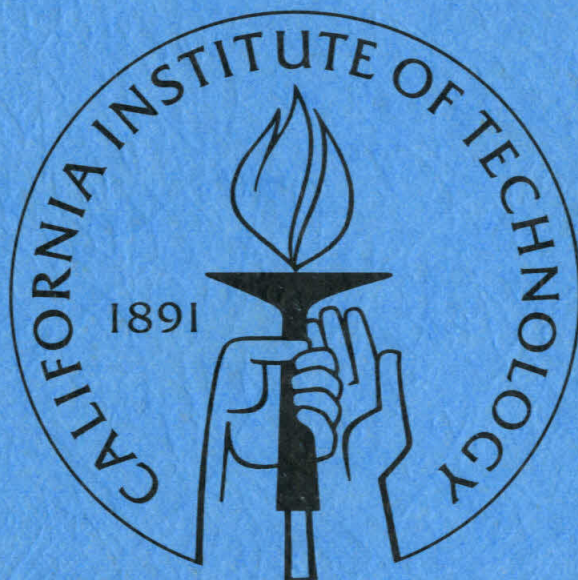


ANNUAL REPORT
OF THE
PALOMAR OBSERVATORY
1988



PALOMAR OBSERVATORY
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Enclosed are selected Annual Reports from observers using the telescopes of the Palomar Observatory. For convenience, the reports are divided by subject.

Galaxies and Quasars

Interstellar Medium

Solar System Studies

Stars

Instrumentation

GALAXIES AND QUASARS

Multicolor CCD Surveys for Faint Quasars

Principal Investigator: Scott F. Anderson
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Co-Investigators: Paul Schechter
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Dept. of Physics
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University of California, Santa Cruz

Subject Heading: Galaxies and Quasars

Anderson and Schechter (MWLCO), in collaboration with Windhorst (ASU) and Koo (UCSC), are conducting surveys for very faint quasars. Using the Four Shooter on the Palomar 5m, deep multicolor CCD images are taken through Johnson B and Gunn g, r, and i filters. These multicolor images allow for the selection of quasar samples to a magnitude as faint as $B < 24.5$. This multicolor selection approach is similar to the photographic technique recently used by Warren et al. (1987) to select several quasars with redshifts $z > 4$. The multicolor technique, however, can be used to select "complete" quasar samples over a very wide redshift range. Normal stars occupy a small, well-defined volume in multicolor space, while quasars, having power-law continuous spectra and emission lines, occupy regions in the multicolor space which are far from the stellar sequence. A primary limitation of the use of photographic plates is the difficulty in obtaining high photometric accuracy at very faint magnitudes: photometric errors artificially broaden the intrinsic "width" of the stellar sequence in multicolor space, making it increasingly difficult to separate quasars from stars. CCD's, on the other hand, are well suited to achieving high photometric accuracy to quite faint magnitudes. The Four Shooter (an imaging device incorporating four, 800X800 pixel TI CCD's) attached to the Palomar 5m is an ideal instrument for the faint quasar surveys because it affords large areal sky coverage ($8.5' \times 8.5'$), as well as the requisite photometric accuracy.

Initially, Anderson and Schechter imaged two fields with the Four Shooter to $B < 22.5$. One of these fields overlaps with the Selected Area no. 57 field (hereafter, SA 57) previously surveyed (photographically) for faint quasars by Koo, Kron, and collaborators, (e.g., Koo and Kron 1988). This initial Four Shooter survey in SA 57 has been used as a test-field to investigate and calibrate the utility of accurate, multicolor CCD photometry in distinguishing quasars from stars. Results from this field confirm the viability of the approach, and a preliminary report on this work is in press (Anderson and Schechter 1989). The second field surveyed to $B < 22.5$ will provide a new, additional sample of faint quasars. This second field was also previously

imaged to very sensitive X-ray flux levels with the Einstein X-ray Observatory. In addition to providing information on the faint quasar optical luminosity function, this second field will be used, in collaboration with S. White (Univ. of Az.), to study the contribution of very faint quasars to the diffuse X-ray background radiation.

Encouraged by the success of the technique to $B < 22.5$, Anderson, Schechter, Windhorst, and Koo are extending the Four Shooter multicolor quasar survey to even fainter magnitudes ($B < 24.5$). This fainter survey will ultimately include 0.3 sq deg. of sky in three fields (SA 57, Lynx.3A, and Hercules). These deeper, multicolor images should also allow for the selection of a high-redshift sample of active galaxies with Seyfert-like luminosities, and will provide a useful data base for studying galaxy clustering as well as the evolution of field galaxies.

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THE ENVIRONMENTS OF QUASARS IN THE EARLY UNIVERSE

Principal Investigator: P. D. BARTHEL
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Co-Investigators: D. R. Tytler (Columbia University, New York)
G. K. Miley (Space Telescope Science Inst., Baltimore)

Subject Heading: Galaxies and Quasars

Using the Double Spectrograph on the 200-inch telescope Barthel, Tytler, and Miley studied emission and absorption line properties of extremely distant quasars. Quasars are objects which appear like stars when photographed through large optical telescopes, but they are in fact situated at enormous distances from our Milky Way Galaxy. They are believed to be the centres of galaxies, undergoing violent explosions. Except for these bright active nuclei, the rest of the galaxies are too faint to be observable in their optical light. Because of the enormous intensities of these explosions, quasars can be seen out to distances which correspond to about 90% of the radius of the Universe. Pictures of the radio emission of some hundred quasars at distances between 5 and 10 billion light years, taken using the Very Large Array, a giant radio telescope in New Mexico, have revealed a high fraction of distorted radio morphologies. Whereas the radio emission from nearby quasars usually has a straight dumbbell-like shape, the distant ones were found to exhibit a more bent and smaller appearance. Astronomers believe that violent activity in quasars is produced by a rotating black hole. The radio emission is thought to be due to twin jets of fast particles which are spewed out along the axis around which this black hole turns. The distorted appearance of the distant quasars has been attributed to collisions between the jets and clumps of gas in the galaxies surrounding them. Since the light and radio waves from the distant quasars take between 5 and 10 billion years to reach the earth, these objects are observed at a time when the universe had only 20% of its present age. This was the period during which most galaxies are believed to have formed, and apparently these galaxies were much more clumpier at the time of their birth than they are today.

Spectroscopic data, obtained with the 200-inch telescope confirms this picture. A high fraction of the observed quasars show strong absorption lines close to the emission lines, indicative of dense gas clouds in the environments of the quasars. Noteworthy is also, that the chemical composition of these absorbing gas clouds appears to change with cosmic time. Metal line absorbers are seldom present around the most distant quasars (that is, around quasars in the very early universe), whereas they are fairly common in later stadia of the universe. The quasar emission lines, which originate in hot gas in the quasar nuclei, show marked asymmetries, indicative of infalling gas. This infalling gas is possibly related to the radio emission from the quasars, via an as yet unknown mechanism.

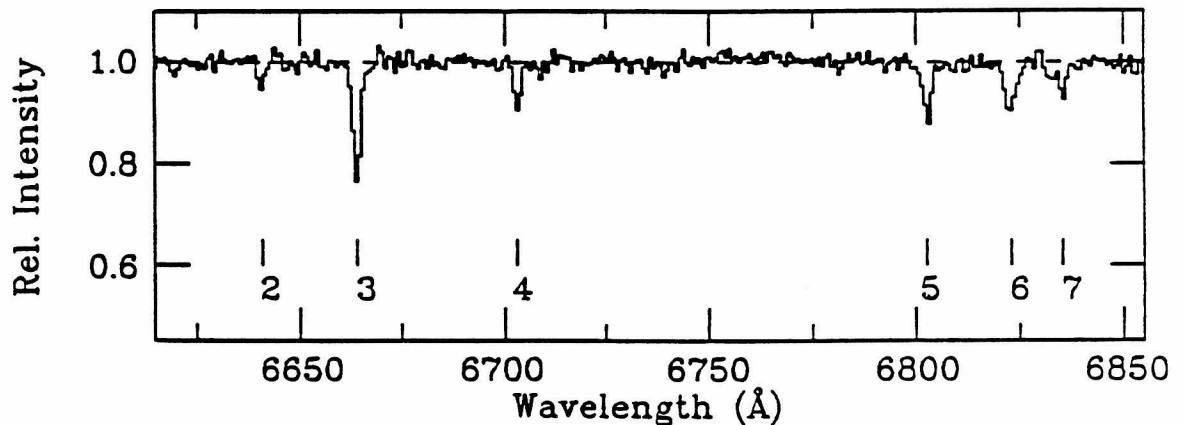
Chemical Evolution of Galaxies at High Redshift

Principal Investigator: Alec Boksenberg
Royal Greenwich Observatory

Co-Investigator: Max Pettini
Anglo-Australian Observatory

Subject Heading : Galaxies and Quasars

We have begun a study of the chemical composition and physical properties of the gas giving rise to the "damped Lyman α " systems in high redshift QSOs. These are absorption systems in which the column density of neutral hydrogen has values similar to those found in interstellar clouds in nearby spiral galaxies and sufficiently high for the profile of strongest atomic transition of hydrogen, the Lyman α line, to develop characteristic damping wings. The mean density of this class of absorbers was much higher at redshift $z = 2 - 3$, when the universe was only one-seventh of its present age, than it is today, leading to the commonly held view that they arise in the progenitors of present-day disk galaxies, possibly while they are still undergoing gravitational collapse. Observations with the Hale 5 m telescope at Palomar observatory were successful in detecting — for the first time — weak absorption lines of singly ionized Zn and Cr in the damped system at $z_{abs} = 2.3091$ towards the QSO PHL 957.



Absorption lines of FeII at $z_{abs} = 1.7975$ (lines 2 and 3), and ZnII and CrII at $z_{abs} = 2.3091$ (lines 4–7) in the red spectrum of the QSO PHL 957. Note the expanded vertical scale. The weakness of the ZnII and CrII lines indicates that in the galaxy where they are formed the process of metal enrichment via stellar nucleosynthesis has not yet progressed very far.

From these measurements it was concluded that metal abundances in this high-redshift absorption system are 20 times lower than in the Sun and that the dust-to-gas ratio is also well below the value typical of the local interstellar medium. Related observations were used to place a stringent upper limit to any Lyman α emission associated with the damped system, which in turn implies that gas in this galaxy is being converted into stars at a rate of at most 3 - 30 solar masses per year. Taken together, the low metal content, the lack of dust and the Lyman α luminosity are strongly suggestive of a galaxy in its early stages of evolution and are generally similar to those measured in present-day HII galaxies. This supports the view that primeval galaxies at high redshifts may resemble nearby blue galaxies in many of their properties. Further observations are in hand to extend these initial results to a large sample of damped Lyman α systems.

Spectra of Quasi-Stellar Radio Sources

Principal Investigator: Todd Boroson
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Subject Heading: Galaxies and Quasars

One of the unexplained characteristics of quasars is that they show a variety of properties at radio frequencies. Although quasars were first discovered as luminous radio sources, it is now known that only a few percent of them are strong radio emitters. Even those can be subdivided into types, the most obvious of which are distinguished by the morphology of the radio emission. One group consists of double-lobed sources, in which the emission comes predominantly from two extended patches on either side of the optical object. The other major group consists of compact sources, in which the emission comes from an unresolved or barely resolved spot, sometimes having a little fuzz around it.

The idea that the basic difference between these two groups is one of orientation with respect to the observer has been around a long time (Scheuer and Readhead 1979). The attractions of such a model include the fact that it provides a simple unifying scheme for radio-source quasars (QSRs) and that it allows the identification and isolation of one of the quantities which determine the observed properties of QSRs.

One of the main objections to this explanation is that some of the other properties of quasars, which ought to be isotropic, appear to differ between these two groups. Boroson and Oke (1984) found that the strength of the forbidden emission lines in the optical fuzz around the quasars and in the quasar nuclei themselves were correlated with the radio morphology. Wills and Browne (1986) have argued, however, that this apparent distinction is due to a difference in total (isotropic) luminosity between the compact and extended sources that were studied.

The purpose of this project is to study two samples of QSRs with the same extended radio luminosity. Together with Ian Browne (University of Manchester), a list of candidate objects were mapped in the radio with the VLA. We then constructed two lists, a total of 34 quasars, having similar redshifts and radio luminosities, but different radio morphologies. We obtained spectra of these objects in the region of the [O III] $\lambda 5007$ line which in previous work showed the effect of the radio morphology most clearly. Most of the optical spectroscopy was done in the past year, using the Hale 5-meter telescope.

Analysis of these spectra shows an interesting effect. The equivalent widths (the strength of the emission lines relative to the continuous emission) are quite clearly different between the two groups. However, this difference is due to the fact that the continuous emission is different rather than the absolute strengths of the emission lines. Thus, although the spectra have the appearance of differing drastically between the compact and double-lobed radio sources, the true distribution of strengths is completely consistent with the beaming (orientation) hypothesis. The additional conclusion is that some part

of the continuous emission shows the same geometrical effect as the radio emission, an idea which has been proposed, but never convincingly demonstrated, before. We are currently writing a paper which explores the implications of these findings.

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Double-Nuclei Markarian Galaxies

Principal Investigator: Todd Boroson
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Co-Investigator: Joseph Mazzarella
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Subject Heading: Galaxies and Quasars

Although it is now believed that the energy released in active galaxies such as Seyferts and quasars is derived from infall of gas onto a massive compact object, the origin and evolution of this process from a galactic standpoint are poorly understood. Do all galaxies contain black holes whose effects only become visible when matter comes close enough to fall in? Does the process deplete the available gas after some interesting amount of time? Can the activity then be reinitiated by the presence of a new supply of gas? In the last few years these questions have led to an increasing examination of the role that interactions between galaxies play in "feeding the monster".

Qualitatively at least, the theoretical basis for a correlation between the fueling of nuclear activity and encounters between galaxies is straightforward. The interaction can remove angular momentum from gas near the black hole, allowing it to drop close enough to be captured. The observational information, though, which might allow us to ascertain how this proceeds is more confusing. Some active galaxies show tidal tails and disturbances which suggest a recent encounter. Studies of galaxies chosen because they are interacting show a deficiency of very active nuclei.

