidate brown dwarfs found by Forrest *et al.* One would expect strong TiO and CaH absorption bands, the Sodium D-lines, and possibly Hα and the Ca IR triplet in emission if the stars are Taurus cloud members. The molecular absorption bands will be absent if these are heavily reddened background stars (and in general emission lines should be absent). Our spectra show that these bands are absent and that the brown dwarf candidates appear to be simply reddened background stars (Stauffer *et al.* 1990).

These results do not rule out the presence of brown dwarfs in the Taurus cloud but indicate that the number of such objects is significantly smaller than that postulated by Forrest *et al.*

REFERENCES

Becklin, E. E. and Zuckerman, B. 1988, *Nature*, **336**, 656.

Forrest, W. J., Skrutskie, M. F., and Shure, M. A. 1988, *Ap. J. (Letters)*, **330**, L119.

Forrest, W. J., Ninkov, Z., Garnett, J. D., Skrutskie, M. F., and Shure, M. 1989, in *NASA Ames 3rd Detector Workshop*, ed. C. McCreight, 221.

Stauffer, J., Hamilton, D., Probst, R., Rieke, G., and Mateo, M. 1989, *Ap. J.*, **344**, L21.

Stauffer, J., Herter, T., Hamilton, D., Rieke, G., Rieke, M. and Forrest, W., 1990, submitted to *Ap. J. Letters*.

Zuckerman, B. and Becklin, E. E. 1988, *Nature*, **330**, 138.

The Remnant of Tycho's Supernova

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Co-Investigator: Debra Levine
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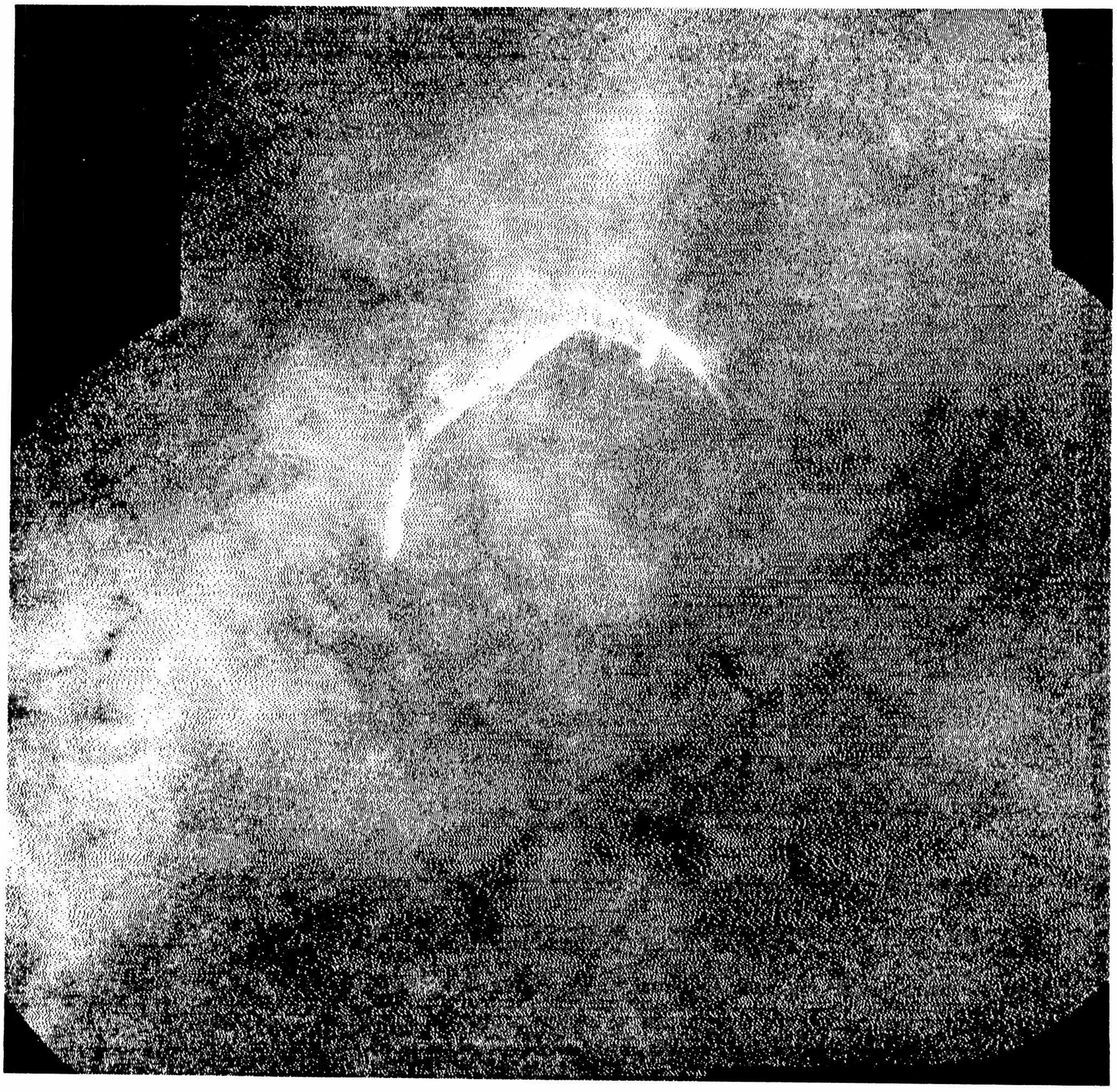
Subject Heading: Interstellar Medium

The remnant of the supernova that Tycho Brahe observed in the 16th century is visible today as faint arc of optical emission. This arc traces the current location of a portion of the interstellar blast wave which is propagating out from the site of the explosion through tenuous interstellar gas. At X-ray and radio wavelengths the appearance of the supernova remnant, or SNR, is much more spectacular. In radio images, Tycho appears as a complete bright thin shell which emits radiation due to the motion of shock-accelerated cosmic rays moving in the region of shock-compressed magnetic fields. Tycho's SNR glows in the X-ray due to thermal emission from the 100 million degree gas in its interior.

Using a wide field reimaging CCD camera on the 1.5 meter telescope at Palomar, we obtained deep images of a number of overlapping fields centered on the SNR. Images were obtained both in the light of emission from atomic hydrogen and through a filter which excludes line emission. The continuum images were used to subtract the starlight from the emission line images, which were then aligned and combined to produce the final image shown in the figure. This image represents approximately 7 hours of integration, and shows features which are 30 to 50 times fainter than those visible on the Palomar Sky Survey plates.

This image contains a number of exciting new results. Optical emission, previously seen only along the northeastern (top left) edge of the remnant, can be traced from 9:00 O'clock around to approximately 5:30, and from 1:30 around to almost 3:00 O'clock. The only portion of the boundary of the remnant which cannot be seen in Hα is a segment on the SW side where an obscurring foreground cloud blots out both the shock emission and the diffuse emission in which the remnant in embedded. These newly discovered filaments are coincident with the boundary of the radio emission, and show that while the medium to the west of the remnant must be much less dense than that to the northeast, the medium into which the remnant is evolving is partially neutral all the way around.

The band of emission seen running from SE to NW across the field is from ambient material with which the remnant is directly interacting. The presence of this denser material accounts for why the remnant is very much brighter along its NE edge. The fact that this gas is glowing in Hα (in much the same way that a fluorescent light glows) means that it is at least partially ionized. The brightness of the shock emission from the SNR, on the other hand, requires that the material being swept up by the shock is partially neutral. This is an unusual situation. Normally, in the presence of a source of ionizing radiation, low density material such as is seen around the periphery of the remnant is completely ionized. We believe that this material may have been flash ionized by the burst of ultraviolet radiation from the supernova itself, and is now radiating as it slowly cools and recombines.



Neutron Stars, Pulsars, X-ray Binaries and Black Holes

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Subject Heading: Stars

Neutron stars are the stellar remnants of stars more massive than eight times that of our Sun. Their birth is usually accompanied by sudden and vast release of energy which result in a supernova. Black holes are the remnants of very massive stars. As implied by the name, the composition of such stars is essentially neutrons. Neutron stars are the densest objects in the Universe. Neutron stars with sufficiently large rotation rate and magnetic field strength are detectable as pulsating radio sources or pulsars. Essentially the rotating star acts as a electrical generator with the radio emission resulting from giant electrical discharges. The evolution of neutron stars in binary systems can be quite complicated. Material can be transferred from the companion to the neutron star during which copious amounts of X-rays are emitted and the neutron star spun up. The end result can be a neutron star spun up to *millisecond* periods. Such millisecond and binary pulsars are turning out to be extremely useful as probes of a variety of astrophysical phenomena and as tests of General Relativity and cosmological theories. Most of my recent research has concentrated on understanding the birth and evolution of the binary and millisecond pulsars.

While x-ray and radio observations are important in identifying neutron star systems it is optical observations which provide many crucial clues. For example, optical observations of the companions of some binary pulsars yield estimates of the ages of such systems. Spectroscopic observations yield the radial motions of the x-ray binaries which in turn tells us something of the origin of such systems. The interaction of the energy generated by pulsars with the surrounding interstellar medium are, in some cases, studied very well at optical wavelengths. The best known example of stellar black holes require extensive optical observations. In particular, observations of the radial motions of the companion star (using the well known Doppler effect) can be used to infer the presence of a massive companion i.e. a black hole (since it can be shown on rather general grounds that the mass of a neutron star cannot be larger than 2 solar masses).

After extensive investigations of the field of the binary pulsar 1855+09 we conclude that the companion to this pulsar is white dwarf which is so cold that it is essentially optical undetectable. We conclude that the white dwarf and hence the pulsar must be at least a few billion years old. This result strengthens our earlier hypothesis that millisecond pulsars are truly ancient objects and that their magnetic field does not decay as appears to be the case for typical pulsars.

Two years ago we discovered a beautiful cometary nebula around the millisecond pulsar 1957+20. This nebula is produced as a result of the interaction of the energy radiated by the pulsar and the surrounding interstellar medium. The spectrum of the nebula is unusal: only the Hydrogen lines are detected. Such emission arises when a shock moves into neutral medium and are rarely seen. Theoretical models make specific prediction of the details of the spectrum. Our recent investigations indeed find good agreement of the observations with the theoretical expectation. Turing the situation around, our observations can be used to reveal the three dimensional motion of this object. This will be the first determination of the actual orbit of a millisecond pulsar and should tell us something interesting about the origin of the system.

Two years ago, using the Hale 5-m telescope we confirmed the existence of a massive star (i.e. a black hole) in the X-ray system A0620-00. New data obtained last year has further strengthened our conclusions. We have monitored two black hole systems (x-ray novae) and in one of them have found tentative evidence for rapid motions. Observations of this possibly interesting system will be continued.

Echelle Spectroscopy of CD -41° 13967: The Young Central Star of a New Planetary Nebula

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Co-Investigator: R. Michael Rich
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Columbia University, NYC

Subject Heading: Stars

On the basis of high resolution, high signal to noise (S/N) ratio spectra obtained with the Palomar 60-inch echelle spectrograph (see the contribution on **Instrumentation** in last year's *Annual Report of the Palomar Observatory*), we discovered that the hot star designated CD -41° 13967 is the young central star of a previously unknown planetary nebula. The central stars of planetary nebulae (CSPN) are stars which have reached the end of their "red giant" evolutionary phases and have ejected their giant envelopes into space by means of a dense stellar wind, leaving only the stellar core behind. CSPN are therefore among the highest temperature stars known, and emit ultraviolet light which ionizes the ejected red giant envelope; this shell of ionized gas is referred to as a "planetary nebula" (PN) and has an emission line spectrum.

CD -41° 13967 happens to be relatively cool compared to most CSPN; its surface has an effective temperature equal to $27,000\,\mathrm{K}$. We determined this by fitting the broad absorption lines seen in our echelle spectra of CD -41° 13967 with theoretical line profiles calculated by computer models of stellar atmospheres. Figure 1 on the next page is a comparison between our observed absorption line profiles and those generated by the computer model atmospheres (which are shown as dashed lines). Because of the high temperature of CSPN, the only strong absorption lines in their spectra are from hydrogen and helium, but note that the surrounding nebulae emit at these same wavelengths also. When observed at low spectral resolution, the emission lines from the nebula dominate and mask the underlying stellar absorption lines (in fact, CD -41° 13967 was originally classified as an "emission line star" since low resolution spectra gave the impression that the emission lines were broad and stellar in origin). At high resolution such as that available with the Palomar 60-inch echelle spectrograph ($\Delta\lambda \leq 0.15$Å/pixel), however, it is possible to separate the strong nebular emission lines, which are quite narrow, from the weaker stellar absorption lines, which are broad (see again, Figure 1). Note finally from Figure 1 that with the echelle spectrograph, many spectral features at different wavelengths in the same object can be detected simultaneously.

In addition to the effective surface temperature of 27,000 K, we were also able to determine the stellar mass of CD −41° 13967 (0.63 times the mass of the sun), an estimate of the time since the star was a red giant (1,250 years), and the distance to the object (10^4 light years). The distance estimate, combined with our measured radial velocity of −91 km/s, implies that this new CSPN is located in the Milky Way's galactic halo. From an analysis of many of the weaker stellar absorption lines in our echelle spectra, we found that CD −41° 13967 is helium enriched — helium having an abundance 3 times solar — and midly silicon and oxygen deficient (see our paper in *The Astrophysical Journal*, 10 April 1991).

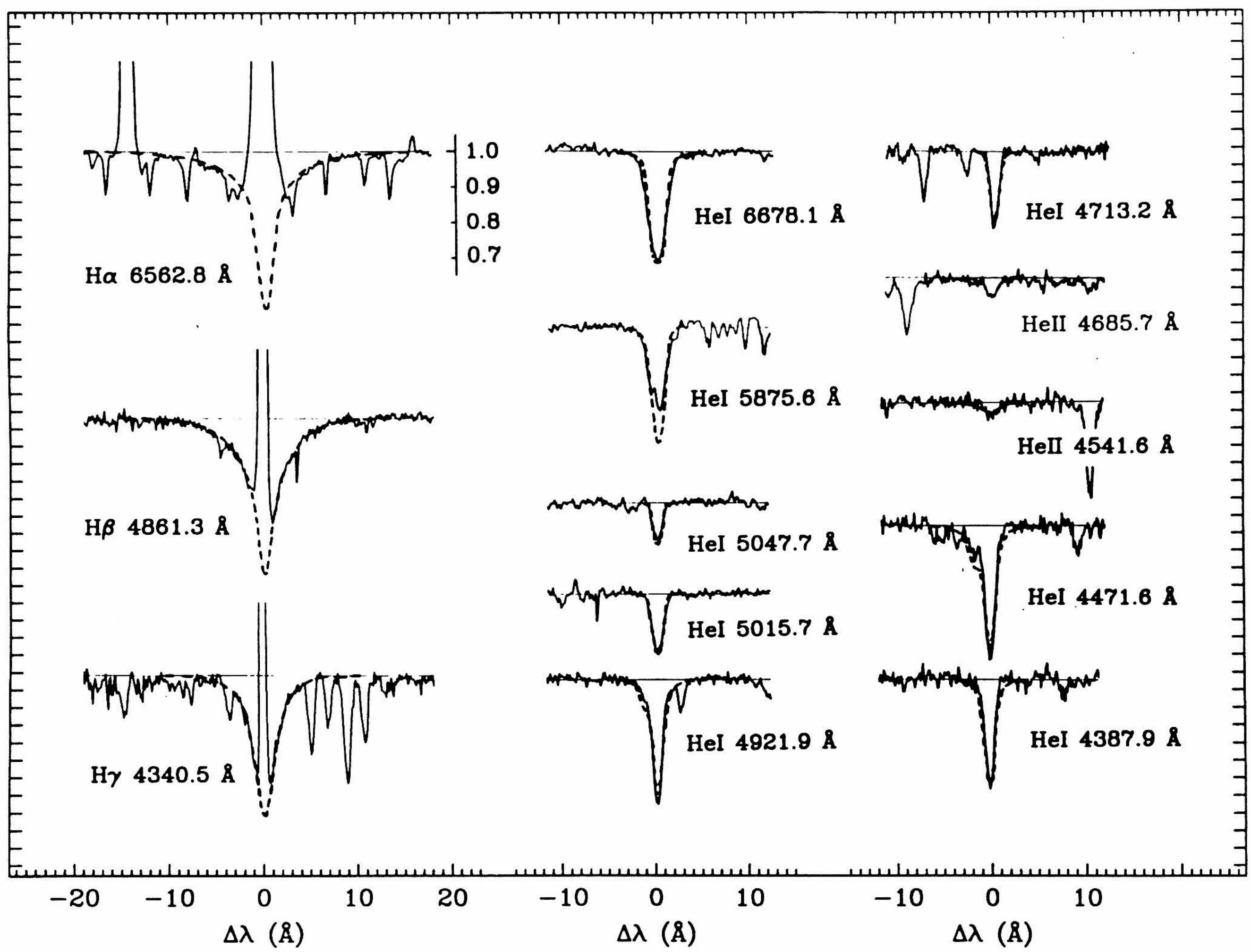

Figure 1: Theoretical computer model atmosphere line profiles (dashed) matched to the observed CD −41° 13967 line profiles taken from our echelle spectra. All profiles share a common normalized flux scale, shown opposite the Hα line at upper left. The weak HeII features rule out $T_{eff} < 27,000$ K.

Deep Near–Infrared Imaging of the W3 Star Forming Region

Principal Investigator: Tom Megeath
Department of Astronomy
Cornell University

Co–Investigators: Terry Herter (Cornell University)

Subject Heading: STARS AND THE INTERSTELLAR MEDIUM

A key issue in the study of star formation is the relationship between high and low mass star formation. Almost thirty years ago, George Herbig suggested that star formation is bimodal, i.e. high mass and low mass stars form in different locations through different processes (Herbig, 1962). This suggestion was based primarily on a comparison of the Taurus and Orion star forming regions, which showed a lack of stars of greater that two solar masses in Taurus, but high and low mass star formation in Orion.

As an alternative to bimodal star formation, it has been suggested that star formation is stochastic. In this model, the mass function for star formation is given by a probablity distribution which is essentially invariant from region to region. The probablility of a star forming would decrease with mass, and the formation of an O star would be an unlikely event, occuring mainly in regions of rampant star formation such as Orion.

Such a stochastic star formation scenario predicts that high mass star forming regions should contain many low mass stars. In contrast, in a bimodal scenario, high mass regions may exhibit a minimum mass, below which star formation does not occur. For this reason, searching for low mass stars in high mass star forming regions would be an observational test of these models, and a lack of low mass stars would certainly be indicative of bimodal star formation. (*cf.* Scalo, 1986)

Unfortunately, high mass star formation regions are relatively distant and highly obscured. Radio observations can only detect the HII regions surrounding the more massive stars, and Far-Infrared observations are dominated by the luminosity of the most luminous sources. To search for lower mass stars in these regions, we have begun a program of deep near–infrared imaging. The first source investigated is the W3 star forming region. This particular area exhibits numerous compact HII regions and bright infrared source showing that it is actively forming high mass stars (*cf.* Hayword *et al.*, 1989; Harris and Wynn-Williams, 1976).

Using the IR Cassegrain camera we covered a region of roughly a square arcminute in the H (1.65 μm) and K (2.2 μm) bands. The mosaic of these images (see figure) shows a multitude of previously undiscovered point sources and associated diffuse emission. In the northeastern corner of the map is the HII region W3a. This is the most evolved region in the source and is illuminated by IRS 2a, the brightest source in the map. The W3a region contains the four brightest sources, all of which have been detected by previous mapping. Our maps also show a host of previously undetected stellar-like sources in this region. These sources may be lower mass stars inside the HII region.