The purpose of this project is to study a sample of galaxies which are clearly interacting and active in order to better understand the connection. In the Markarian lists of galaxies with ultraviolet excesses (indicative of activity or unusually large amounts of star-formation), there are a number of objects which are denoted as having more than one nucleus. A large fraction of these are the results of a particular type of interaction, one which results in a merger into a single system. We hope to 1) classify the systems in terms of type of activity and nature of interaction, 2) examine the statistics relating the two processes, 3) obtain more precise data on the objects for which it is probable that there is a connection.

In the past year, we have completed the first phase of the observational program. We have obtained CCD images in two colors of the entire sample of 90 systems. Some of these images were obtained at the Palomar 1.5-meter telescope, the rest at the McGraw-Hill 1.3-meter telescope. We have also obtained low-resolution spectra of all 198 nuclei in these systems with the McGraw-Hill 2.4-meter telescope. We have begun the classification of the objects, and the preliminary results show some interesting and unexpected effects. There seems to be a deficiency of systems with strong activity (Seyfert 1's) compared to

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Todd Boroson
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the non-merging remainder of the Markarian ultraviolet excess lists. Also, there seems to be an excess of pairs of weaker activity nuclei (Seyfert 2's) over what would be expected given the number of single nuclei of this type.

We are hoping to follow this up in the coming year by studying in more detail the objects which are unambiguously active and interacting, to see how they differ from the other objects. To do this we will attempt to map out the velocities of the material in and around the nuclei with spectra of high spatial and spectral resolution to be obtained with the Hale 5-meter telescope.

Polycyclic Aromatic Hydrocarbons in Galaxies

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Co-Investigators: Charles Beichman
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Keith Matthews

Subject Heading: Galaxies

Near and mid-infrared observations of the interstellar medium in the solar neighborhood (Sellgren et al. 1983, Boulanger and Perault 1988), the Galaxy (Price 1981, Giard et al. 1988) and external galaxies (Ghosh et al. 1986) have demonstrated that the interstellar medium contains small particles ($50 < N_{\text{atoms}} < 10^4$) with sizes intermediate between molecules and dust grains. For these small particles the absorption of a single photon represents a large input of energy which transiently heats them to temperatures much higher than the equilibrium temperature of dust grains. For example, a particle with 50 atoms gets heated to a temperature of about 1000K by the absorption of a single photon, and cools down in a fraction of a second by emitting around 3 micron. Most of the energy radiated by interstellar matter in this part of the spectrum comes from a band at 3.3um which along with other features at 6.2, 7.7, 8.6, and 11.3 micron, is characteristic of aromatic hydrocarbons. It has been suggested by Leger and Puget (1984) that the small particles emitting between 3 and 12 micron are large molecules composed of several benzene cycles tied together (Polycyclic Aromatic Hydrocarbons, hereafter PAHs). About 15% of the interstellar carbon needs to be in such molecules to explain the observed emission. As a family these molecules are one of the most abundant constituents of interstellar matter; their existence has important consequences on the physics and chemistry of interstellar matter (Omont 1986, d'Hendecourt and Leger 1987, Lepp and Dalgarno 1988).

Much has been learned about small particles from IRAS observations. Several studies of the variation of infrared colors around nearby ionizing stars suggest that the small particles emitting in the 12 micron band of IRAS are destroyed near strong ultraviolet sources (Ryter et al. 1987, Boulanger et al. 1988). These studies also show that for an increasing intensity of the heating radiation the emission of interstellar matter follows a sequence similar to that of galaxies in the color-color diagram $I_{\nu}(60\mu\text{m})/I_{\nu}(100\mu\text{m})$ versus $I_{\nu}(12\mu\text{m})/I_{\nu}(25\mu\text{m})$ (Helou 1986). These two results suggest that the mid-infrared emission of galaxies comes from the interstellar medium, and that PAHs are partially destroyed in active galaxies. To test this last idea we completed in the Spring of 1988 3.3um observations of several galaxies. Sensitivity requirements and the necessity of observing compact objects to be able to compare ground

observations obtained with a 10" aperture with IRAS fluxes led us to select bright galaxies of small angular size. These objects with high infrared surface brightness are galaxies with a higher degree of star formation activity than the Galaxy. In 1 and 1/2 nights of observations we observed 6 galaxies, and detected the 3.3um band of 4 of them. From the 4 detections we derived a ratio between the 3.3 and 12 micron, $I_{\nu}(3.3\mu\text{m})/I_{\nu}(12\mu\text{m})$, of about 10^{-2} ; the 2 upper limits are consistent with this value. This ratio is a factor 10 smaller than the value obtained by Giard et al. (1988) for the cirrus emission of the Galaxy. Our results thus confirm that PAHs are significantly destroyed in regions of intense radiation field. We hope to be able to carry on this project this year. With the new InSb Camera this study of PAHs in external galaxies could be extended to less extreme objects. We plan to map the 3.3um emission of star forming regions in nearby galaxies, and edge-on galaxies. The long line of sight integration in edge-on galaxies should enable us to detect 3.3 micron from cirrus at high altitude above the plane of the galaxies.

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The Nature of IRAS 12 um Sources

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Co-Investigators: C.A. Beichman (IPAC)
G. Neugebauer (CIT)

Subject Heading: Stars, Galaxies and Quasars

The Infrared Astronomical Satellite (IRAS) surveyed the entire sky at four infrared wavelength bands, cataloging over 400,000 sources, many of them never before identified at other wavelengths. A number of groups have undertaken the task of understanding the nature of different classes of IRAS sources. For example, IRAS objects bright at 60 and 100 um have, for the most part, turned out to be infrared bright galaxies, some of them extremely luminous objects that may hold the key to understanding the origin of quasars. These have been observed extensively at Palomar by Soifer and his collaborators. We have concentrated on a different group of IRAS sources, high Galactic latitude objects that are brightest at 12 um and which have either no or only a faint optical counterpart.

Objects found at high Galactic latitudes are typically either located within a few tens or hundred light years of the earth or are distant extra-galactic objects. Our motivation in studying these sources is two-fold. One is simply to identify new types of astronomical objects, always an exciting prospect when a new spectral window on the Universe has been opened. Second, we are searching for brown dwarf stars intermediate in mass between a giant planet such as Jupiter ($\sim 0.001 M_{\text{sun}}$) and the smallest stars capable of fusing hydrogen into helium ($\sim 0.05 M_{\text{sun}}$). Brown dwarfs are powered solely by gravitational energy released by their slow contraction and are characterized by low temperatures, 1000 K, and very low total energy outputs, $< 10^{-4} L_{\text{sun}}$. Candidate brown dwarfs have recently been identified as companions to a number of nearby stars. The general importance of finding isolated brown dwarfs comes from the fact that some analyses show that there is less mass observed in stars and gas than is required to explain the motions of stars in the gravitational potential of the solar neighborhood. If this local missing mass is real, then brown dwarfs are a likely repository and the IRAS survey is a promising place to look for them.

Our procedure has been to eliminate from consideration all 12 um IRAS sources associated with known stars and then, additionally, to eliminate sources with optical counterparts brighter than about $R \sim 15$ mag as measured on the Palomar Sky Survey plates. This procedure winnows a list of some 4000 12 um

sources above galactic latitude of 50 degrees down to a manageable list of some 60 objects. These sources were then examined with both near infrared photometry and optical spectroscopy using the 5m telescope.

To date we have found no brown dwarf stars. Although the limit on the space density of brown dwarfs depends on a number of assumptions, we feel that our observations limit the density of brown dwarfs to a value just above that of the putative missing mass. We are continuing the search using the IRAS Faint Source Survey which reaches a magnitude fainter at 12 um than the original Point Source Catalog and thus probes a factor of five more volume; over 50 brown dwarfs are predicted to be in the data base. If, after completing the task of observing previously unknown 12 um sources in the Faint Source Survey, no brown dwarfs are identified, then brown dwarfs can be eliminated as possible contributors to the local missing mass.

Despite the failure to find plausible brown dwarfs, we were successful in satisfying our first goal of identifying new types of astronomical sources. Our search found a new class of extragalactic object. One 12 um source turned out to be the first infrared bright quasar; this source, at a redshift of 0.1, may represent the transition between the infrared luminous galaxies studied by Soifer and his colleagues and the classical optical/ultraviolet quasars. The search also turned up an extremely unusual carbon star characterized by 1250 K blackbody emission that could be due to either hot dust or a surprisingly cool photosphere.

Asymptotic Giant Branch Populations in Resolved Systems

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Carnegie Institution of Washington

Co-Investigator: Edward Olszewski
Steward Observatory
University of Arizona

Subject Heading: Galaxies and Quasars

Asymptotic giant branch stars are believed to be significant contributors to the chemical evolution of our Galaxy—in particular carbon and *s*-process elements. An investigation of the asymptotic giant branch (AGB) luminosity function of a stellar population will yield a broad range of information about that population as well as constraining stellar evolution theories of AGB evolution. For example, the AGB luminosity function has been used to probe recent star formation history and mass loss along the AGB (Reid and Mould 1985). A system's carbon star luminosity function can also provide a constraint on its distance (Blanco, McCarthy and Blanco 1980), and the C-to-M star ratio correlates to the mean metallicity (Frogel, Blanco, McCarthy and Cohen 1982; Cook, Aaronson and Norris 1986). As well as giving insight into *s*-process element formation and the chemical evolution of stellar systems, AGB studies probe abundances a few gigayears ago (Iben 1984).

The investigation of the AGB in nearby galaxies has been aided by the use of narrow- or intermediate-band filters to distinguish carbon from M stars in CCD images (Richer, Crabtree, and Pritchett 1984; Cook, Aaronson and Norris 1986). The technique we have used involves CCD imaging through two intermediate-band filters centered at 7850Å and 8100Å. These filters measure TiO absorption in M stars and CN absorption in C stars. The 7850-8100 color combined with broad band photometry enables straightforward selection of C and M types. The TiO band strength also provides a direct estimate of the metallicity of relatively metal rich M stars. A preliminary report of results in selected fields of five Local Group galaxies has been published (Cook, Aaronson and Norris 1986).

We are using this technique with the 4Shooter on the Hale 5-m telescope to examine the surface distribution of carbon and late-M giants in M31 and M33. A direct result of this project will be a determination along the metallicity gradients of these galaxies of the effect, if any, of local metallicity upon the C and M star luminosity functions. The C-to-M ratio probes the metallicity gradient as it existed a few gigayears ago and will provide needed information on the history of the gradients's formation. The fact that the current, global metallicity correlates well with the C-to-M star ratio hints that the gradients's existence is not strongly linked to events within the last few gigayears. Such data are particularly important to discriminate between global and local effects on star formation and chemical evolution. We are also probing the halos of M31 and M33 which provide relatively pure Population II fields to compare to the Galaxy's halo where there are few, if any, luminous C stars. A halo field will also provide a quantitative estimate of halo contamination of the major axis fields. The comparison of the halos of M31 and M33 should also be instructive since the M31 halo is relatively metal rich and has a large metallicity dispersion while M33's halo has a much lower dispersion and metallicity (Mould and Kristian 1986). This study will allow us to model star formation and chemical evolution of these systems a few gigayears ago. M33 will provide an excellent test of the universality of the total AGB and C star luminosity functions found in the LMC, since it has a similar luminosity and metallicity, but different morphology and environment.

We are also using the 4-Shooter to obtain deep color-magnitude diagrams and determine the carbon-to-M star ratio and C star luminosity function for four, very low luminosity dwarf galaxies selected from the HI survey of Sargent and Lo (1986)—LGS 3, CVn dw A, Pegasus and Leo A. These systems represent the full range of M/L found by Sargent and Lo. By a careful study of the star formation history in these objects, we will address the question of to what extent they represent a transitional, evolutionary link between dwarf irregular and dwarf spheroidal systems. Our primary target is LGS 3 found by Sargent and Lo to have a mass-to-light ratio of 27. Similar high M/L values have been claimed for several low luminosity dwarf spheroidals by Aaronson and Olszewski (1986). Whether such dwarf systems really contain dark matter has important consequences for both the nature of the non-luminous material and on biased galaxy formation models. It can be argued that the high M/L's found by Sargent and Lo are a misleading artifact of gas stirring by recently formed massive stars. However, a (not so deep) color-magnitude diagram of LGS 3 obtained by Christian and Tully (1983) indicates that the brightest stars there are *red*, not blue, leading these authors to propose that the most recent epoch of star formation occurred (possibly much) greater than 10 million years ago. Unfortunately, this conclusion and the high M/L rest on a crudely estimated distance of 1.0 Mpc. We have several observing goals in mind for these dwarfs. First, we want to obtain deep color-magnitude diagrams to see if there is any sign of younger stars in the form of a blue main sequence (particularly in LGS 3). Second, we want to employ our AGB search technique to look for C and M stars, and in particular determine the C star luminosity function. These observations should allow us to put much tighter constraints on the distance, the most recent epoch of star formation, and the mass-to-light ratio.

In 1987 we obtained data on two major axis fields in M31, one field in M31's halo, one major axis field in M33, Pegasus and LGS 3. The surface coverage in M31 and M33 was less than hoped for because of problems with the large intermediate-band filters needed for the 4Shooter. Data reduction and analysis is underway.

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Studies of Extremely Distant Galaxies

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Co-Investigators: P. Barthel, J. B. Oke, G. Grueff (Bologna), M. Vigotti (Bologna)

Subject Heading: Galaxies and Quasars

Study of the formation and evolution of galaxies, and the origins of nuclear activity in them, are among the central topics of the modern cosmology. Knowing how galaxies formed and evolved, and how the population of active galaxies and quasars changed in time, are fundamental and interesting problems on their own. Such knowledge is also necessary if we want to use distant galaxies and quasars as test particles in cosmological tests which probe the global geometry of the Universe (i.e., answer the question whether the Universe will expand forever, or whether it will ultimately recollapse). But before one can study these problems, one must first *find* galaxies at extremely large redshifts ($\sim$ distances), and do so in a systematic way.