The most interesting part of the map is the cluster of sources surrounding IRS 5 (the bright source southwest of center). If IRS 5 is a high mass protostar deeply embedded in a molecular core, these images suggest that the core is concurrently forming a series of lower mass sources. Further analysis is needed to determine whether the luminosity function of the sources shows a cutoff above our detection limit. Such a cutoff would be the result of a lower mass limit in the star formation occuring in W3.

Associated with the region is also a number of lower luminosity sources. It is not clear whether these sources are background reddened giant stars or young low mass stars. A study of these sources should be useful in understanding how the cloud core fragments. If they are low mass stars, they show that the low mass stars form over a larger region than the higher mass stars. On the other hand, if they are background stars, estimates of their exinction will give a measure of the clumpiness of the cloud core.

Further analysis and modeling are proceeding to determine whether a minimum mass is apparent in our data; however, our results do show that the extent of star formation and the number of sources is far in excess of what was previously observed. From this, it is clear that the cloud cores forming O and B stars are concurrently forming many lower mass stars.

References

Hayward, T.L., Grasdalen, G.L., Woodward, C.E., Hackwell, J.A., Gehrz, R.D., and Pipher, J.L. 1990, *Ap. J.*, **345**, 894.

Harris, S., Wynn-Williams, C.G. 1976, *Ap. J.*, **174**, 649.

Herbig, G.H., 1962, *Adv. Astron. Astrophys.* 1, 47.

Scalo, J.M., 1986, *Fundam. Cosmic Phys.* 11, 1.

The mass distribution of white dwarf stars

Principal Investigator : I. N. Reid
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Co-Investigator : G. Wegner
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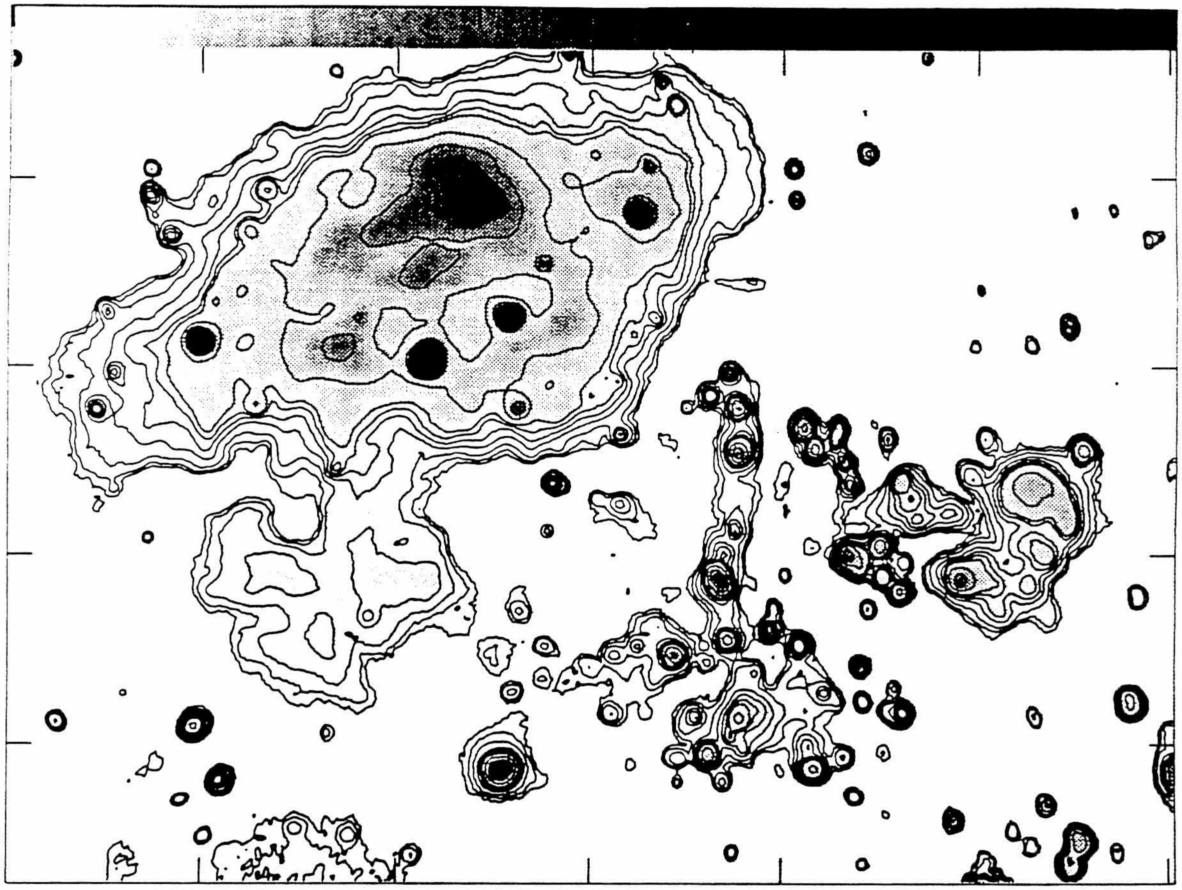
Subject Heading : Stars

Most stars with masses of less than $\sim 8M_{\odot}$ spend their twilight years fading into obscurity as white dwarf stars. The majority of these objects are the degenerate central cores of second, or asymptotic, red giant branch (AGB) stars, exposed after the outer envelope was ejected to form a planetary nebula. Since the core grows in a well-determined way on the AGB, the mass distribution of white dwarfs gives an estimate of the lifetime of AGB stars, while the relation between the initial and final mass tells us how much mass is returned to the interstellar medium. Moreover, the mass-radius relation directly tests theories of the structure and evolution of white dwarfs, while the overall mass distribution can yield important information on the Galactic star formation history.

The most direct method of determining the mass of a white dwarf is through orbital dynamics - but only one star, 40 Eridanus B, is both in a binary system and close enough to permit an accurate astrometric determination of the orbit. Gravitational redshifts offer the next best method - white dwarfs are exceedingly compact, with 0.5-1 $M_{\odot}$ of material confined within a sphere the radius of the Earth, and the surface gravitational field ($\sim 10,000$ times that of the Sun) is strong enough to cause a noticeable redshift (through the principle of equivalence) in the emitted radiation. In the case of DA white dwarfs, which have spectra dominated by hydrogen lines, we can measure the the apparent stellar velocity and, if the white dwarf is a member of a cluster or has a physically associated main-sequence companion, we can determine the true radial velocity. The difference between these two values is the redshift - typically 20-40 kms^{-1}. Given the radius of the white dwarf, which can be calculated if the distance, effective temperature and luminosity are known, the mass is easy to compute - typical uncertainties are $\sim 0.03 - 0.05M_{\odot}$.

We have been working on this project over the last five years, obtaining spectroscopic observations of more than 55 systems, using both with the Isaac Newton Telescope on La Palma and with the Hale 5-metre, with most of our data taken with the double spectrograph on the latter telescope. Figure 1 shows the results of this survey - the mass distribution - where we have separated the field binaries and the cluster dwarfs. The two distributions are similar, but not identical. In the case of the field stars, most degenerates fall in the mass range $0.4 \leq \frac{M}{M_{\odot}} \leq 0.65$ with the peak at 0.55 $M_{\odot}$ and 0.63 $|M_{\odot}$ the mean of the complete sample. In contrast, the Hyades stars have a mean mass of $0.69M_{\odot}$, reflecting the fact that they are descended from younger ($\tau \leq 3 \times 10^8$ years), more massive ($\geq 2M_{\odot}$) progenitors than the average field white dwarf. Thus the Hyades dwarfs have lost $\sim 1.3M_{\odot}$, primarily during the evolution along the AGB.

The low mass white dwarfs in the field-star distribution represent something of a problem for stellar evolution theory, since the minimum mass expected for an AGB core is $\sim 0.52M_{\odot}$. It is possible that these dwarfs represent the culmination of an alternative evolutionary route, with the stars missing out the AGB and evolving across the H-R diagram after helium core ignition at the tip of the first giant branch. If so, these dwarfs are the descendant of the hot ($T_e \geq 40,000$ K) sdB and sdO subdwarfs.



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Peak contour flux =  1.1291E+04
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 0.400, 0.600, 0.800, 1.000, 2.000, 4.000,
 6.000, 8.000, 10.00)
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This figure shows a section of our K-band (2.2μm) map. This map is a mosaic of more than one hundred separate images made with the IR Cassegrain camera. In this map, north is toward the top, west is toward the right, and the scale is 30″ per tic-mark. The dark rings are point sources which are most likely recently formed stars embedded in the molecular cloud core.

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Co-Investigator : G. Wegner
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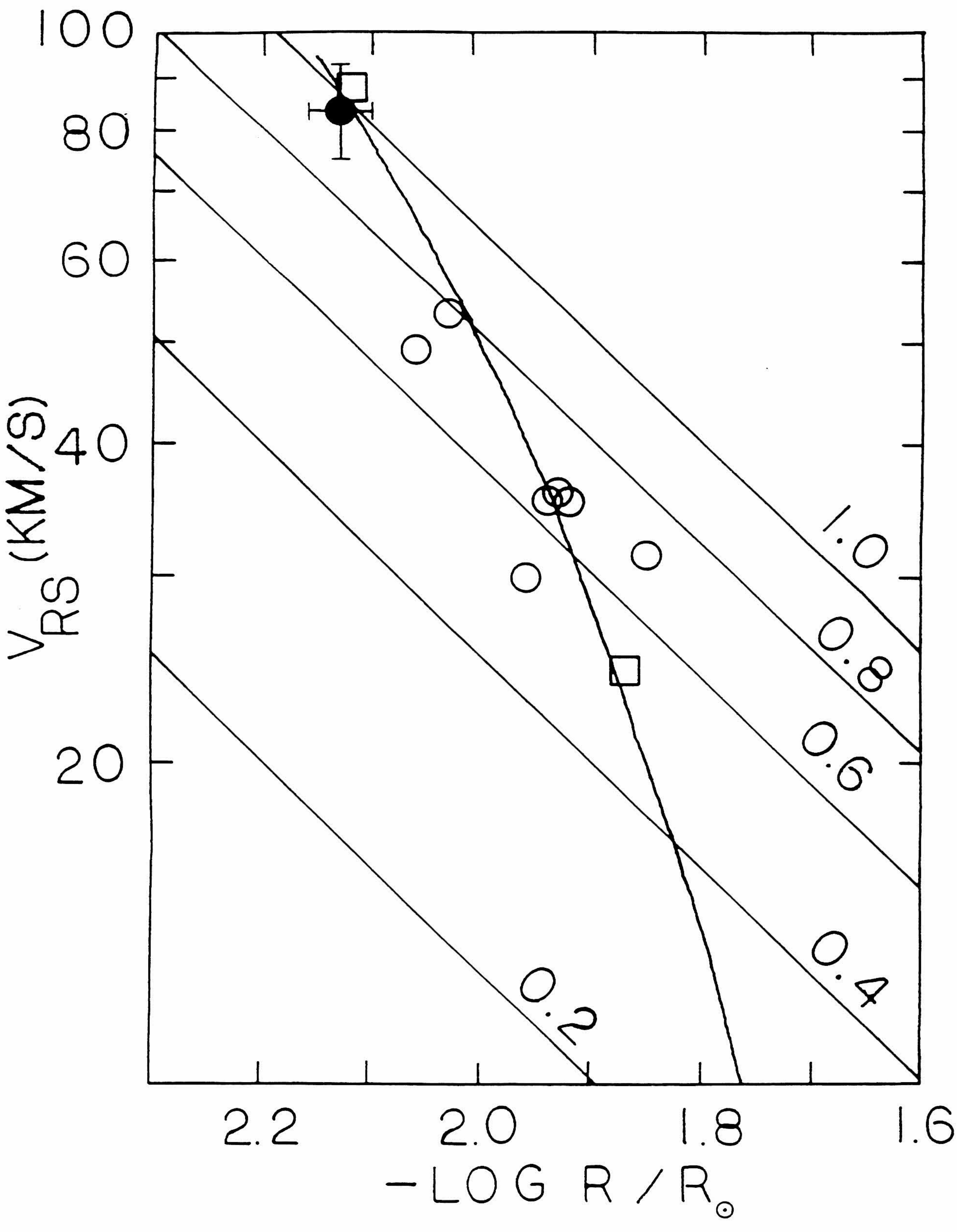
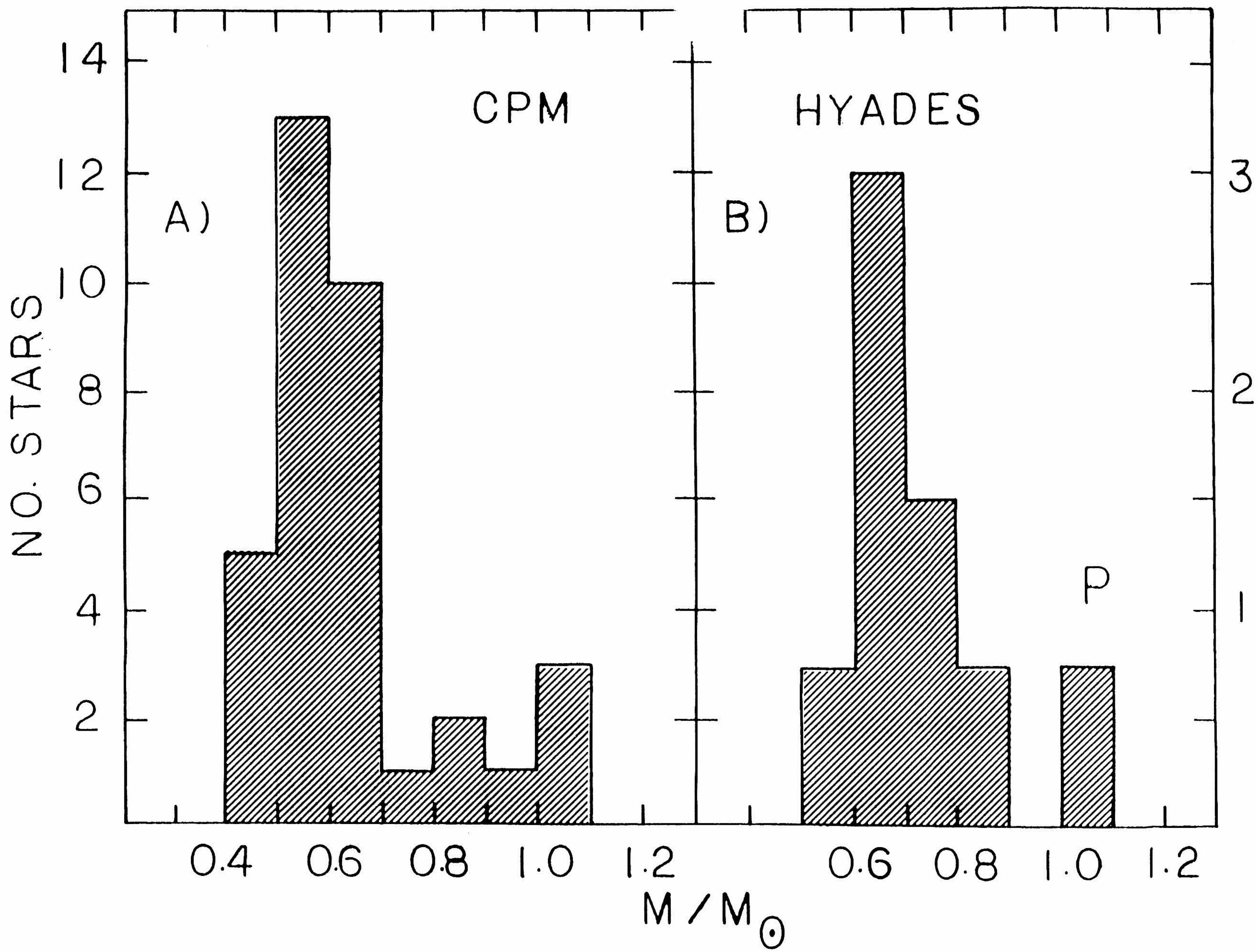
Finally, we have measured the mass of LB 1497, the only known white dwarf member of the Pleiades, as $1.02 \pm 0.04 M_{\odot}$. This is only the second white dwarf to have a reliably determined mass near 1 $M_{\odot}$ - the other is Sirius B. (There are several high mass candidates amongst the field stars in figure 1, but it remains possible that at least some of these are chance alignments rather than physical binaries, in which case the velocity difference between the white dwarf and the main-sequence star is not due to gravitational redshift.) The high mass white dwarfs are a particularly sensitive test of the theoretically-predicted mass-radius relation. Figure 2 plots our results for the Hyades stars (open circles) and the Pleiad (solid circle) together with previously published data for Sirius B (Greenstein, Oke & Shipman) and 40 Eri B (Wegner). The diagonal lines are lines of constant mass, labelled in solar units, and the curved line is the predicted mass-radius relation for carbon white dwarfs. The agreement with the observations is excellent.



Wegner, Reid, & McMahan: FIG. 3



Wegner & Reid: FIG. 1

Low luminosity stars in the Hyades cluster

Principal Investigator : I. N. Reid
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Subject Heading : Stars

Star formation is amongst the least well understood of astrophysical processes. From observational work it is clear that stars form in the vicinity of molecular clouds, but exactly what triggers collapse and, more particularly, what determines how many stars of a given mass are formed, remains a subject for informed speculation. One method of constraining theoretical models is through observation of the stellar mass function - the number of stars per unit mass per unit volume - with particular emphasis on the shape of the mass function at the low mass end. Objects less massive than $\sim 0.07 M_\odot$ fail to ignite hydrogen burning in the core during collapse and, as a result, fade rapidly into obscurity. If the mass function is still increasing approaching this H-burning limit, it is reasonable to suppose that it continues to increase beyond the limit, and that there are numerous 'brown dwarfs' in the Galaxy - with important implications both for star formation and for the overall mass distribution in disk and halo ("missing mass").