In the past year, I have initiated several related projects, whose aim is to provide complete samples of extremely distant galaxies and quasars, and study their evolution. In this work, quasars (active galaxies in which the nonthermal light from the central "engine" outshines by far the integrated starlight of the host galaxy) serve mainly as beacons or probes indicating places in which to look for more normal galaxies. The hope is also to find objects or systems which are close to their initial formative stages, so-called primeval galaxies or protoclusters of galaxies. Once the evolutionary processes of carefully selected samples of distant galaxies are well understood and quantified at the optical wavelengths, we can try to use them as "standardizable candles" in the near-infrared, where the evolutionary changes are much smaller, and employ them in a classical cosmological test first proposed by Hubble (apparent brightness *vs.* the redshift). Clearly, this work will continue for a number of years.

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

In collaboration with the team from Bologna, led by Drs. Grueff and Vigotti, who provide the radio data and some astrometry, I started a program to identify a complete subsample of about 150 promising B3VLA sources. So far, we obtained about 20 new optical counterparts, some of which are clearly galaxies in very distant clusters (this is complementary to the purely optical searches for distant galaxy clusters conducted at Palomar by Oke, Gunn & Hoessel, or by Picard & Mould). Spectra were obtained for a handful of sources, already identified on the old Palomar Sky Survey prints by the Bologna group, and they turned out to be a mixture of moderately distant galaxies, and relatively

ordinary quasars. However, the most interesting sources are the faint ones, which so far defied our attempts to identify them optically. This work will continue, and may start yielding more exciting results in a year or less.

On a low-redshift end, one can try to capitalize on the existing complete samples of powerful 3CR radio galaxies, and optically selected brightest cluster galaxies. The latter were studied extensively at Palomar by Gunn, Oke, Hoessel, Schneider, and others, and provide a solid low-redshift base for the Hubble diagram. The relation between the radio-selected 3CR galaxies and brightest cluster galaxies is still not adequately understood. With this in mind, I completed observations of a complete sample of low-redshift 3CR radio galaxies, and brightest cluster members with comparable distances. Once the data are fully analyzed, it may be possible to tie the two samples, and the sample of distant 3CR galaxies, which reach out to the look-back time of the order of $\sim 80\%$ of the present age of the Universe, and probe the evolutionary and cosmological effects over the full range of redshifts (that is, cosmic epochs) which the joint sample would cover.

Another technique for discovering extremely distant galaxies is to look near known, high-redshift quasars, in the light of the Lyman α emission line of ionized hydrogen. The idea is simple: galaxies tend to cluster, and galaxy encounters and collisions are thought to be the trigger of the quasar activity. It then makes sense to look for companion galaxies near a known quasar. The choice of the band containing the Lyman α light is based on the fact that this line is strong, and so the contrast between the on-line and off-line images can be used to pick out the emission-line galaxies near the quasar. The technique yielded 2 or 3 high-redshift galaxies so far, but the searches for galaxy companions around randomly selected quasars have been largely unproductive. One can choose the quasars carefully: if they have associated carbon absorption in their spectra, indicating that there is some dense gas on the line of sight near the quasar, *and* if the quasar is a radio source with distorted jets, indicating that there is some dense, confining material in the plane of the sky near it, then the chances of detecting nearby galaxies should be much higher. In collaboration with P. Barthel and J. B. Oke, several quasars satisfying these criteria were selected, and deep images in the Lyman α light and continuum were obtained at the 200-inch telescope. The preliminary results are ambiguous, but two of the four quasars surveyed so far have very faint apparent galaxy companions within a few arcseconds. The spectroscopic confirmation of their nature will have to wait for the next observing season.

Finally, I would like to emphasize that any work on very faint galaxies demands a dark sky: the objects are tens or hundreds of times fainter than the brightness of the night sky. It is still possible to conduct these fundamental studies from Palomar, but if the light pollution increases substantially, the work will have to be moved to some other site, or cease altogether.

A Search for Gravitational Lenses

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Subject Heading: Galaxies and Quasars

Since its discovery in 1979, the phenomenon of gravitational lensing has been one of the most active areas of research in extragalactic astronomy. Basically, if there is a large mass concentration (e.g., a galaxy, or a cluster of galaxies) between the observer (us) and a distant light source (e.g., a quasar), the gravitational field of the lensing mass will magnify and split, or otherwise distort, the image of the background source. The phenomenon is very rich in applications: it provides us with a unique probe of the distant Universe, and the large-scale distribution of matter; it is a testing range for the theories of gravitation; a ruler for the size measurements of intergalactic clouds; a new handle on the values of cosmological parameters, etc. However, the theoretical papers outnumber the observational ones by a large margin, and more lenses are needed.

Most quasars are identified on low-resolution photographic plate material, and close-separation lensed images could be easily missed. We started a quick optical CCD (charge-coupled device) imaging survey of a large number of bright, high-redshift quasars, preselected as promising lens candidates by their apparently large absolute luminosity and large redshifts. A sample preselected in this way should have a considerably higher lens frequency than a "random" quasar catalog. Digital image deconvolution methods can be tried on the promising candidates, viz., Maximum Entropy (MEM), Wiener filtering, etc. One can improve the resolution of images by a factor of $\sim 2 - 3$ by using these methods.

This survey already provided at least one very probable gravitational lens, UM 425 = QSO 1120+019, shown below, several other interesting lens candidates, which are now awaiting spectroscopy, and a binary quasar associated with the radio source PKS 1145-071. Based on the data so far, the quasar Hoag-1 is almost certainly a gravitational lens. Some data were obtained at other observatories, e.g., Las Campanas, or Cerro Tololo.

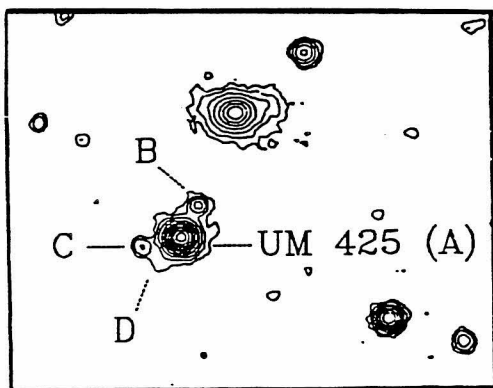


Image of the newly discovered gravitational lens UM 425. The field shown here is 50×40 arcseconds, and the intensity contours have a logarithmic spacing. The components of the quasar's multiple image are indicated with letters. Other objects are foreground galaxies. Some of the initial data on this system were obtained at Palomar, with a spectroscopic follow-up at Las Campanas and ESO. From Meylan & Djorgovski (1988 *Astrophys. J. Lett.* in press).

Binary quasars like PKS 1145-071 may be just as interesting: they may teach us something about the origin and maintenance of quasar activity, and the two images can serve as probes of the sizes and physical parameters of intergalactic clouds, from the studies of correlated absorption lines. A quasar pair may be also pointing towards a high-redshift cluster, useful for the study of galaxy evolution. As another interesting byproduct of this survey, we have discovered several close (within a few arcseconds) projected pairs of quasars and faint foreground galaxies. Studies of such systems can provide important information about the origin of metallic line absorption in quasar spectra.

Spectroscopy of Distant Galaxies

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Subject Heading: Galaxies and Quasars

The goal of our ongoing program is to compare the properties of nearby galaxies to distant galaxies, which, because of the finite speed of light, are viewed as they were billions of years ago. This allows a direct assessment of the history of star formation and activity in the nuclei of galaxies, the primary processes that determine how galaxies evolve to their present types.

During the last several years, we have obtained spectra for ~ 200 galaxies in the fields of 11 rich clusters in the redshift range $0.36 < z < 0.90$. This corresponds to lookback times of 5-8 Gyr, 30-50% of the present age of the universe. Because of their great distances, these galaxies are extremely faint. Therefore, the combination of the Hale 5-m telescope at Palomar Observatory, a state-of-the-art CCD detector system (the "4-Shooter"), and lengthy observations are required to obtain their spectra. During the 5 nights on which observations were made this year, a multi-slit technique, previously developed by the P.I., was employed to allow the observation of many galaxies simultaneously, with typical integration times of 4 hours per setup.

The data sample has now become large enough that general trends have emerged, permitting statistically meaningful statements about high- z cluster galaxies in general instead of the focusing on populations of individual clusters as was done at first. Our findings have been recently summarized in Dressler (1987), Dressler and Gunn (1988), and Gunn (1987, 1988). Our data basically confirm the claim of Butcher and Oemler (1978, 1984) based on photometry alone that the populations of high- z clusters are different from their low- z counterparts. Specifically, "active" galaxies, those with signs of recent star formation or nuclear activity, comprise $\sim 30\%$ of the distant cluster sample, but only $\lesssim 5\%$ of low- z clusters. (However, even distant clusters are still dominated by "passive" galaxies, those with the spectrum of an old stellar population, in which significant star formation has not occurred within the last ~ 5 Gyr.) This increase in the percentage of active galaxies is all the more remarkable because of the specific *kinds* of galaxies that are found. Most are *not* normal spiral galaxies like the Milky Way (which is *active* in star formation), but rather there is an order-of-magnitude increase in "E+A" types, where one finds a basically old population but with Balmer absorption lines of equivalent width $W \gtrsim 5$ angstroms. Of these, some, perhaps most, are "post-starburst" galaxies, systems which experienced a strong episode of star formation that has since subsided. Among ~ 1000 low- z cluster galaxies, less than 1% have this type of spectrum,

yet we have found 23 examples in the distant clusters. We also find a greater proportion of *active* starburst galaxies and AGNs as well.

I consider the discovery of starburst galaxies in every cluster we have studied to be our primary finding (Dressler and Gunn 1986). The cause of this phenomenon remains unclear. We have, however, suggested that much of this activity is caused by ram-pressure-induced star formation as gas rich galaxies fall into these relatively young clusters and encounter the hot, high-pressure gas that fills the cluster. Still we can not yet rule out other causes like galaxy-galaxy interactions and mergers, or a greater volatility for gas-rich systems that requires no external trigger. Images with the Hubble Space Telescope Wide Field Camera may be decisive in choosing among these models, and Butcher, Oemler, Gunn, and I have proposed such a program. However, we already have a few clues that support the idea of interaction with the intracluster gas: (1) the characteristic velocities of the active galaxies are a factor of 2 higher than those of passive galaxies and (2) active galaxies seem to be preferentially located ~ 0.5 -1.0 megaparsecs from the cluster center, just where an infalling galaxy would encounter the very high density of the intracluster gas.

We are now in the early stages of very difficult observations of four more distant clusters at $z \sim 0.7$ -0.9. Our first data indicate a large fraction of active galaxies, but we are unable to tell, at this point, if the percentage is higher than the $z \sim 0.5$ sample. Perhaps more important than this is the preliminary indication that the 4000Å "break amplitude", a sensitive gauge of stellar population (Dressler and Shectman 1987), is systematically different for *the entire population* as compared to low- z cluster galaxies. This could indicate that we have looked far enough back into time to see evidence of evolution in even the least-active galaxies.

In summary, this program has provided perhaps the best evidence that normal galaxies like our own are evolving with cosmic time. This is a crucial demonstration of the Big Bang theory of the birth of the universe. The data gathered in this study points the way to future investigations with an eye toward understanding the relative importance of nature vs. nurture in the evolution of structure and stellar populations in galaxies.

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Distances to Nearby Galaxies and Calibration of the Hubble Constant

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Most determinations of the Hubble constant, which is a measure of the expansion rate or the size of the universe, have relied on Cepheid variable stars to provide accurate distances for nearby galaxies. For several years now, Freedman has been undertaking a recalibration of the Cepheid distance scale by obtaining new CCD photometry in nearby resolved galaxies. The aim of the program is to provide a new calibration for the determination of the Hubble constant. In the course of the program, new CCD photometry is being obtained for all galaxies in which Cepheids have previously been discovered, and where periods have been determined.

In collaboration with Caltech graduate student Christine Wilson, and Barry Madore (IPAC), Freedman is currently studying the distance to the nearby spiral galaxy M33 based on an analysis of CCD data of its known Cepheids, some data for which has been obtained at the Palomar 60 inch. An analysis of the Cepheid data indicates that the dust inside of M33 is obscuring a fraction of the light coming from those stars. The blue light is scattered more than the longer wavelength red light, and in the blue, the galaxy is measured to be *apparently* further away than in the red. By observing at many wavelengths, this effect can be corrected for, and an estimate of the amount of obscuration by dust obtained. Several phase points for many Cepheids, and a photometric zero point calibration were obtained at the 60 inch using the RCA CCD camera.

The new data indicate that obscuration by dust is a significant correction which needs to be applied to the apparent distance moduli before the true distance modulus can be derived. The new, lower value determined for the distance to M33 has the effect of increasing the value of the Hubble constant. M33 is one of only 4 galaxies currently available to calibrate the infrared Tully-Fisher relation. Adopting the new value of 24.5 for the distance modulus to M33, and applying the new calibration to the infrared Tully-Fisher relation yields a value of $H_0 = 90$ km/sec/Mpc.

A new photometric calibration was also obtained at the 60 inch for the galaxy IC 1613. *BVRI* photometry was obtained for Cepheids in this galaxy, the amount of obscuration determined, and a new distance modulus determined by Freedman (1988a). IC 1613 is a faint member of our Local Group of galaxies with a very low metal composition. It thus provides an ideal test case for determinations of its distance based on a variety of methods to test for sensitivities in the various methods to chemical composition.

An independent estimate of the distance to IC 1613 was obtained by Freedman (1988b) from an analysis of the photometry of the brightest resolved red giants. The calibration for these data again came from Palomar 60 inch data. Measuring the position of the tip of the red giant branch yields a distance in very good agreement with the Cepheid distance. This agreement suggests that metallicity may not be introducing systematic effects into the determination of Cepheid distance moduli. A new Four-Shooter program to discover RR Lyraes in IC 1613 has just been initiated, and should yield yet another independent distance estimate to this galaxy, providing a more stringent test of metallicity effects.