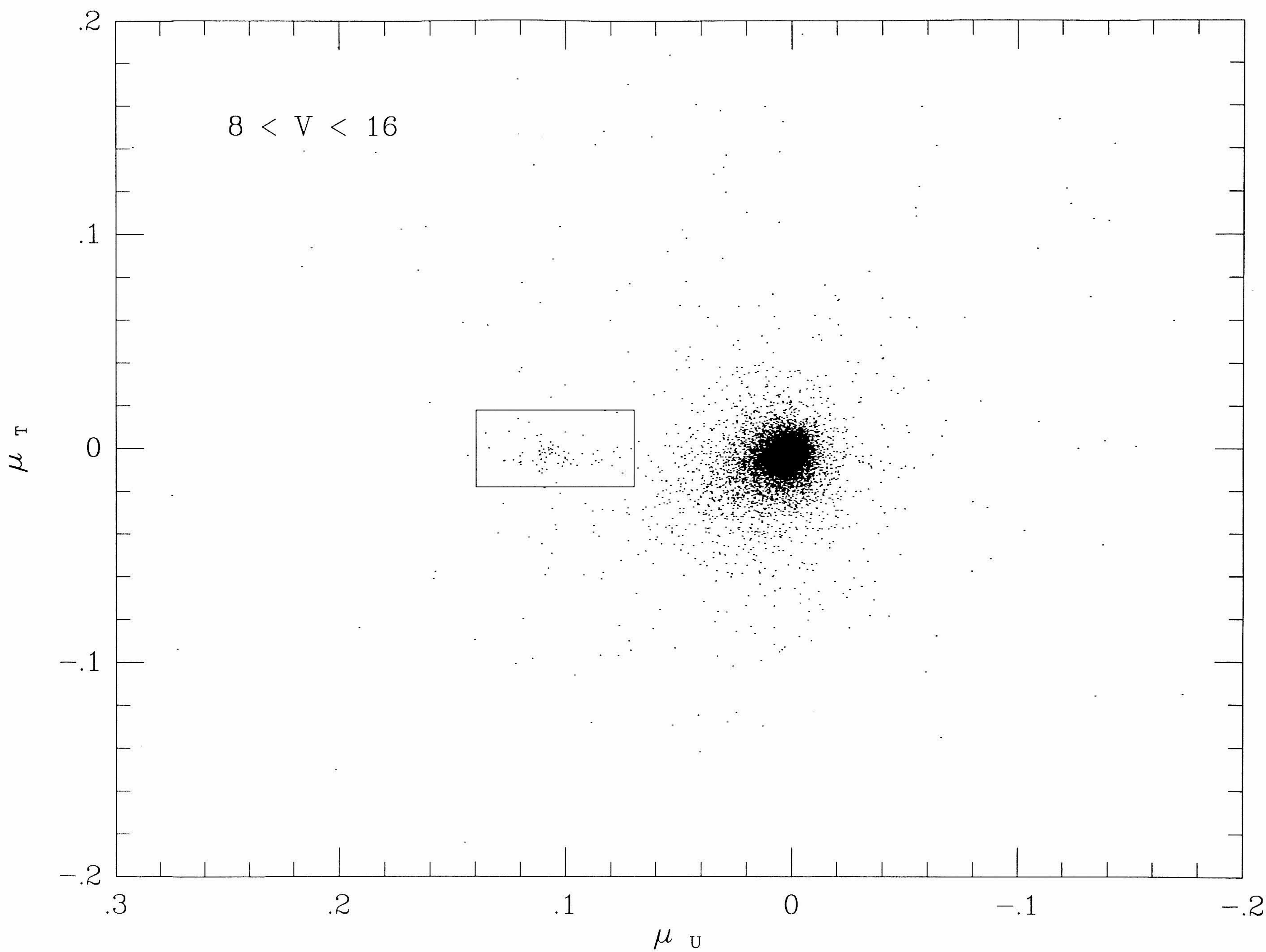
One method of probing the luminosity function is to survey a volume of space within the Solar Neighbourhood and count the number of stars as a function of luminosity. C. Tinney (C.I.T. graduate student) is collaborating with Mould and Reid in using photographic plates from the second Palomar Sky Survey for this type of project. However, an alternative approach is to pick a nearby open cluster and look for low luminosity members. This has the advantage that one is dealing with a group of stars of known age and abundance, which formed together in one episode of star formation, while in the field one is dealing with stars which have formed throughout the history of the Galactic disk. The disadvantage of cluster studies is that one has to separate unambiguously cluster members from background (and foreground) field stars, as well as allowing for such effects as mass segregation, which leads to the lower mass stars being distributed over a larger volume of space than the more centrally concentrated higher-mass stars.

At a distance of only 45 parsecs and with an age of $\sim 6 \times 10^8$ years, the Hyades cluster is an obvious candidate for study. The cluster covers more than 100 square degrees on the sky, and the brighter stars have been identified, mainly from proper motion surveys by Luyten (Minnesota), van Altena (Yale) and Hanson (Lick). However, little work has been done fainter than $\sim 16th$ magnitude. This corresponds to an absolute magnitude of $M_v \sim 12.5$ - and the field star luminosity function peaks at this magnitude. Clearly it would be interesting to extend the Hyades studies to fainter magnitudes to see how closely the cluster function follows that of the field.

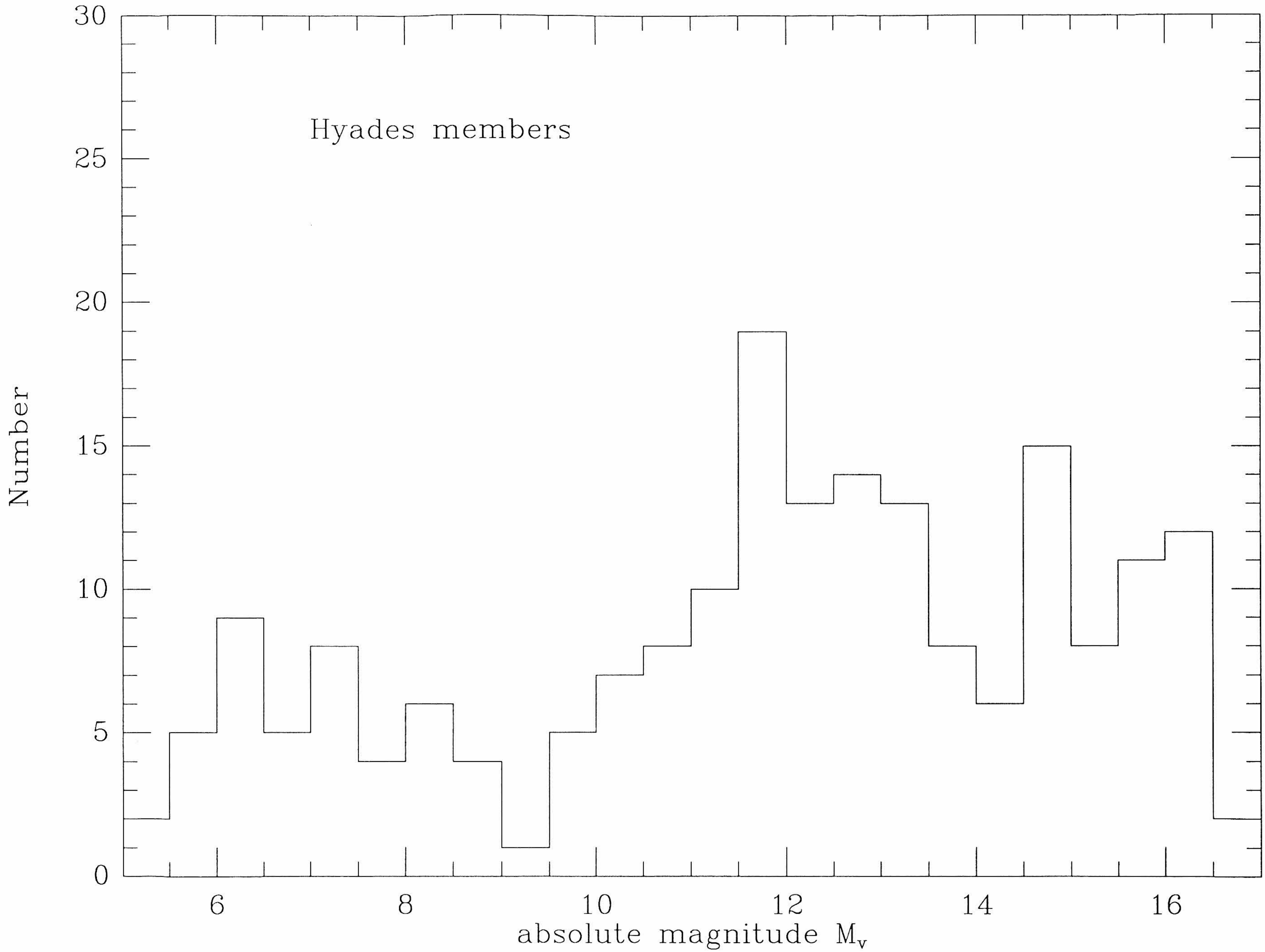
In order to study the Hyades it is essential to cover a large solid angle. We have combined the O and E plates taken as part of the first Palomar sky survey (epoch 1955) with B- and V-band plates taken between October, 1985 and March, 1986 in a proper motion survey that extends to $V \sim 19.5$ or $M_v \sim 16$. We have photographic plates for four fields, each of $\sim$ 36square degrees, covering the bulk of the cluster. The plate material has been scanned using the COSMOS measuring engine at the Royal Observatory, Edinburgh, giving positions, magnitudes and shape information for typically 100,000 objects per field. To date we have combined the separate scans for two of the four fields, calibrating the instrumental magnitudes using CCD observations made on the Palomar 60-inch telescope and deriving proper motions from the positional measurements at the two epochs.

The initial proper motion reductions are made dividing the photographic plate into a number of sub-units and using 15th-17th magnitude stars to define the reference frame within each area. However, COSMOS provides sufficient information about the properties of an image that it is possible to identify stars and galaxies - essentially galaxies are lower surface brightness than stars, and therefore have a larger area for a given magnitude. As a result it has proved possible to use measurements of the galaxies, which have zero proper motion, to set the stellar motions onto an absolute system. In any event, the Hyades have a substantial proper motion ($\sim$ 0".1 per year), while the uncertainties in the measured motions are only $\sim$ 0".01 per year. Figure 1 shows the proper motion diagram for all stars in the apparent magnitude range $8 < V < 16$ in one of our fields. The motions have been transformed onto a system where μ_U is directed along and μ_T is tangential to the vector towards the Hyades convergent point. The concentration of Hyades members within the marked box is clear.

We have constructed a preliminary luminosity function from these observations, and the results are shown in figure 2. As yet we have made no corrections for possible effects due to mass segregation, nor have we accounted fully for possible field star contaminations, and we have still to complete reductions from the two other fields. However, the data, although sparse, suggest that the luminosity function may remain relatively flat beyond $M_v \sim +12.5$.



8 < V < 16
μ T
μ U
.2
.1
0
−.1
−.2
.3


Hyades members
Number
absolute magnitude M_v
0
5
10
15
20
25
30
6
8
10
12
14
16

<u>Spectroscopy of the X-ray Transient V404 Cygni</u>

Principal Investigator: R. Michael Rich
Department of Astronomy, Columbia University
Co-Investigators: J. P. Halpern and E. Gotthelf
Department of Physics, Columbia University

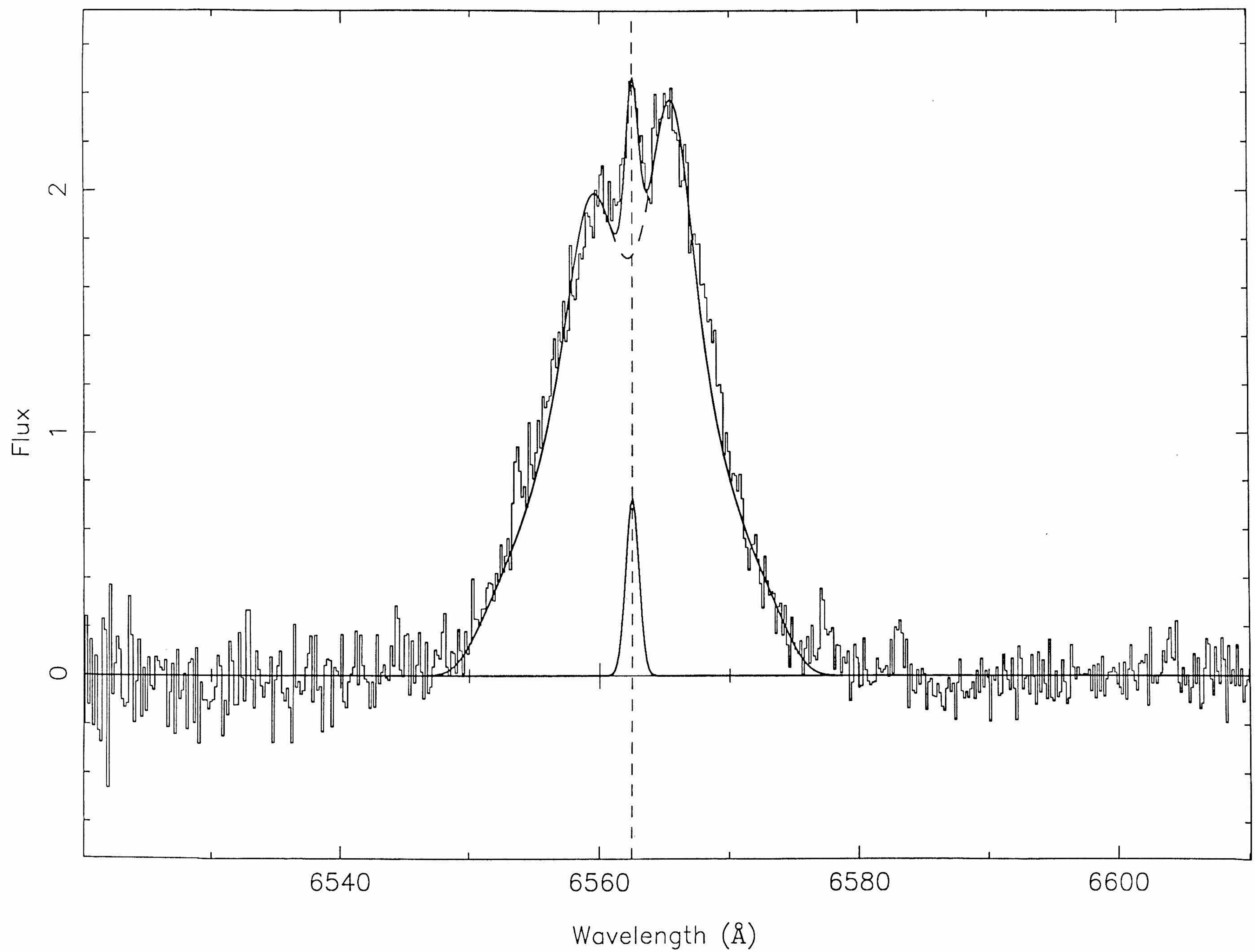
Subject Heading: Stars

Occasionally, a very faint star will suddenly emit a burst of x-rays, briefly becoming among the brightest x-ray sources in the sky. V404 Cygni was discovered by the All-Sky monitor aboard the Japanese X-ray satellite Ginga. As it flared in X-ray, it also brightened in the optical, producing strong emission lines and a blue continuum. We believe that such X-ray outbursts arise in binary star systems, where an evolved star transfers material onto a compact object–a neutron star or perhaps a black hole. We know for certain that the dark companion must be more compact than a white dwarf, for the accreting material emits X-rays. Where there is accretion, we should see an accretion disk. Theory predicts that a high resolution spectrum of the emission lines from the accretion disk should produce double-peaked line profiles. K. Chen and J. Halpern have recently calculated the appearance of the line profile from a relativistic accretion disk.

The spectrum below shows the Hα line at 0.3Å resolution, obtained using the echelle spectrometer (built by J. McCarthy) on the 1.5-m telescope. The spectrum was obtained on 14 July 1988– 2 months following the discovery by the Ginga satellite; V404 Cygni had faded below V=14. The double-horned line profile and model fit demonstrate that there is in fact an accretion disk in this binary system.

The solid line is a model fit to an asymmetric double-peaked emission line profile of an accretion disk containing a 'hot spot' which is localized to the outer edge of the disk. The 'hot spot' probably is the location where material from the evolved companion star actually streams onto the disk. The 'hot spot' accounts for the asymmetry in the relative heights of the two peaks. Superimposed on this profile is a symmetric emission line at the systemic velocity. The dashed line shows the contribution of the accretion disk alone; while the central emission line contribution is reproduced below the spectrum.

From these model fits we can determine the accretion disk parameters for the system and thus help to constrain the mass of the binary components. The model assumes a thin Keplerian disk with a hot spot localized in radius and polar angle. The separation of the peaks determines the outer disk velocity, while the extent of the wings depends on the ratio of inner to outer radii. The shape of the sides of the profile reflects the radial dependence on the flux across the disk. Time resolved spectroscopy can determine the binary period from the modulation of the relative heights of the peaks. As the disk, which is fixed about one member of the binary system, orbits the binary system center of mass, the hot spot alternatively contributes excess flux to the red and blue peaks. On longer time scales, the relative strength of the peaks monitors the accretion rate.


Flux
0
1
2
6540
6560
6580
6600
Wavelength (Å)

The Luminosity and Mass Functions for Very Low Mass Stars

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

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

Subjects Heading - Stars.

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

In this study we are attempting to examine the question - "What is the number density of extremely low mass stars?" That is, what is the shape of the luminosity function (LF) for the very lowest masses? Does it increase so that there are large numbers of small dim stars which escape our attention and are so not counted in estimates of luminous matter? Or does it decrease such that Very Low Mass stars (VLMs - stars less than one tenth of a solar mass) could not make up the missing mass. Such stars are also of interest intrinsically. Because they are so dim, very few are known, and their properties are poorly understood. In particular their atmospheres are not understood at all. Moreover, the shape of the LF may give clues to some of the processes determining the way stars collapse and form. Different theories of star formation predict different functions - in particular, different minimum masses. A study of the LF may give clues into the processes which regulate star formation itself, as well as into the individual properties of these poorly understood objects.

This study is based on the selection of objects using photographic plates from the Second Palomar Sky Survey. By scanning the plates and examining the digital photometry automatically, it is possible to sample huge areas of sky (in this survey 360 square degrees) looking for extremely red objects. Follow up observations are then made using both the Palomar 60- and 200-inch telescopes of the selected stars. Infrared observations, in particular, are essential for understanding these stars - since their effective temperatures are so low, they radiate most of their energy between wavelengths of 1 and 2 micrometres. We are also carrying out (for the first time at Palomar) a program of trigonometric parallaxes on the 60-inch telescope for the nearest stars in our sample. This is being done in order to tie down the colour-magnitude relations for these rare stars by increasing the number with trigonometric parallaxes form about four to about twenty. Using the combined optical-infrared photometry and the improved colour magnitude relation, we are able to determine the luminosity of each star in the sample.

Within the last year we have been able to carry out the initial CCD calibration of the photographic plates using the 60-inch telescope, and observation in the infrared of about 20% of our total sample of VLM stars. In particular, some of these extremely faint stars are very close (distances less than 30 parsecs) and have been included in our parallax program - within two years we should have trigonometric distances to these objects which are independent of any assumptions about the star's luminosity or temperature. Even with this small subset of the total sample observed, we have found we can detect stars as faint as the faintest known M-dwarfs, and expect that when our survey is complete we can determine the LF for the lowest mass stars with a degree of precision that has not been previously possible.

Infrared images of compact HII regions

Principal Investigator: Dave Van Buren
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California Institute of Technology *and* Jet Propulsion Laboratory

Co-Investigator: Jeffrey Hester
Infrared Processing and Analysis Center
California Institute of Technology *and*
Jet Propulsion Laboratory

Subject Heading: Interstellar Medium

Scientific context

Compact HII regions - small, bright regions of ionized hydrogen gas - result from the intense heating by a new-born massive star of its leftover natal cloud. They contain clues to the star formation process and provide nearby and convenient laboratories for studying matter under conditions that prevailed during the time that galaxies were born.

Long-term program

Only now are we beginning to understand the interaction of massive stars with the clouds from which they were born. There are three main ways that the stars influence the gas. First, their gravity induces motions which can tell us about the amount of material present. Secondly, their strong winds move material about, sweeping up shells of gas and driving strong shock waves. Thirdly, massive stars are the most luminous stars, and their light illuminates and heats nearby material, ionizing it and making it visible, as well as driving strong motions as the heated material expands.