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Deep Surveys with the Four-Shooter

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Subject Heading: Galaxies and Quasars

For the past two years the four-shooter camera (Gunn et al 1987) has been used to produce a survey for very distant clusters of galaxies. This work is an extension of survey work begun in 1970 by Gunn and Oke with the aim of finding a homogeneous set of clusters of galaxies at ever greater distances. The present survey aims to assemble such a set to reshifts of order unity. The previous stage in the survey (Gunn and Oke 1976, Gunn, Hoessel, and Oke 1986) completed in the early 1980's using fine-grain infrared photographic plates on the 4-meter Mayall telescope, provided a few rich clusters to nearly this redshift (two clusters at $z=0.92$ are the most distant objects in that survey) but it is clear that that survey is seriously incomplete at redshifts greater than about 0.5.

The new survey is being done using the four-shooter camera in drift-scan mode, in which data is collected continuously as the telescope is slowly moved in declination. It covers six square degrees in six one-degree square fields, one in each of the original six-degree square survey fields. The data are in two colors (roughly Johnson V and I), making use of the fact that the four-shooter can be equipped with one set of filters for the leading two cameras in the scan and another set for the trailing ones. The survey is actually a two-stage one; in the first stage the entire area is covered with equivalent exposure times of 300 seconds per detector. In the second one strip 9 arcminutes wide by one degree high in each of the six survey fields is repeated ten times, for a total exposure of 3000 seconds. This 'ultra-deep' sub-survey will go to a depth of fainter than 25th magnitude in the V band. The first stage is substantially complete; a few strips are left to be done, and others taken in unsatisfactory conditions need to be repeated; the ultra-deep survey is about half done.

The present survey will consist entirely of calibrated digital data, and the analysis is being handled entirely in an automated, objective way. A serious problem with previous cluster catalogs, including our own, is

that the identification of clusters of galaxies by eye is a very subjective affair. Since the difficulty of identification increases dramatically as one goes to fainter and fainter limits because the background contamination becomes more and more severe, it becomes very difficult to relate the number of clusters found, say, with the real density of clusters in space. The evolution of the latter quantity is of very great interest, because the dynamics of clusters suggest that they are relatively young structures, and many of them must have formed between the present epoch and the epochs corresponding to the look-back times to the most distant objects we can see, about two-thirds the present age of the universe ago. The rate at which they form depends sensitively upon the cosmological model, and so then does the evolution of their space density with time (redshift).

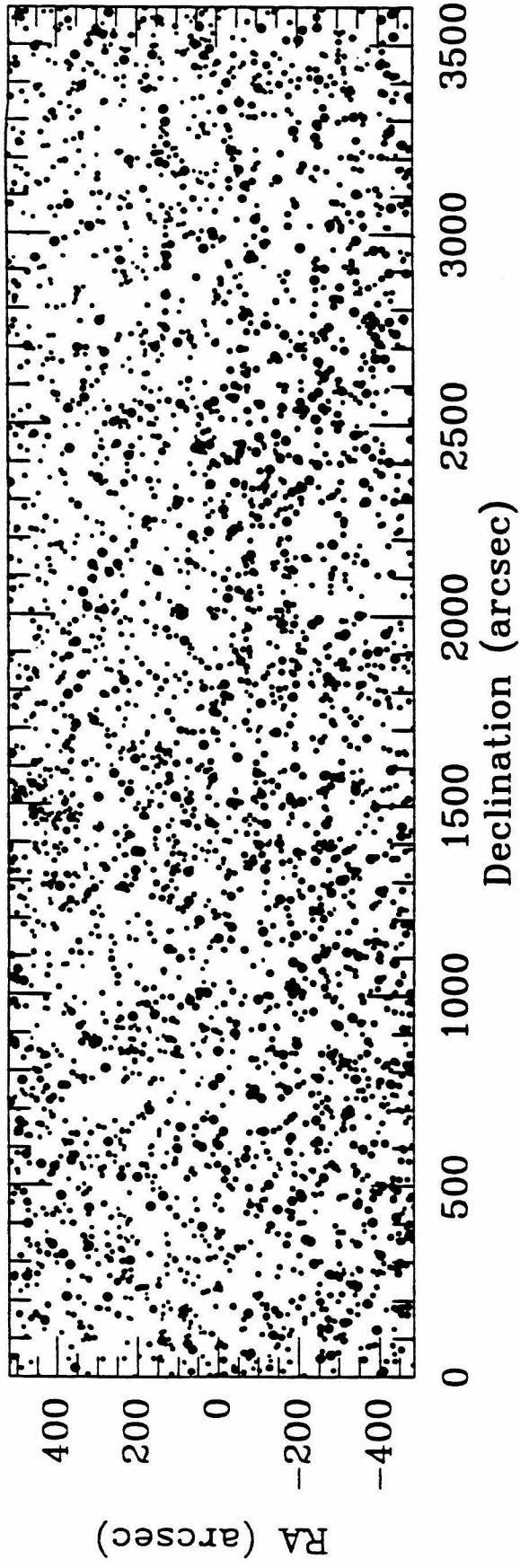
The data are being analyzed by first constructing a catalog of all galaxies. That part of the analysis, using a very heavily modified version of the FOCAS code of Tyson and Jarvis, produces lists of all significant objects in the survey fields, separates resolved objects (galaxies) from unresolved ones (stars) and classifies the galaxies as best it can into form classes based on the averaged radial profile and flattening. This code is complete and thoroughly tested; maps illustrating a sample of its output are shown in Figure 1. (Gunn, 1988) The next step, which is still at a very preliminary stage, is to identify clusters in the catalog by means of an optimal filter in all three dimensions (x,y, and brightness). This is a very difficult task because of the very low contrast of high-redshift clusters against the background, as a quick perusal of the faint part of figure 1 illustrates.

Besides the evolution of clusters themselves, such a survey provides a means for studying the evolution of galaxies (Gunn, 1988, Dressler and Gunn 1987, Lilley and Gunn 1985) in controlled environments; one of the surprises in the study of galaxies in distant clusters is that the evolutionary changes are very rapid, the indication being that most cluster galaxies at redshifts bigger than about 0.75 are in states of activity rare or absent in cluster galaxies today. In addition, comparison of the 'ordinary', passive galaxies in the clusters with similar galaxies in similar clusters at the present epoch (see, e.g Schneider et al 1983ab) provides an important way to date galaxy formation, since the evolution of these galaxies is almost certainly dominated by the evolution of a single stellar population formed very early in the history of the galaxy.

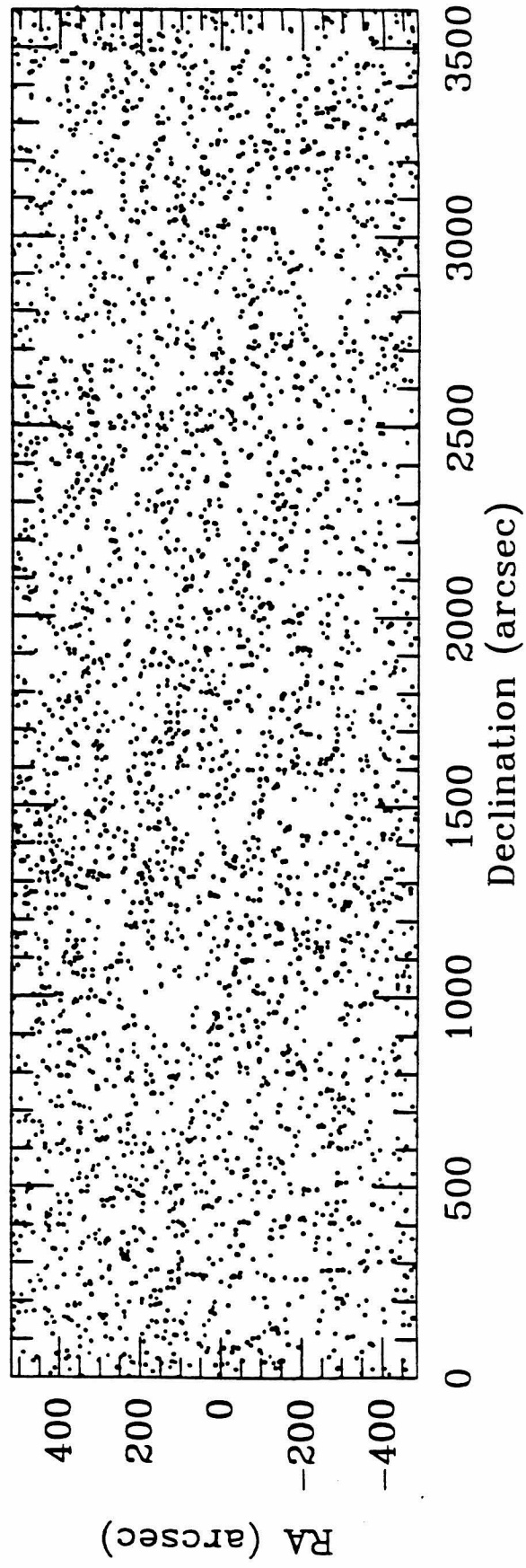
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$0.28^\circ \times 1^\circ (16^h)$ Strip: $V \leq 23.21$



$0.28^\circ \times 1^\circ (16^h)$ Strip: $23.21 < V \leq 24$



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THE EVOLUTION OF GALAXIES

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Subject Heading: Galaxies and Quasars

Introduction

The evolution of the stars which constitute galaxies plays a central role in modern cosmology because of the connection between structure in the Universe now and the character of the perturbations at very early epochs. If galaxies and larger structures have grown largely by purely gravitational processes (from small to large structures), then the observed density distribution will have an almost direct relationship to what it was in a much younger universe. If on the other hand, galaxies fragmented out of larger structures (from large to small structures), and if the collapse of galaxies was induced by explosions, then the distribution of galaxies on the sky would be largely influenced by astrophysical, rather than cosmological processes. Moreover, there is the notion that the formation of luminous galaxies may be biased to regions of high density, so that the distribution of luminous structures may not directly reflect the distribution of mass. In the small-to-large formation picture (also called hierarchical), structures that are the size of galaxies would form early at very high redshifts (redshift is greater than 10, but smaller than about 30). In the second formation picture (called the "pancake"), galaxies would form when the Universe is old (redshift ~ 1). Even rough observational results could make a major contribution by establishing, or even limiting, the redshift of the first major epoch of star formation in galaxies.

The best probe of distant dispersed matter is probably absorption lines observed against high-redshift quasars. Of these, the best case for gas in galaxies is the damped Lyman- α lines. If this interpretation is correct, then at least some gaseous discs had formed by redshifts of about 2.5. A self-consistent picture however requires that these discs be enormous and be common, in order to account for the observed number of cases. The mass of gas in the proposed discs is comparable to the mass in stellar discs now, implying that these discs are seen before most of the disc stars had formed. Based on observation, a general luminous phase can be ruled out for forming galaxies at relatively low redshifts (less than 1.5).

Deep Ultraviolet Imaging

Recently a new electronic detector has been used at the prime focus of the Hale Telescope which offers a powerful combination for the study of distant galaxies in the ultraviolet. This detector, a charge-coupled device (CCD), has excellent imaging qualities, but most importantly it is very sensitive in the ultraviolet, where most other CCD's are blind. This detector along with the large light collecting power of the 200-inch telescope and the excellent skies over Mt. Palomar allow us to image the distant Universe in a region never seen before. The region of the spectrum below 4000Å (the bluest the eye can see) is where the greatest change is expected in the spectra of high-redshift galaxies. Young stars yield most of their light in the ultraviolet, a region where old stars are dim enough almost not to be detectable.

The approach is to take many long integrations with this CCD, and then to add these pictures together to form a very deep image of what the ultraviolet universe looks like. This has been done for several fields which have galaxies of known redshifts. One goal of this program is to see how the number of faint galaxies changes with depth: it is expected that at a redshift of 3.5, the dark Lyman continuum found blueward of 912Å to have shifted into our ultraviolet region. Therefore, by comparing the changes in the structure of galaxies as we image deeper, we can set limits on when galaxies formed.

Redshift Survey of Blue Compact Dwarf Galaxies in Virgo

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Blue Compact Dwarf galaxies are a class of objects first identified by F. Zwicky and co-workers at Caltech during the sixties, distinguished by their small size and their high brightness, hence the "compact" description, and their unusually blue colors. With more detailed studies (in particular by W. Sargent and L. Searle also at Caltech in the early seventies), the definition was refined so "Blue Compact Dwarf" (BCD for short) now refers to an intrinsically small galaxy (at most 10% of the Milky Way in mass) undergoing an intense episode of star formation, and whose gaseous interstellar medium contains an unusually low abundance of elements heavier than Helium. Since heavy elements are "cooked" inside stars, it follows that the gas in these objects has not cycled through stars as often as the gas in "normal" galaxies. With this conclusion, the BCD class acquires particular significance, for it may provide some of the least evolved galaxies known, which are of great interest to cosmologists. A number of questions then come up concerning the history of these little-evolved objects: Are they forming stars for the first time, or have they undergone one or more brief episodes of star formation activity separated by long quiescent periods? What do they look like during a quiescent phase? What triggers the episode during which they become BCD galaxies?

Samples of BCD galaxies adequate for tackling the questions above are hard to obtain. In a collaboration with Lyle Hoffman (Lafayette College) and Ed Salpeter (Cornell University), I have been concentrating on a list of 65 galaxies classified as "BCD" based purely on appearance, identified in the course of a survey of the Virgo Cluster of galaxies by B. Binggeli, A. Sandage and G. Tammann (1985). Because of the refined definition above, appearance is an insufficient criterion, and distance to these objects is needed to firm up (though not entirely guarantee) the BCD classification. We therefore applied for time at the 200 inch telescope to measure redshifts (from which distances can be deduced) for those objects on our list that still lacked them. We had already collected atomic hydrogen data at 21 cm (including redshifts) at the Arecibo Radio Observatory, and far infrared data from the Infrared Astronomical Satellite (IRAS) survey for as many objects as possible.

The 21 cm data give for each galaxy the total mass of neutral hydrogen, whereas the infrared data measure the emission from dust grains mixed with the gaseous interstellar medium and heated by the stars.