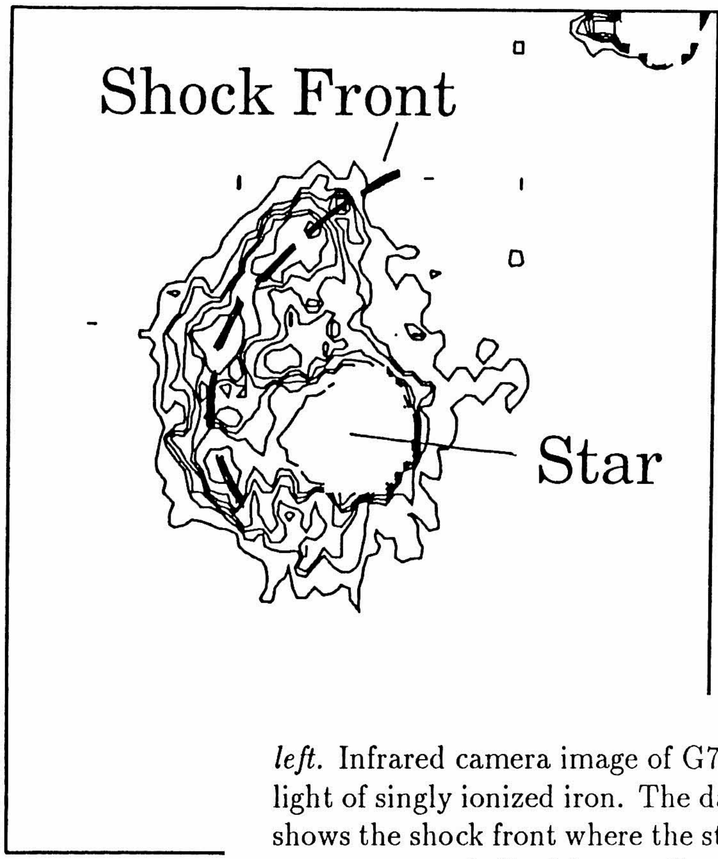
Since the same stars that move the gas around also heat it and make it visible, there are a great many diagnostics available to the astronomer. In most cases the HII regions are hidden by dense veils of dust so they can only be seen in the infrared and radio portions of the spectrum. Our long term program is to collect diagnostic information using our infrared camera and apply physical models we are developing to come to a better understanding of the processes at work in regions where stars are formed.

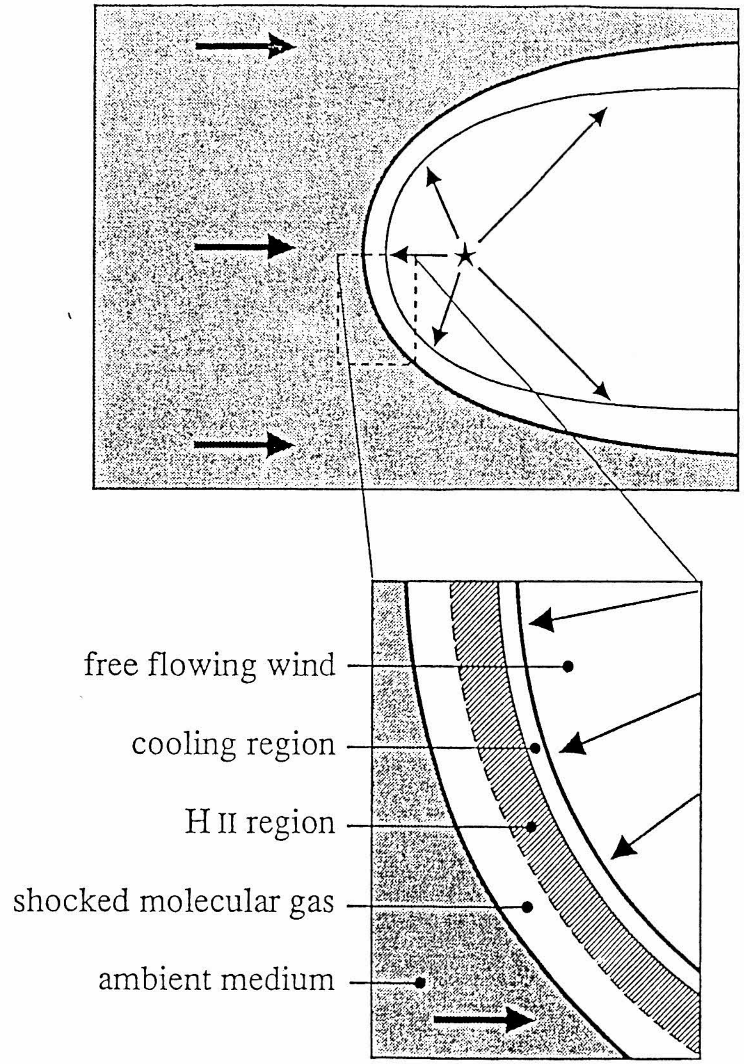
Short-term program

In the last year we used the Prime Focus Infrared Camera to observe the compact HII region G70.7 in the light emitted by molecular hydrogen, atomic hydrogen, singly ionized iron and interstellar dust. In the figure below we present a near infrared contour image of G70.7 in the light of ionized iron, which shows where the gas is being influenced by the stellar wind. Because the star is moving toward the left G70.7 has an arc-like appearance. Also shown is our schematic model for the object (Van Buren, Mac Low, Wood and Churchwell 1990).

These data were collected only a few months ago, so their analysis is not yet complete, but it is already apparant that a picture including very strong winds and stars moving through the gas can account for what is seen. As analysis of our data progresses, we will come to a better understanding of the physical conditions in G70.7, and consequently of its origin.

Van Buren, D., Mac Low, M.-M., Wood, D. O. S., and Churchwell, E. 1990, *Ap. J.*, **353**, 570.





left. Infrared camera image of G70.7 in the light of singly ionized iron. The dashed line shows the shock front where the star's wind sweeps up a shell of interstellar material. The star has been suppressed. *right.* Our model for this object. The star moves to the left (north) through a dense medium. A powerful wind from the star sweeps up the medium into a shell via a shock. The inset shows some details of our model which are testable using infrared diagnostics.

SOLAR SYSTEM

PHOTOMETRY OF THE COMET 2060 CHIRON

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Subject Heading: Solar System

Since its discovery by C. Kowal at Palomar Observatory in 1977, the comet 2060 Chiron has proven to be an interesting and enigmatic object. Situated between the orbits of Saturn and Uranus, it was originally classified as the most distant asteroid. It began to show cometary behavior in 1987 by increasing a full magnitude in brightness and developing a coma; there is evidence for similar, earlier outbursts (Bus et al., 1989; Hartmann et al., 1990; Luu and Jewitt, 1990; Meech and Belton, 1990). The diameter of Chiron is ~200 km - larger than other well-observed comets - and it has a geometric albedo and spectrum similar to primitive C-type (carbonaceous chondritic) asteroids. A rotational light curve with a period of 5.92 days has been observed, although its amplitude decreased significantly during the recent outburst. Chiron's chaotic, inward evolving orbit provides evidence that it formed in the Oort cloud. A thorough study of Chiron is important for two reasons: 1) it is a transition object defining the relationships between comets, asteroids, and meteorites; and 2) a full description of its changes in brightness - particulary on time scales of hours - will provide an empirical foundation for understanding the physical mechanisms (including outgassing, sublimation of volatiles, and even significant mass ejections) driving the evolution of comets.

In early 1989 Chiron began to show a decrease in brightness. Short term outbursts were observed (Luu and Jewitt, A. J., 1990, in press), and on 1990 January 19, we observed with the Palomar 60-inch a rapid decrease in the brightness of Chiron's coma in the V and R filters (Buratti and Dunbar, Ap. J. Let., submitted; Figure 1). We also detected a rotational lightcurve of the nucleus with an amplitude only 1/4 that observed in its quiescent state: this fact indicates the increased importance of the optically thin coma to the observed brightness. Clearly, Chiron appears to be undergoing short term fluctuations in its brightness, as well as a general decrease associated with the demise of its coma. The short term changes may indicate outgassing events, rapid sublimation, or the escape of dust which is possibly electrostatically charged. The fact that no color changes to a 1% level were observed during the night - a period corresponding to an increasing importance of the nucleus in the detected signal - implies that the coma is laden with dusty material from the nucleus.

Our observational strategy over the next two years will be to obtain CCD images with temporal resolution of 5-10 minutes in the V and R filters. Our specific measurement goals and scientific objectives are to 1) derive an absolute magnitude to tie our observations in with the secular (~months or year) decrease in Chiron's brightness; 2) detect and characterize short term (~ hours) outbursts or decreases in brightness and understand their cause(s); and 3) measure the light curve of the nucleus to monitor the growth and decay of the comet's coma and to understand the dynamical properties of the nucleus (e.g., whether it's precessing).

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

REFERENCES

Buratti, B., Dunbar, R.S. 1990, submitted to **Ap. J. Let.**
Bus, S.J., Bowell, E., Harris, A.W., Hewitt, A.V. 1989, Icarus, 77, p. 233.
Hartmann, W.K., Tholen, D.J., Meech, K.J., Cruikshank, D.P. 1990, Icarus, 83, p. 1.
Luu, J.X., Jewitt, D.C. 1990, **Astron. J.**, in press.
Meech, K.J., Belton, M.J.S. 1990, **Astron. J.**, in press.

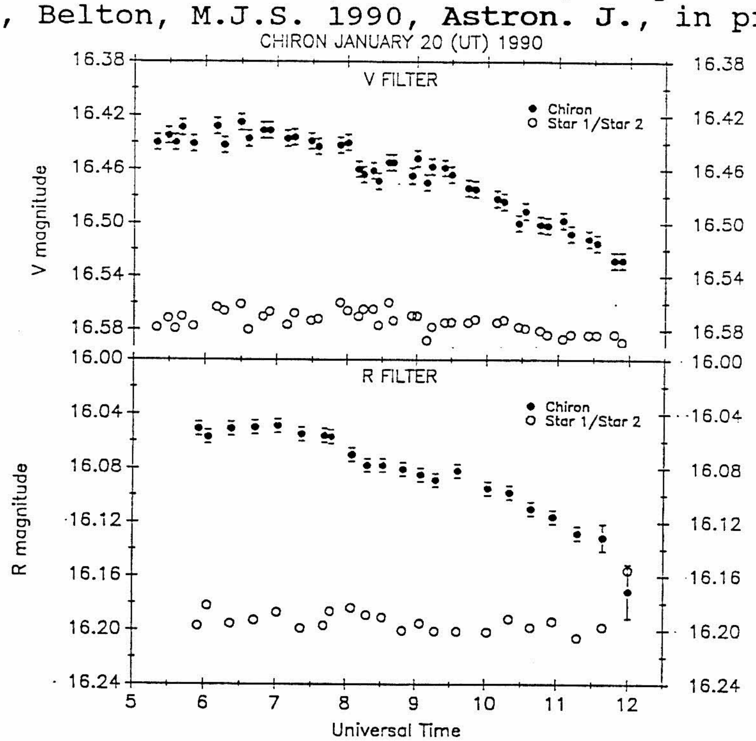

Figure 1. Palomar 60-inch observations of 2060 Chiron in the R and V filters. The ratio of two on-chip comparison stars used in our photometric reductions is also shown to demonstrate the certainty of the observations (the ratio of these 16th magnitude stars has been rescaled). From Buratti and Dunbar (1990).