We observed in May 1988 at the Hale 200 inch reflector twenty-three objects, and managed to determine redshifts for twenty of them. Combining these results with the atomic hydrogen and infrared data, we establish the following results:

1. All BCD galaxies in the Virgo Cluster have substantial amounts of atomic hydrogen.
2. Compared to normal galaxies, BCD galaxies in general have a reduced amount (by a factor 2 or 3) of infrared emission given their atomic hydrogen content. We interpret this as the result of a reduced dust-to-gas mass ratio (again by a factor 2 or 3), which again reflects the reduced heavy element content in the BCD class. This is the first instance where such a property is established based on IRAS data.
3. Given the above, we favor a picture where the typical BCD galaxy in the Virgo Cluster has had between 10 and 30 episodes of star formation, lasting about 30 million years each, and resulting in a heavy metal abundance deficient with respect to normal galaxies by a factor of 3.
4. There are two groupings of galaxies within the Virgo Cluster that are strikingly rich in BCD galaxies compared to the rest of the Cluster. A possible explanation is that these groupings are in a singular epoch from the dynamical point of view, as they appear to be falling into the Cluster. There may be in this dynamical singularity a clue to the mechanism that triggers star formation episodes in dwarf galaxies.

The Luminosity-Velocity Relation for Spiral Galaxies

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Subject Headings: Galaxies and Quasars

For many years the Tully-Fisher relation has been of fundamental importance as a secondary distance indicator for determining the size and structure of the Universe. This relation links the rotation velocity of a galaxy with the intrinsic luminosity of the system. Since the rotation can be measured independently of how distant the system is the Tully-Fisher relation thereby becomes a means of determining distances to galaxies once their apparent luminosities are known. Despite the success that the Tully-Fisher relation has had, no secure understanding of the physics behind the correlation is in hand. This is especially worrisome with the realization that most of the mass in the outer regions of most spiral galaxies is not in the form of luminous material, but it is in the form of so-called 'dark matter' which nevertheless affects the dynamics.

In an attempt to better understand the physical and observational underpinnings of the Tully-Fisher relation Madore and Woods undertook a study of all galaxies with detailed surface photometry and high spatial resolution rotation curves. From published data we discovered a very stable, and until then, a totally unknown relation between the rate of rise of the rotation curve and the rate of accumulation of light in the inner bulges of all the spiral galaxies we studied. Since the dark halos are thought to be a weak contributor to the mass in these nuclear regions, and since the stellar population is known to be of a much purer type than that integrated over the entire extent of the galaxy, it is reasonable to assume that the mass-to-light ratio in a spiral galaxy bulges is much more of a constant than global M/L values. Accordingly, the relation that we have discovered should have a correspondingly small dispersion in zero point as well as in slope.

Using the 200-inch double spectrograph during bright time last year we obtained H α rotation curves for eight of the twenty Virgo galaxies which were originally targetted to calibrate the zero point of their newly discovered relation between rotation rate and cumulative interior luminosity (Madore and Woods, *Ap. J. (Lett.)*, 323, 12, 1987). This fall we are making similar observations of galaxies in the Perseus cluster. It is our intention to use these cluster galaxies as one means of determining the total spread in the Luminosity-Velocity relation and thereby calibrate the relationship for use as a distance indicator. Once this is done we will be in a better position to assess our internal and external errors before proceeding on to do cosmology.

Photometry of our galaxies has been obtained both at Palomar and at Las Campanas. The Virgo rotation curves have been reduced and the comparison with the photometry is being prepared for publication. These observations will constitute the basis for Woods' thesis.

Infrared Variability of Optically Selected Quasars
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Subject Headings: Quasars

Variability has been recognized as a characteristic feature of the radiation observed from quasars since their discovery, and temporal studies of the continuum energy distributions of quasars are potentially important in distinguishing between the physical processes involved in the production of the observed luminosities. More recently, evidence has been mounting that infrared emission, especially at the very long wavelengths observed, e.g., with the IRAS satellite, plays a crucial role in the total luminosity of many quasars; see, e.g., the report by Soifer *et al.*. Unfortunately, the origin of the infrared emission, whether it is nonthermal synchrotron emission from high energy particles or thermal reradiation from dust grains heated by a central luminosity source, is unknown and has been the subject of much debate. Near infrared observations which can be made from Palomar cannot, unfortunately, sample the peak of the radiation. If, however, the emission at the longest infrared wavelengths which can be observed from Palomar is assumed to be produced by a similar mechanism as that at the peak of the emission, the discovery of large amplitude rapid variations would strongly favor a nonthermal interpretation.

Large variations at 10 μm have, in fact been observed in one quasar, the bright radio "loud" quasar 3C273. The observations were part of a 20 year study, at five infrared wavelengths, of the variability of 108 optically selected quasars which was completed by Neugebauer and his collaborators in the Caltech infrared group. No rapid large amplitude variations were, however, observed in the other quasars. Furthermore, about half the quasars showed no variability on a five to ten year time scale, in distinct contradiction to the evidence at visible wavelengths. The maximum variations were about 50%, and those quasars that did vary, except for 3C273, showed very similar changes at all the wavelengths sampled. The results are also consistent with there being a distinction in the pattern of variability between the radio "loud" quasars with flat radio spectra and the radio "quiet" quasars. Thus the observations slightly favor, but cannot prove, that the infrared emission in the majority of optically selected quasars is indeed thermal emission from dust grain surrounding the central heating/luminosity source in the quasars.

Broad-Line Regions in Active Galaxies

Principal Investigator: S. E. Persson

Mount Wilson and Las Campanas Observatories

Subject Heading: Galaxies and Quasars

Quasars and certain "active galaxies" have long been recognized by their distinctive spectra, as well as by their extraordinary luminosities. Very bright and broad features in their spectra indicate strong emission by high velocity gas that contains a variety of chemical elements. Through a long process (25 years) of observational and theoretical work, we now have the outline of a physical picture (a three-dimensional model) of the region within the quasar that emits the strong spectral signatures. It is believed to be a collection of a large number of gas clouds, moving at high speed around a black hole that is roughly 100 million times as massive as our sun. It is the release of gravitational energy by material near the center of this cloud and falling in toward the black hole that provides the ultimate source of power for all the high energy phenomena observed. Most importantly it makes the quasars so bright that we can observe them at enormous distances. Determination of the geometry, velocity, origin, and evolution of the gas that is closely associated with the black hole nucleus depends in part on our ability to understand the observed spectra of the gas clouds that are illuminated by the nucleus. This note describes some recent progress made as a result of observations made on the Hale Telescope at Palomar, combined with some new theoretical work. The observations could not have been done without the superb instrumentation used.

It is now generally supposed that the "broad-line" gas (so-called because the indicated doppler velocities are so large) is energized by ultraviolet and X-ray radiation from the inner edge of a disk-like reservoir of gas just outside the black hole. Theoretical calculations of the expected appearance of the gas subjected to this intense radiation have been explored sufficiently that we think we know what the basic properties of the clouds are. That is, various observational tests and predictions have led to a "model" of the density, composition, and location of the gas. It is an internally consistent picture, but because our information is incomplete, we have no proof that it is correct—further effort is needed to explore other possibilities, and to thus refine or even perhaps upset the accepted wisdom.

Recent additions and improvements to the spectral data have, indeed, left some important features of the overall picture in doubt. One of these concerns the production of emission from atomic species such as iron and calcium that are so vulnerable to ionization by the quasar that they must lie protected behind enormous quantities of material (they can only "live in the shade"). The trouble is, these quantities of material are grossly inconsistent with the "standard" picture outlined above. The basic problem is one of balancing the energy budget. If one imagines protecting a species well enough to keep it from being ionized, then one cannot avoid cutting off its supply of energy, in which case it cannot radiate the light that we see.

The most glaring such example is that of a trio of spectral emission features due to once-ionized calcium. Recently the Hale telescope was used to assess quantitatively the occurrence and characteristics of this type of emission in active galaxies. The number of active galaxies displaying calcium emission was high enough to prompt a theoretical investigation. G. J. Ferland of Ohio State University has developed the best computer

simulations needed for this work; but a large number of modifications and additions to his computer program were required. The basic job was to extend the limits of the calculation so as to include conditions, processes, and species in the gas that were heretofore not included and therefore unexplored. It turned out that some previously neglected species are in fact extremely important in the heavily protected parts of the gas clouds where the calcium features arise. Of greatest interest is the H^- ion, which is a hydrogen atom with a weakly attached extra electron. What happens is that enough H^- exists to absorb all the energy needed to keep the gas warm, and thus solve the problem. Recognition of this and careful inclusion of numerous ancillary physical effects has allowed us to simultaneously solve two other outstanding (but closely related) problems of energy balance in the broad-line region of active galaxies. It is amusing that this forgotten substance actually controls to a large extent the way energy escapes from the surface of the sun—that fact was discovered many years ago.

During the past observing season, Persson, Boroson, Morris, and Meyers have used the Hale Telescope to further improve the spectral data on a few active galaxies to the point that it will be possible to make another step forward in concert with new and more detailed theoretical work. The result, we hope, will allow us to understand better the location and motions of the gas clouds relative to the black hole nuclei of quasars and active galaxies. It looks now as though the challenge to our previous conception of the nature of the gas clouds in question will lead us to a different model, one closer to reality. In this way we hope to understand not just the present state of affairs, but also the formation, time evolution, and eventual fate of the nuclear gas.

Echelle Spectroscopy of Active Galactic Nuclei

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Co-Investigator: James K. McCarthy
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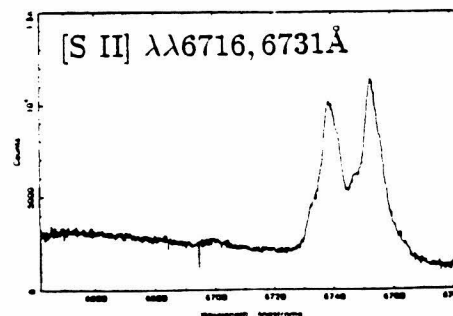
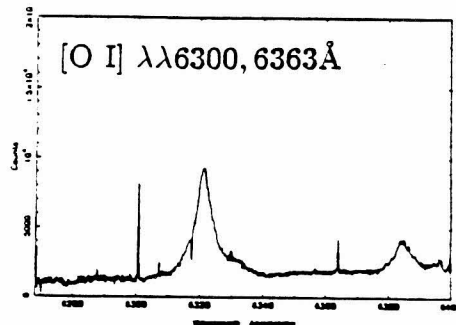
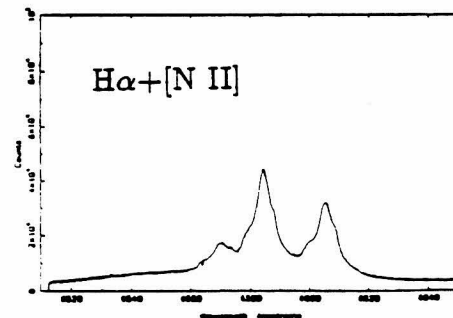
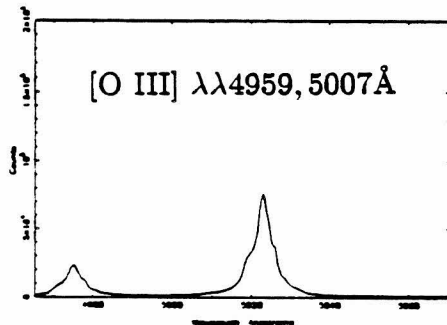
Subject Heading: Galaxies and Quasars

The echelle spectrograph on the 60-inch telescope (McCarthy, 1988 Caltech Ph.D. Thesis) was used to obtain $0.2\text{\AA}$ resolution spectra of NGC 1068 and NGC 4151, covering the range $\lambda\lambda 3500 - 9000\text{\AA}$. These are the two brightest Seyfert galaxies, of type II (narrow lines) and type I (broad lines) respectively. Because the data have nearly complete wavelength coverage, and exceptionally high signal-to-noise ratio over this interval, they are a unique resource, and will be compiled into two echelle spectrum atlases. There are no other published data with this unique combination of high resolution and wavelength coverage.

The prime motivation for studying Seyfert galaxies is, of course, to understand the nuclear engine which drives the activity. The emission line profiles reflect the velocity, density, temperature, and composition of gas near the central engine. It is therefore of great value to work at high resolution, presuming the lines have fine enough detail. It is evident from the figure below that they do.

With data of these quality, it is possible to examine the relationship of the detailed line profile and the critical density. Analysis of these data is currently underway.

The figures below illustrate [O III], [O I], $H\alpha + [\text{N II}]$, and [S II]. Note how similar the line profiles are, including bumps on the shoulders, *except* for [O I]. For [O I], notice how narrow the night sky lines are compared to the lines due to NGC 4151.



Dynamics of Spiral Galaxies

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Subject Heading: Galaxies and Quasars

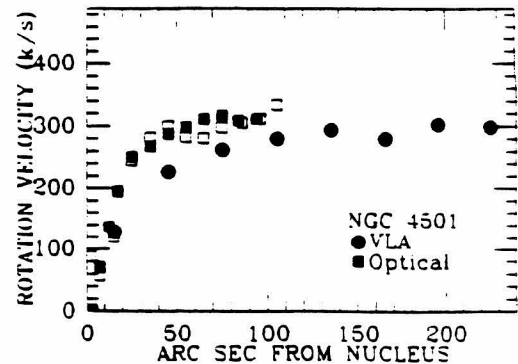
Galaxies rotate. Stars and gas in the disks of spiral galaxies move in response to the gravitational field of all of the other mass in the galaxy. Research work over the past decade, some of it by myself and my colleagues, has taught us that a relatively isolated spiral galaxy rotates in a very predictable rotation pattern, with stars at the edge of the disk moving with velocities too great to be produced only by the observed matter in the galaxy. This has led to the generally accepted concept that most of the mass in the universe is dark, and is distributed, halo-like, about galaxies. It is the gravitational effect of this dark matter that keep the stellar velocities high.

Galaxies evolve. Following their birth early in the history of the universe they continue to evolve; they may acquire more mass or lose mass; they may spin up or merge or be torn apart; they may be stripped of their gas, thus preventing substantial future star formation. Much of their evolution is directed by the density of the local environment which they inhabit. Thus it is likely that the dynamics of spiral galaxies in clusters and in compact groups differs from the dynamics of isolated field spiral galaxies.

Several years ago, my colleagues and I embarked on an observing program at the 200-inch and 60-inch telescopes to learn about the dynamics and the mass distributions within spiral galaxies located in dense regions. We are presently obtaining spectra for galaxies in the Virgo cluster, the closest large cluster of which we are an outlying member, and in a second study we have completed observations for galaxies in small, very compact groups.

For the Virgo program, we wish to determine rotation curves for about 100 galaxies encompassing a broad range of morphologies, luminosities, positions within the cluster, and velocities with respect to the mean cluster velocity. We hope to learn if galaxies close to the cluster core have had their halos modified or stripped by tidal interactions with their neighbors, and how their properties compare with those of galaxies at the cluster periphery and galaxies in the field. Last year we obtained spectra for 30 Virgo galaxies, most of

Fig. 1. The rotation curve of NGC 4501, a Virgo cluster galaxy, as determined from a CCD spectrum taken with the 60-inch telescope; the open and filled squares indicate the two sides of the major axis. The VLA velocities (Guhathakurta et al. 1988) are low, due to the lower resolution of radio telescopes.



them with the 60-inch telescope. The spectra are of high quality, and accurate velocities have been determined. In the mean, the spectra taken with the 60-inch telescope reveal measurable emission over only 50% of the optical disk, for emission lines are often very weak beyond this distance. In contrast, spectra of Virgo galaxies obtained with the 200-inch telescope extend to 70 or 80% of the optical disk, and hence will be most important for determining the mass distribution within the extended halos. We hope to continue and perhaps complete the observations in 1989, after which the analysis of the rotation properties and mass distributions will be carried out.

One early result from the Virgo program has been the discovery that rotation curves determined from neutral hydrogen observations with the VLA (very large array of 27 radio telescopes) still suffer from too low resolution. This is indicated by rotation velocities which are low, compared with the optical rotation curve for the same galaxy. Figure 1 compares the rotation curve for the Virgo spiral NGC 4501 as measured from a 60-inch spectrum with that recently published by Guhathakurta et al. (1988). Although the 21-cm curve extends twice as far as the optical measures, the VLA velocities are low over the entire region covered by the optical data. This is an important result for those who use rotation curves to derive mass distributions, or those who use the maximum rotational velocity to establish the absolute magnitude of the galaxy. For 7 galaxies which we have in common with the VLA, the VLA curves are low by 14% in the mean, and 26% in the worst case.

A second observing program to obtain spectra of galaxies in the compact Hickson groups has now been completed. In these small groups of 4 to 8 galaxies, where the galaxy density is as high as that in the centers of large clusters, the evolutionary histories must be complex. We have obtained spectra across the disks of 43 galaxies located in 14 groups. For 12 of these groups, we also have red and H α images taken with the Kitt Peak National Observatory 36-inch telescope. The combined study of spectra and images will permit us

to study the variation of surface brightness and mass-to-luminosity across these galaxies. Although we chose for observations groups which contain several spirals, we have observed both elliptical and spiral galaxies within each group. All of the spectra have been measured and studied, and we are presently completing analysis of this valuable material.

Twenty-one of the spectra come from galaxies of types Sa through Sc. In general, the rotation curves show a much wider diversity of forms than do the field spirals. About 40% of these galaxies have rotation curves which are indistinguishable from field spirals; the remainder show a wide range of peculiarities. But two peculiar forms are seen with considerable frequency; rotation curves in which the velocities beyond the nucleus are strikingly different on the two sides of the major axis, and rotation curves which resemble sinusoids. This diversity of forms of rotation curves suggests that mass distributions within the dark halos are substantially modified by interactions with other matter within the compact groups. It also suggests that spirals in regions of high galaxy density have had a more diverse evolutionary history than have isolated spirals. We hope that our continuing study of spiral galaxies which inhabit crowded environments will teach us more about this history, and of the distribution of dark and luminous matter in the universe.

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Ultraluminous Infrared Galaxies

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Subject Heading: Galaxies and Quasars

During the past year Sanders, Soifer, and Neugebauer began a major program of observations with the Double Spectrograph on the 200-inch telescope to obtain high-resolution, high sensitivity optical spectra of a complete sample of 20 ultraluminous infrared galaxies detected by the Infrared Astronomical Satellite (IRAS). The twenty galaxies in this study have been taken from our extensive ground-based survey of bright IRAS galaxies. All of the ultraluminous infrared galaxies have luminosities more than 50 times larger than that of the Milky Way. They emit more than one trillion times the energy of the Sun, and are among the most luminous objects in the local universe. Soifer *et al.* (1987, *Ap. J.*, 320, 238) have shown that the space density of ultraluminous infrared galaxies is slightly greater than that of optically selected quasars. Sanders *et al.* (1988, *ApJ.*, 324, 74) have proposed that these objects represent the initial, dust-enshrouded stages of quasars, and that most, if not all quasars begin their lives in an intense infrared phase. For all 20 of the ultraluminous objects under study, the trigger for the intense activity appears to be the collision/merger of two gas-rich spiral galaxies. The collision presumably funnels gas, primarily in the form of molecular clouds, into the merger nucleus where it first triggers an intense nuclear starburst, and, ultimately either the gas or the newly formed stars builds and/or feeds a quasar.

The high-resolution optical spectra we have obtained are allowing us to study in detail the excitation and kinematics of the ionized gas in these galaxies, and to classify the underlying stellar populations. In particular, we are searching for direct evidence of broad-line nuclear emission that would provide direct evidence for an active nucleus or quasar. Since the quasar nucleus is expected to be heavily obscured by dust, it is likely that the broad-line emission has been missed in previous lower resolution, lower sensitivity spectra. We will also be able to spatially separate the point-like quasar nucleus from the surrounding regions where we expect that a powerful circumnuclear starburst is underway. In the starburst region, the spectral line strengths and widths should differ dramatically from the spectrum of the central source. During the past year, spectra were obtained for 7 ultraluminous infrared galaxies and observations of the remaining 13 galaxies are planned for next year. Preliminary analysis of the data in hand suggests that weak broad emission lines are present in several galaxies, and the spectra do indeed become more star formation-like just off the nucleus.

In addition to obtaining optical spectra, Sanders, Soifer, Neugebauer, and Carico have also obtained large aperture, near infrared photometry of the same sample of ultraluminous infrared galaxies using the Persson infrared photometer on the Palomar 60-inch telescope. These observations are primarily designed to probe the outer disks of these interacting galaxies. By comparing the infrared colors in the large aperture with colors obtained earlier in smaller apertures, we have been able to show that the stellar populations far away from the nuclei of these interacting systems lie somewhere between those of starburst galaxies and those of more normal spiral disks. These data suggest that the starburst is limited to the inner regions of the merger disks; the size of the starburst disk is approximately one third that of the size of the merger disks as measured in optical photographs.

Low-Luminosity Active Galactic Nuclei

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Subject Heading: Galaxies and Quasars

The most luminous and distant objects in the universe are probably quasars. Their observed properties differ greatly from those of ordinary galaxies. The radiation emitted by the majority of galaxies, for example, is predominantly starlight, whereas that of quasars is produced by nonstellar processes. There are, however, certain galaxies whose nuclei bear a striking resemblance to quasars. The physical conditions in these "Seyfert nuclei" and other active galaxies appear to be quite similar to those in quasars. In some individual cases it is possible that low-luminosity Seyfert nuclei evolved through time from quasars, but the activity in most of these objects has probably always been mild. If the prodigious quantities of energy emitted by quasars are produced by matter falling into a supermassive black hole, as many researchers currently believe, then it is logical to suppose that the centers of low-luminosity active galaxies generally harbor less massive black holes accreting matter at only modest rates. By studying these mildly active galaxies, we can obtain valuable insights into their luminous counterparts, thereby exploring some of the most energetic phenomena in the universe. We can also provide important constraints on galaxy evolution, physical processes in dense gases, and many other astrophysical areas of interest.

In view of this, we are attempting to discover, and determine the properties of, nonstellar activity in the nuclei of bright, nearby, apparently normal galaxies. This can be achieved by careful scrutiny of high-quality optical spectra obtained with the Hale reflector at Palomar Observatory. A major problem is contamination by light from normal stars, which effectively dilutes the contribution of the nonstellar activity to an almost undetectable level. The starlight in a given galactic nucleus is eliminated by detailed comparison with the spectra of normal galaxies in which activity is entirely, or almost entirely, absent. For example, our research confirmed and extended the discovery, initially made by other astronomers, that very faint quasar characteristics are present in the nearby spiral galaxy M81. We determined that a black hole about 500,000 times as massive as the Sun may be present in its nucleus (*Astrophysical Journal*, 324, 134.) Since low-luminosity quasar activity exists in such a nearby galaxy, one suspects it to be almost ubiquitous among galaxies in general.

There are roughly 500 galaxies in our survey, and each one must be observed for a considerable length of time for the data to be of sufficiently high quality. The necessary observations were completed in 1988 after a total of five years. Although thorough analysis of the data will require several more years of work, weak Seyfert nuclei have already been detected in many galaxies, showing that the quasar phenomenon is indeed quite common at faint levels. The most exciting recent result is the discovery of a Seyfert nucleus in the intrinsically very faint spiral galaxy NGC 4395. This Seyfert activity is roughly one-tenth as bright as in M81, the least luminous previously known mini-quasar. In fact, the nonstellar continuum radiation of NGC 4395 is no brighter than the stellar continuum emitted by the most luminous *single* supergiant stars! For comparison, the most luminous quasars are comparable to about 100 million such stars. The nucleus of NGC 4395 demonstrates that a fundamental lower limit to quasar activity, should one exist, must occur at extremely low luminosities.

QUASAR ABSORPTION LINES AND EARLY HEAVY ELEMENT ENRICHMENT IN GALAXIES

Principal Investigator: Wallace L.W. Sargent

Co-Investigators: A. Boksenberg (Royal Greenwich Observatory),
C. C. Steidel

Since the classic papers by Hoyle (1946) and Burbidge *et al.* (1957) it is believed that the heavy elements in the interstellar gas in galaxies are produced by stellar nucleosynthesis. However, so far it has only proved possible to explore the evolution of composition in time in our own Galaxy. Thus, the gradual rise, by about a factor of 3 from an initially enriched state, in the heavy element abundance of the local Galactic disk has been measured via the study of stars of different ages (Twarog 1980). The evolution of the Galactic halo population has been more controversial. Eggen, Lynden-Bell and Sandage (1962) argued in their seminal paper that the halo was produced in a rapid initial radial collapse on a timescale of 2×10^8 years which formed a radial gradient in the composition of the halo stars and which culminated in the formation of the disk. Some later workers argued for a large dispersion in the ages of the globular clusters and suggested that the halo was formed over a timescale of billions of years. The differences of interpretation are related to difficulties in fitting the results of stellar model evolutionary calculations for different assumed heavy element compositions to the observed color-magnitude diagrams. In any case, for a variety of reasons, our knowledge of the history of the chemical evolution of our own Galaxy is far from secure.

The absorption lines observed in the spectra of quasars in principle offer a direct way of studying galactic chemical evolution by examining the composition of the interstellar gas in galaxies as a function of redshift and hence as a function of time. Such an approach is clearly completely different to the ones used heretofore which involve the study of local stars or clusters of known age. In the course of recent work on the statistics of QSO absorption lines we have obtained the first results which are applicable to this kind of analysis. These results were presented in a recent *Ap J. Letter* (333, L5 1988) as an indication of what might be possible and to encourage further observations.

Sargent, Boksenberg, and Steidel (1988) studied the absorption redshifts defined by the C IV $\lambda\lambda 1548, 1550$ doublet in uniform spectra of a sample of 55 QSOs with $1.8 \leq z_{em} \leq 3.6$. A total of 229 C IV absorption redshifts with $1.2 \leq z_{abs} \leq 3.5$ were found. Several unbiased subsamples were formed, and various analyses all lead to the result that the comoving density of absorbers $N(z)$ is *decreasing* with increasing redshift rather than increasing as would be expected if galaxies with constant properties are merely getting closer together as we go to higher redshifts and see the Universe at earlier and earlier times. We also found that there is statistically significant evidence that the C IV(1548)/C IV(1550) doublet ratio increases (toward the optically thin limit) with redshift over the above range. Both trends are consistent with an actual decrease in the abundance of C IV in the absorbing gas with increasing redshift.

At the same time, there has been a considerable improvement in our knowledge of the behavior with redshift of absorption systems containing the Mg II $\lambda\lambda 2796, 2803$ doublet. Sargent, Steidel, and Boksenberg (1988) found 40 Mg II redshifts in the range $0.2 \leq z_{abs} \leq 1.46$ in the spectra of the 55 QSOs observed in the C IV study. A further 62 Mg II systems in the redshift range $0.72 \leq z_{abs} \leq 1.45$ were found by Sargent, Steidel, and Boksenberg (1989) in the spectra of 58 QSOs which were observed in order to determine the incidence of Lyman limit absorption in high redshift QSOs. Adding these new data to samples recently published by Boulade *et al.* (1988), Lanzetta, Turnshek, and Wolfe (1987), and Tytler *et al.* (1987), we assembled a complete sample of 60 Mg II redshifts with $W_0(2796) > 0.6 \text{ \AA}$, and covering the range $0.16 \leq z_{abs} \leq 2.12$. Qualitatively confirming the results of earlier work, the density of Mg II systems is found to increase with increasing redshift, completely at variance with the behavior of C IV. However,

while certainly showing a steep rise up to $z \sim 1$, there is a suggestion that the Mg II evolution curve flattens off at higher redshift. One thus has an impression, which cannot be supported statistically by the available data, that the decrease in C IV number density at high redshift is a natural extension of the Mg II behavior above $z \sim 1$. It could be that there is a systematic change in the state of ionization of the absorbing gas as a function of redshift. However, the existing analyses of QSO absorption systems (e.g., using the ratio C IV/C II) give no hint of such an effect. We have therefore deduced that the evolutionary trends evidenced by the Mg II absorbers at low redshift and by the C IV absorbers at high redshift are due only to the combined effects of the expansion of the universe and systematic changes in heavy element abundance. If this hypothesis is correct, then the heavy element abundance increased in the absorbing material from high redshift down to $z \sim 1$, while for $z < 1$ the expansion of the universe became the dominant factor in determining the shape of the $N(z)$ curve.