Discovery of the First Mars Trojan

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Subject Heading: Solar System

More than 200 years ago, J.L. Lagrange proved mathematically that a small third body may oscillate stably about the vertices of two equilateral triangles whose base is the line between two larger, more massive bodies that revolve in circular orbits about each other. If we take the Sun to be one of these massive bodies and a planet the other, then the vertex which lies 60° ahead of the planet is referred to as the L4 point (Lagrange 4 point) and the vertex 60° behind the planet is the L5 point. The theoretical prediction of Lagrange was fulfilled in 1906 by Max Wolf's discovery at Heidelberg of the asteroid 588 Achilles, which librates (oscillates) around the L4 point with respect to Jupiter. Since then, more than 250 asteroids have been found in the L4 and L5 libration regions of Jupiter. Following a tradition established at Heidelberg, asteroids librating about the L4 and L5 points have been named after the heroes of the Trojan war and are called Trojans.

Numerous searches have been made in the past 20 years for Trojans of planets other than Jupiter. Despite theoretical and numerical investigations which suggest that regions of stable or quasistable libration may exist near the orbits of other planets, none of these searches has been successful. On the other hand, Trojan satellites of Saturn were discovered, from images obtained by the Voyager spacecraft, that librate about the triangular Lagrange points on the orbits of the satellites Tethys and Dione. A discovery made this past year with the Palomar 46-cm Schmidt has finally demonstrated the existence of another type of Trojan.

Asteroid 1990 MB was discovered by D.H. Levy and H.E. Holt on 20 June 1990 during the course of the Palomar Asteroid and Comet Survey conducted by E.M. and C.S. Shoemaker and H.E. Holt. An orbit based on a 9-day arc and the asteroid's location near the longitude of Mars' L5 point led E.L.G. Bowell to speculate that it might be in libration around the L5 point, analogous to the Trojan asteroids of Jupiter. Subsequent observations strengthened this possibility, and later calculations by M. Yoshikawa and by B.G. Marsden confirmed it (Green, 1990). The most recent orbit by Bowell, from observations spanning a 68-day arc, shows that the semimajor axis of 1990 MB (1.52356 AU, epoch 5 November 1990) is very similar to that of Mars (1.52361 AU). The existence of 1990 MB appears to provide confirmation of computer simulations performed by S. Mikkola and K.A. Innanen (in press). These self-consistent n-body simulations indicate stability for Trojans of all the terrestrial planets over at least a 2-million year time base, provided that they have only a small range of libration.

1990 MB, which is a few kilometers in diameter, is unlikely to have survived the heavy bombardment known to have occurred in the terrestrial planet region early in solar system time. More likely, it is a collision fragment injected into the neighborhood of Mars from the main asteroid belt. Another asteroid found at Palomar, 3800 (1984 AB), has a semimajor axis of 1.578 AU, close to that of Mars, but is not a Trojan. It can be inferred that multiple encounters with Mars may lead to orbits rather similar to those of Trojans. We suggest that 1990 MB probably has been captured from a free orbit into a Trojan orbit fairly late in solar system time. The mechanism of capture remains to be studied. Very precise, long integrations of the motion of 1990 MB should be carried out to determine the long-term stability of the libration. We suspect that 1990 MB will ultimately escape into a free orbit, owing to perturbations by the other planets, chiefly by Jupiter. If this proves to be correct, it is likely that capture was facilitated by perturbations by planets remote from Mars.

The discovery of the first Mars Trojan suggests that others of similar or fainter magnitude may be found; a systematic search of the L4 and L5 libration regions is planned. The estimated range of libration of 1990 MB is about 2.4°, and the eccentricity of its orbit is 0.065. Studies by Mikkola and Innanen indicate that the range of stable libration of Mars Trojans is less than 4°. Most of the oscillation of longitude of 1990 MB relative to the Lagrange point is due to eccentricity of its orbit. The search should be concentrated on swaths of sky about 25° to 30° wide centered on the libration points. The inclination of 1990 MB is 20.3°. When it is near opposition, the apparent position of this elusive asteroid is more than 35° from the ecliptic most of the time, which helps explains why its discovery was so long delayed. The search swaths should extend at least 50° north and south of the ecliptic, in order to find Mars Trojans with inclinations comparable with that of 1990 MB. Search of such a large area of the sky is a task suited to the Palomar 46-cm Schmidt. It is anticipated that discovery of additional Mars Trojans will provide insight into the mechanisms of capture.

References

Green, D.W.E., 1990, IAU Circular 5075.
Mikkola, S., and Innanen, K.A., in press, IAU Colloquium 123.

INSTRUMENTATION

The Norris Spectrograph

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Subject Heading: Instrumentation

The Norris Spectrograph, built with a generous grant from the Norris Foundation, is a large spectrograph for the 5-meter Hale Telescope designed to be used with a large number of fibers. It has 176 fibers which can be deployed over a 20 arcminute diameter field at the Cassegrain focus of the telescope. The fibers are moved automatically under computer control with a large xyz machine. The spectra are recorded using a 2048 by 2048 Tektronix CCD. The engineering and programming for the spectrograph were provided by Michael Carr, John Cromer, Earle Emery, and Frederick Harris.

The main part of the spectrograph was completed and tested over one year ago. It was not put into regular operation because the large complex camera lens had not been delivered. The lens still has not been delivered. It turns out, however, that the blue camera of the Double Spectrograph is a fairly good match to the Norris Spectrograph even though the focal length is 9 inches instead of the more ideal 12 inches. This camera will work well on the Norris Spectrograph if the large 2048 by 2048 pixel Tektronix CCD which was purchased for the spectrograph is used. Special mountings were designed and fabricated to mount this camera temporarily on the Norris Spectrograph. In addition a few modifications were made to the spectrograph to imporve its performance and a large effort was made to refine the control software and the software used to select and calculate the objects to be observed.

The first observing run with all the above changes implemented was in September 1990. Because of problems with the large CCD which now appear to be curable, we had to use a smaller but excellent CCD for the observing run. The run was a complete success. Very simple procedures for placing individual calibration stars and large fields of galaxies in the fibers were developed and tested. The scale of the Cassegrain focus of the 5-meter Hale telescope was acurately measured since it is needed in calculating fiber positions. Both star and galaxy fields were observed to test the performance of both the hardware and software and to measure the overall efficiency of the instrument. A start was also made on the first major program of the Norris Spectrograph which is a study of the structure of the universe at a look-back time of several billion years.

It is hoped that the final large camera lens will be delivered in the next two months. If this does not happen, then the Double Spectrograph blue camera and the large 2048 by 2048 pixel CCD will be used for observations in December. The main loss with this temporary system is a decrease in the wavelength coverage available but this is not a serious problem. Spectra from all 176 fibers will still be recorded efficiently.

IMAGING FABRY-PEROT FOR THE PALOMAR 60″

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Subject Heading: Instrumentation

We have built a Fabry-Perot for imaging spectroscopy of optical emission lines from galaxies and galactic nebulae for use on the Palomar 60″. An imaging Fabry-Perot has major advantages over the conventional technique, slit spectroscopy, for studying the kinematics and dynamics of extended objects such as galaxies and nebulae. With a Fabry-Perot, velocities can be determined over the entire field of view of an imaging detector such as a CCD, in contrast to slit spectroscopy for which velocities are obtained only for points which lie along the slit. This year we completed the wide-field instrument, which has a 16′ field of view with 1″ pixels; this makes it ideal for studying large, prototypical galaxies such as M31, M51, and M101, and for studying galactic nebulae. The resulting sensitivity compares favorably with Fabry-Perots on larger telescopes because of the high throughput, the large format, and excellent CCD's. The JPL Ford 1024 CCDs are perfect for Fabry-Perot work because of their low readout noise and excellent charge transfer properties, and because their flatness permits good focus to be obtained over the entire chip. We have developed efficient techniques for reducing and analyzing the 100 megabyte data cubes produced for each object. Various time-variable systematic effects which distort the velocity structure and have plagued Fabry-Perot efforts have been greatly reduced by developing calibration techniques which lower the rms systematic error to about 2 km/sec, about 10% of the instrumental line width.

In the figures we show two examples of the work done this year. Figure 1 shows Hα emission from NGC 6888, an expanding shell around a Wolf-Rayet star. Two of the monochromatic planes are shown. In the upper panel emission near the center of mass velocity shows the partial limb-brightened ring; the lower panel shows blueshifted gas at about 60 km/sec, the "cap" of the wind bubble, and reveals the filamentary nature of the shell. The left panel in Figure 2 shows integrated Hα emission from the prototypical grand design spiral M51. The middle panel is a grey-scale representation of the velocity field. We are able to measure accurate velocities even throughout most of the interarm regions. On the right we show a grey scale representation of the velocity residuals relative to an axisymmetric rotation curve fit to the data. It is difficult to adequately present all the features of the velocity field in a grey-scale plot, although a number of kinematic features are evident. A preliminary analysis indicates that 1) there is a large twist in the kinematic major axis (causing the NE-SW asymmetry), presumably induced by the companion; and 2) even in this crude representation the streaming motions across the spiral arms are visible.