The best available information on the evolution of the neutral hydrogen (HI) component of galaxies is afforded by the "Lyman limit" absorbers, which have column densities $N(HI) > 10^{17} \text{ cm}^{-2}$ and which can be observed over the whole redshift range $0.37 \leq z_{abs} \leq 4.5$ (Tytler 1982). We recently surveyed 59 QSOs with $z_{em} > 2.75$ at low resolution for Lyman limits. Combining the data on 33 LLSs with other published data, we found that for these absorbers the evolutionary curve continues to rise at the highest redshifts observed. Moreover, most of the high redshift Lyman limits have accompanying heavy element lines and are therefore not associated with the Lyman α forest of absorbers. The behavior of the Lyman limits, which we take to be representative of the HI component in galaxies, is in marked contrast to that of the C IV absorbers. Thus we infer that the decrease in C IV number density with increasing redshift is not due to a decrease in the number of absorbers *per se*, but is due to either a systematic change in ionization state with redshift, or, as we have suggested above, to a systematic change in heavy element abundance. If this hypothesis is correct, we have a way to determine the timescale for initial heavy element enrichment in the outer parts of galaxies.

We thus infer that heavy elements were synthesized over the redshift interval $3.3 \geq z \geq 1.3$, which corresponds (for $q_0 = 1/2$) to the time interval from $t = 1.5$ billion years to $t = 4$ billion years. For $t > 4$ billion years ($z < 1$) the heavy element abundance appears to have leveled off so that expansion effects dominate the $N(z)$ curve. For both the C IV and LLS absorbers, the typical line of sight passes about 50 kpc (~ 4 Holmberg radii) from the center of a typical large galaxy. For galaxies with flat rotation curves, the dynamical timescale t_D scales linearly with radius so that $t_D \sim 1$ billion years at 50 kpc. Thus, we find that the timescale for early heavy element enrichment in galaxies is of order t_D .

It turns out that, on the simplest model of galactic evolution, the results obtained above imply that gas is being transformed into stars at a constant rate with time during the initial heavy element enrichment.

Our conclusions are at first sight at variance with prevailing models of galactic evolution, which universally envisage an initial burst of star formation lasting ~ 1 billion years. It was by this means that the present, fairly static, composition of the local galactic disk reached its value early in the life of the galaxy. However, we must recall that the QSO absorption lines are produced predominantly in the outer parts of galaxies, where the dynamical timescales are much longer. Consequently, our results probably shed light on the evolution of Population II abundances rather than those of Population I.

In summary, the arguments presented above imply that the heavy element composition in the outer parts of galaxies reached a saturation value at a redshift of ~ 1 , i.e., relatively recently, and that before this the enrichment proceeded roughly linearly with time for 2.5 billion years, comparable to the dynamical timescale. During this period, the rate of gas consumption was approximately constant. Beyond these results, which are still uncertain, the main point of this exercise is to show that QSO absorption lines are capable of providing information on galactic chemical evolution which is not obtainable by any other means. Future work must stress the determination of actual abundances as a function of redshift for the main elements found in QSO absorption spectra.

The Redshift Cutoff of Quasars

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Subject Heading: Galaxies and Quasars

Quasars are objects of such high luminosity that they can be detected and studied at very large redshifts. Thus quasars provide an opportunity to study the evolution of a population of objects over a large range of redshift or cosmic time. In the past twenty years, we have gained much insight in the evolution of quasars for redshifts below 2.2. For such quasars, the ultra-violet excess is an effective criterion in selecting candidates among stellar objects. Analysis of quasars in samples with well-established completeness criteria has shown that the luminosity function evolves strongly with redshift. For quasars of high luminosity, the co-moving space density increases steeply with redshift, while for quasars of lower luminosity the density increase is less steep.

For redshifts larger than 2.2, the ultraviolet excess criterion does not separate stars and quasars effectively and most of the quasar searches have been conducted on the basis of the presence of emission lines. These searches were usually based on visual inspection of photographic objective prism or grism surveys, leading to considerable uncertainty in the completeness limit. For that reason, various claims of a redshift cutoff remained unsubstantiated for years.

Schmidt, Schneider (Institute for Advanced Study, Princeton), and Gunn (Princeton University) are now engaged in a long-term program to search for high-redshift quasars. Their goal is to document the variation of quasar density with redshift based on surveys to well-defined limits of completeness. The surveys are based on spectroscopic searches for emission-line objects with the 200-inch telescope in stationary position. Many thousands of low-dispersion spectra are recorded in a night as a long strip of sky moves across the telescope field. The data are reduced and emission lines are searched for by computer. Follow-up slit spectroscopy of hundreds of candidate emission-line objects is required to select the quasars and obtain their redshifts.

About one-fifth of the total survey material, covering 14 square degrees, has now been analyzed completely. A total of 143 emission-line detections were confirmed, resulting in a list of 44 quasars and 85 galaxies. Among these, 15 quasars were detected by their Lyman-alpha emission. The most remarkable result of this work is that the space density of these quasars,

which have a mean redshift of 3.3, is much lower, by a factor of about 7, than the space density of quasars at redshift 2.

This result confirms that the density rise seen at low redshifts changes into a steep decline at large redshifts. Rather than an abrupt redshift cutoff, there appears to be a gradual turn-around in density. The maximum in quasar numbers probably occurs at a redshift between 2 and 2.5. Since light from objects at such redshifts requires about 80% of the age of the universe to reach us, we conclude that the peak of quasar activity occurred about 3 billion years after the Big Bang. This epoch may represent the time it took to form the black hole and to accrete sufficient material to "turn on" the quasar phenomenon. Since all nearby quasars are observed to be in galaxies, it is tempting to speculate that galaxy formation also took place around this epoch.

The Energy Distribution of Quasars

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Subject Headings: Galaxies and Quasars

As part of our program to understand the relationship between ultraluminous infrared galaxies (discovered in the IRAS survey) and quasars, we have completed a comprehensive study of the energy distributions of the brightest quasars known, i.e. those found in the Palomar Bright Quasar (PG) Survey (Schmidt and Green, 1983) from radio to X-ray wavelengths. This study has utilized new infrared observations of nearly all the PG quasars from 1-10 μ m, as well as published data from radio, optical, UV, and X-ray wavelengths, and reprocessed data from the IRAS survey. This study represents the first large survey of quasars to extend the energy distributions beyond 2 μ m in the infrared, and required the full sensitivity achievable with the Palomar 5m and the 10 μ m photometric system to permit detection of most of these quasars beyond 3.7 μ m.

The PG quasars, selected via their ultraviolet excess, are thought to properly represent the relative numbers of radio "loud" and "quiet" quasars. We have found that the flat spectrum radio loud quasars show a smooth extrapolation of their energy distributions from the radio through the infrared to the optical and UV, and this radiation can be attributed to synchrotron emission, optically thick at millimeter wavelengths, but becoming more optically thin at submillimeter and shorter infrared wavelengths.

The steep spectrum radio loud quasars and the vast majority of quasars, the radio quiet quasars, show quite similar energy distributions in the infrared, optical, UV, and X-ray. This energy distribution can be described as consisting of two broad peaks in the infrared and UV, with a shallow minimum between them that always occurs at 1 μ m in the object's rest frame. The UV peak, the "big blue bump" occurs between 0.3 and 0.003 μ m, while the infrared peak is found between 1.5 and 100 μ m. Beyond 100 μ m the flux emitted by the quasars drops sharply to a low level, often not detected until centimeter wavelengths. The infrared bump typically carries 10 - 20% of the energy output of the quasar, which is dominated by the "big blue bump". In a few cases, most notably PG 0157+00 and PG 1351+64, the infrared output represents the bulk of the luminosity emitted.

The UV peak is most often attributed to emission from the accretion disk of the quasar, i.e. gas within tens of AUs of the central (black hole) power source. We believe that the most natural explanation of the infrared emission is thermal radiation by dust grains heated by the central accretion disk, and lying at distances of ~ 1 pc to ~ 2 kpc from the power source. The hottest dust, at distances of ~ 1 pc from the accretion disk, and at distance commonly associated with gas moving at many thousands of Km/s (the broad line gas), is radiating at temperatures of 1000 - 1500 K. The material that is emitting at 10 μ m is radiating at temperatures of 100-200K, and is at distances of tens of pc from the power source. This dust is most likely associated with the "narrow line" gas found in quasar. The dust that radiates at 100 μ m is found at a temperature of ~ 50 K at a distance of 1-2 Kpc from the central source, and must be associated with the interstellar medium of the host galaxy. The relatively constant short wavelength cutoff of the infrared peak, at 1.5 - 2 μ m, suggests a common physical process, which we identify with the sublimation of dust at temperatures above 1500K, while the fraction of the total luminosity emitted in the infrared measures the dust covering factor, and is typically 10-20%. We estimate that the mass of dust required to produce the infrared emission, $\sim 0.01 M_{\odot}$ for the hottest dust, and $10^5 M_{\odot}$ for the coldest dust, is quite consistent with the amount of gas found in these environments and the known fractional abundance of dust to gas.

We believe that the continuity in the energy distributions between the Ultraluminous Infrared Galaxies, the "warm" ultraluminous infrared galaxies, and the UV excess (PG) quasars strengthens the connection we previously suggested between these classes of objects, that of an evolutionary sequence where quasars begin as dust enshrouded ultraluminous infrared galaxies, and emerge from their "cocoons" as the central quasar disrupts the environment. We believe that the UV excess quasars, the last stage in this process, are showing the vestiges of their previous dust cocoons.

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Very High Redshift Elliptical Galaxies.

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Subject Heading: Galaxies and Quasars

During the last four years Rogier Windhorst (Arizona State University, previously at Mount Wilson and Las Campanas Observatories) and David Koo (Lick Observatory) have carried out an extensive project of deep CCD imaging on various ultra-deep radio survey fields, for which also very accurate VLA positions were available. In 15 dark nights with the Palomar 200 inch Four-shooter, they imaged a complete sample of 450 weak radio sources in 2.5 deg^2 down to levels as faint as ~ 26.5 mag (in the filters Gunn g and r), while in 3 grey nights they imaged a complete sub-sample at far-red wavelengths down to ~ 25 mag (in Gunn i). The data processing of this gigantic data set is nearing completion now. The identification fraction is over 90% down to $V=25.5$, and 100% down to 26.5 mag (Windhorst et al. 1987). This 100% identification fraction rules out that the Universe is heavily obscured by dust at very high redshifts, if the weak radio source population extends significantly beyond redshifts of 3.5. Together with 161 redshift measurements at brighter optical levels (down to $V\sim 24$ mag, and complete to $V\sim 22$ mag), this data set enabled Windhorst and Koo to determine the nature and the spectral evolutionary history of weak radio galaxies out to redshifts of unity. One of their major conclusions is that weak radio galaxies form over a wide range in cosmic time, and evolve through subsequent repeated starbursts, induced by dynamical events like merging and interaction.

Because the radio sample is now completely optically identified, there is no bias in the Windhorst and Koo sample other than their selection as radio sources. Since the radio luminosity function and the radio source redshift distribution are rather well known, the sample can be corrected for this bias. In addition, the microJansky radio limit can trace giant ellipticals out to redshifts >10 . Hence, the radio selection will pick out all ordinary elliptical galaxies at these limits, and provides a unique opportunity to study a complete sample of very high redshift ($z \gg 1$) giant elliptical galaxy candidates. From their Hubble diagram of 161 radio galaxies with $V < 24$ mag, Windhorst and Koo estimate that the sample has about two hundred radio galaxy candidates with redshifts well beyond unity ($V > 23.5$ mag). Since 1987, Windhorst and Koo therefore concentrated their spectroscopy on the best candidates for very high redshift giant elliptical galaxies. These galaxies were selected from their radio properties, their high optical surface brightness, and their Four-shooter colors, and occasionally deep IR photometry or imaging.

During the summer of 1988, Windhorst et al. spend four nights with the Kitt Peak 4 meter Cryocam and the Multiple Mirror Telescope (MMT) at Mount Hopkins to measure a redshift of 2.389 for HERC202, which they believe is a normal elliptical galaxy with current age of 14-15 Gyr, but seen 1-2 Gyr after its turnaround from the Hubble expansion. It was selected from their ultra-deep VLA-Fourshooter survey as the faint ($V=23.5$), high surface brightness optical counterpart of a weak, steep spectrum radio source. At brighter optical levels these are exclusively associated with passively evolving giant ellipticals at $z < 1$ (Kron et al. 1985). Long integrations with the Palomar IR systems showed that this galaxy has fairly blue optical-IR colors, which does not imply strong evolution, but is simply consistent with a passively evolving stellar population seen at $z \sim 2.4$ (Windhorst 1986). In 72,000 sec with the MMT and the 4 meter Cryocam, Windhorst et al. secured the redshift for this object: in two nights with the MMT, they found the extraordinary weak ($EW < 100 \text{ \AA}$) and narrow ($< \text{few } 100 \text{ km/sec}$ in the restframe) emission lines of Ly- α and N-V, and with the Cryocam they confirmed its redshift of 2.389 through even weaker lines of CIV, CIII and possibly CII and HeII (Windhorst et al. 1988). The image of HERC202 is quite compact ($\text{FWHM} \sim 1.4''$), and its overall extent at $z=2.389$ corresponds to a size of 25-30 kpc. The slopes of its optical-IR spectrum are consistent with the ultraviolet spectra of nearby ellipticals, some of which show the same weak lines. Windhorst and Koo believe that HERC202 is the closest one can get with the current technology to find (nearly) normal giant elliptical galaxies at very high redshifts. A deep Lick narrow band image (in the redshifted Ly- α line) showed several very faint, low surface brightness structures

surrounding HERC202 not visible in the continuum. Windhorst and Koo believe that HERC202 is a young, but otherwise normal giant elliptical galaxy surrounded by a forming proto-cluster of very low surface brightness protogalaxies.

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A New Survey for Damped Lyman-alpha Absorption Systems

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Subject Heading: Galaxies and Quasars

In this investigation we are using a new technique to find the progenitors of galaxies. The idea is to look back in time, some 15 Gyr, to epochs when the universe was about 10 percent of its current age and detect objects which are likely to be protogalaxies; i.e., galaxies in the earliest stages of evolution. Until recently protogalaxies have not been observed directly. The only information that we have about the galactic past stems instead from indirect evidence inferred from old stars in our own Galaxy. The classic study of Eggen, Lynden-Bell, and Sandage(1961) indicates that long ago the Galaxy was a huge slowly spinning sphere of gas that collapsed under its own weight. The first generation of stars, which formed out of gas in the sphere, did not collapse along with the gas since there is no way for stars to dissipate the energy of their orbits. Today these are the population II stars that occupy a vast spherical halo surrounding the disk of the Galaxy. On the other hand the gas falls inward, because it can dissipate the kinetic energy of collapse through radiation emitted behind shock waves. As it collapses the gas spins more rapidly owing to conservation of angular momentum until it reaches an equilibrium structure; i.e., the centrifugally supported disk that we see today. After collapse is completed, stars begin to form, enriching the disk with heavy heavy elements as time goes by. Elements such as carbon, oxygen, silicon, and magnesium are formed from nuclear fusion processes that occur in hot stellar cores. Chemically enriched gas is ejected into the interstellar medium when the stars die in supernova explosions. Because the next generation of stars form out of gas enriched in heavy elements, further cycles of stellar births and deaths cause the average element abundance of the disk to increase to its present value.

This scenario, the widely accepted "standard picture" for the formation of the Galaxy, has never been tested directly. The problem is that the events described above are predicted to occur so long ago that light emitted by stars which inhabit the protogalaxy is too faint to detect. We have devised a method for discovering protogalactic disks, which does not rely on detecting starlight, but rather focuses on the gas. The idea is to detect the gaseous disk in absorption against the bright light emitted by even more distant quasars. The quasar light is absorbed at discrete wavelengths corresponding to atomic transitions of abundant elements in the gas. Since the depth of the absorption lines is comparable to the brightness of the quasar, the lines are easy to detect. Due to the large amount of cold neutral hydrogen that characterizes galactic disks, the principal spectroscopic imprint that the gas leaves on the radiation is a very strong damped Lyman alpha, i.e. $\text{Ly}\alpha$, absorption line. Lyman alpha is the strong atomic transition that arises between the ground and first excited atomic states of atomic hydrogen. When the number of hydrogen atoms along the line of sight is sufficiently high, the $\text{Ly}\alpha$ line develops extensive wings (see fig. 1) owing to a line broadening mechanism called radiation broadening. Because they are less abundant than hydrogen, the heavy elements create absorption lines which are much weaker than $\text{Ly}\alpha$. The presence of strong $\text{Ly}\alpha$ and much weaker heavy-element lines (see fig. 1) is a unique signature that distinguishes galactic disks from other types of gaseous clouds that populate the distant universe.

A few years ago we began a survey for these "damped" $\text{Ly}\alpha$ absorption systems. Our preliminary results were very interesting (Wolfe *et al.* 1986). First we found 5 times the number of predicted gaseous disks of ordinary spiral galaxies. Secondly the mass per unit volume contained in the damped systems dominates the

matter content of the distant universe. Moreover, it is comparable to the mass of stellar disks in nearby spiral galaxies. Third detailed spectroscopic studies of 16 absorptions systems showed that they exhibit the physical conditions found in the gaseous disks of nearby galaxies. In one system we found a radio absorption line, the 21 cm line, that arises in the a spin-flip transition in the hydrogen ground state (Wolfe *et al.* 1985). A recent study with a very long baseline interferometer, i.e., a world wide array of radio telescopes, shows that the gas is a disk-like structure with a transverse dimension comparable to that of a galaxy (Briggs *et al.* 1988).

For these reasons it was suggested that the damped Ly α systems are the progenitors of disks of stars and gas in ordinary spiral galaxies (Wolfe 1988). In order to explore the implications of this idea, we started a survey at Palomar for new damped Ly α absorption systems. The new survey is designed to (a) more than triple the existing sample of damped systems, (b) probe further back in time, and (c) include radio-bright quasars as background sources. With a prospective sample of ~ 60 damped Ly α absorption systems it will be possible to address several issues for the first time. For example, the distribution of objects with look-back time will indicate how they evolve into current galaxies. Furthermore by probing further back in time we can detect protodisks at an earlier phase of evolution, perhaps at the epoch of disk formation. In addition we have included radio-bright quasars in the survey in order to find new 21 cm lines in the same gas which creates damped Ly α lines. Radio interferometer maps in the 21 cm line are powerful diagnostic tools for measuring the spatial extent of the gas transverse to the line of sight.

Our two runs at Palomar resulted in the detection of 3 confirmed damped Ly α absorption systems in front of 2 bright radio sources. We will search for the corresponding 21 absorption lines with the Arecibo radio telescope. In combination with an analogous survey carried out by Sargent, Steidel, and Boksenberg (1988), and a search by ourselves with the 100 inch telescope at Las Campanas we have found a total of ~ 30 absorption features which are *candidates* for damped Ly α lines. We are now involved in a program of detailed spectroscopy which will test whether or not these are damped Ly α lines. Preliminary estimates indicate that incidence of the new systems is consistent with our previous result.

Our results suggest that the standard picture for the formation of galactic disks needs to be changed. First the large number of damped systems indicates that protogalactic disks were considerably large than current disks. Apparently the collapse of the protogalaxy is a two stage affair. the gaseous sphere collapses into a giant disk-like structure, a damped Ly α system, which then contracts in the plane to its current size. Secondly, the existence of large gaseous disks at early times is difficult to understand in the context of currently popular theories of galaxy formation. The "cold dark matter model" in particular predicts frequent galaxy-galaxy interactions that result in disk destruction. That is, in these models disk formation occurs later than the epochs at which the damped Ly α systems have been observed.

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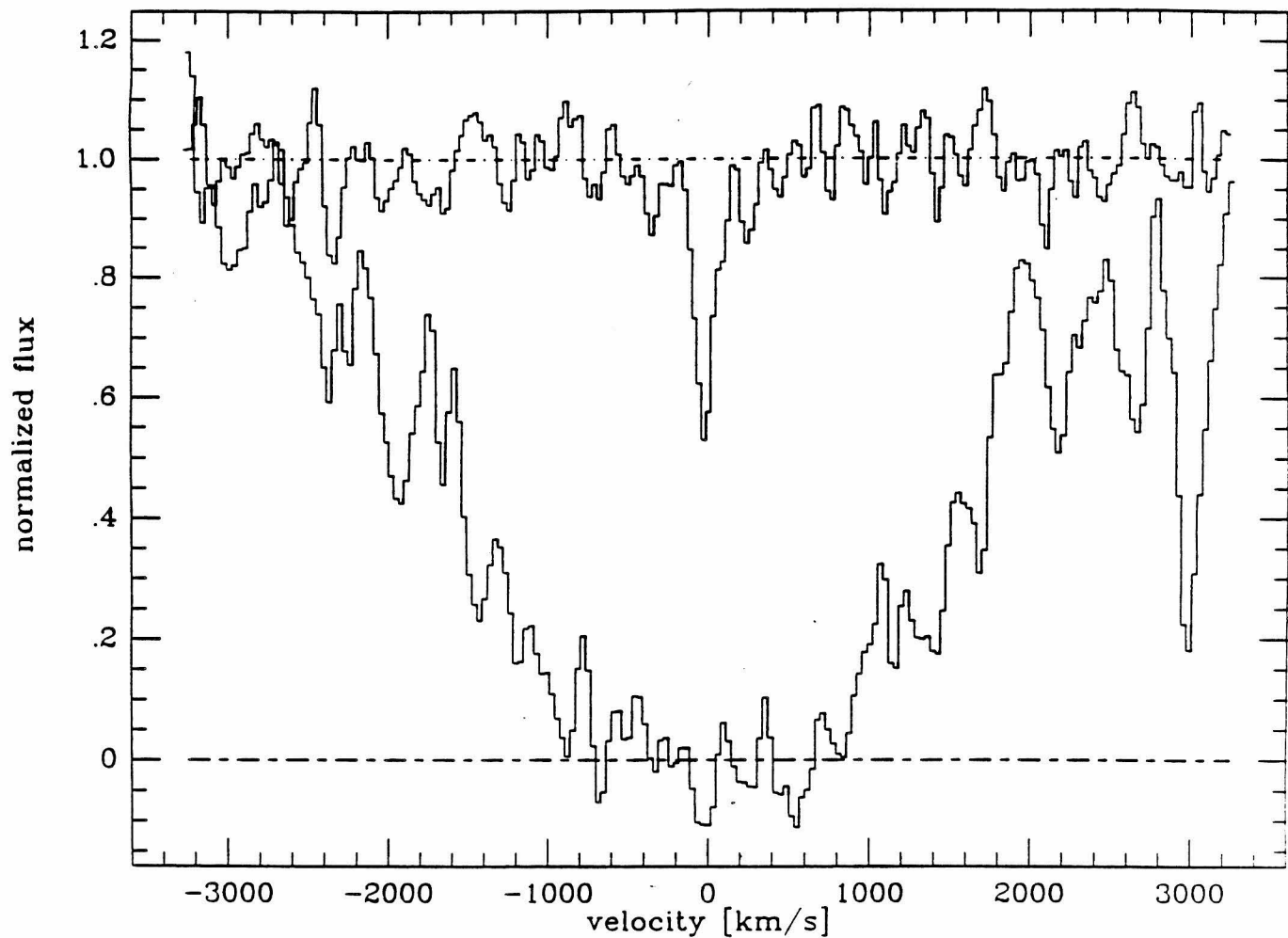


Fig.1: Comparison between damped Ly α line and atomic transition arising in singly ionised carbon. The x axis is Doppler velocity with respect to the mean velocity of the absorption system. The wide feature centered at $v=0$ is Ly α , and the narrow feature centered at $v=0$ is the carbon line.

INTERSTELLAR MEDIUM

Interaction of a Pulsar with an Old Supernova Remnant

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Subject Heading: Interstellar Medium

The peculiar nebula CTB 80 has long puzzled astronomers. While it clearly shows emission that in some respects is characteristic of supernova remnants (what is left over after a massive star explodes, releasing an enormous amount of energy), the morphology of CTB 80 does not fit into any known class of these objects. We became especially interested in CTB 80 when a rapidly rotating pulsar – the collapsed stellar remnant left behind by the supernova explosion – was discovered in the nebula. By obtaining very deep images of the nebula through filters which isolate light emitted by various types of ionic species, and following up these observations by obtaining spectra at a few key locations, we were able to determine that the emission from this object was definitely excited by interstellar shock fronts. In addition to spinning rapidly, pulsars have strong magnetic fields. These fields are “wrapped up” by the spinning neutron star in a way that causes them to carry energy away from the pulsar. In other words, the rotational energy of the pulsar is slowly drained off as the pulsar generates a wind of highly energetic particles and electromagnetic waves. Astronomers have for a long time worried about how the energy dissipated in this way interacts with surrounding material. The energy which we identified as being dissipated by the observed shocks in CTB 80 was nearly equal (within a factor of 2) to the energy being lost by the pulsar as it gradually slowed down. Hence we had identified a new class of object – a “Pulsar Wind Nebula” – in which the spin down energy of the pulsar goes directly into doing mechanical work on the interstellar medium through which the pulsar is travelling.

CTB 80
H α



SOLAR SYSTEM STUDIES

SOLAR SYSTEM

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This year 239 new asteroids have been discovered during the Planet-Crossing Asteroid Survey's (PCAS) monthly observing runs at Palomar Observatory. Of particular interest, are three Near-Earth Asteroids (NEA), Apollo 1988 EG and two Amors, 1987 QB and 1988 PA. To date (calendar '88), 1988 EG and 1988 PA are the only near-Earth asteroid discoveries found worldwide, although the search activity for these rare objects has increased substantially. In addition, about 40 high-inclination objects, 15 Mars-crossing asteroids and inner-belt region objects: 6 Hungarias and 13 Phocaeas have been found. Since 1982, we have more than doubled the known number of these intriguing asteroids which seem to be precursors to the near-Earth asteroids and probably number among them, a few degassed comets. Short-period comet 1987w (P/Comet Helin) was found on the photographic plates taken on August 24 and 26 for the Palomar Sky Survey II. On discovery, it displayed prograde motion and an intricate tail of about 8 arcsec. It has a semi-major axis ($a = 5.8$ AU), eccentricity ($e = 0.56$), and a low inclination ($i = 4.7^\circ$). It travels in an elliptical orbit that takes it from beyond the orbit of Mars (perihelion $q = 2.5$ AU) to the vicinity of the orbit of Saturn (aphelion $Q = 9.3$ AU). The obvious primary influences on comet 1987w are Jupiter and Saturn. Therefore, it may have suffered major effects with repeated encounters suggesting that 1987w may have been captured into its present orbit as a result of the two-planet interaction. With a short period of 14.5 years, comet 1987w will next be observable in 2001.

Of special note are the number of recoveries of PCAS discovered asteroids. Amor asteroid, 1982 XB, was recovered in November, 1987. These observations refined its orbit sufficiently well that it was possible to acquire this tiny asteroid of only 350 meters by radar from Arecibo (S. Ostro, JPL). These radar results ensure its future recovery over the next 25 years. This asteroid has been identified by C. Lau and N. Hulkower (JPL) as a prime mission candidate based on its low delta V (5.2km/sec) requirement for rendezvous. There are thirteen opportunities between 1990 and 2010, the most favorable in 1992, 1997, 2002 and 2007. With its recent recovery data and resultant well-established orbit, it has been officially numbered (3757). Two other very faint NEA's, 1986 LA and 1986 PA have been recovered. They are two of the smallest objects of the some 110 known near-Earth asteroids. Our PCAS Amor, 1985 DO2 was recovered in August, 1988. Physical observations from Mauna Kea indicate it is very unusual and is thought to be similar in composition to (2)Pallas. Unique Mars-crosser, (3800) 1984 AB, and strong Mars-crosser, (3737) 1983 PA were recovered and numbered this year also.

Earth-crossing Apollo, 1988 EG, was discovered March 9, 1988 after it had already made its closest approach to the Earth on February 26 at 0.040 AU (6 million Kilometers/about 4 million miles) and was already moving away from us. It travels in an orbit that takes it inside the orbit of Venus

(perihelion distance of 0.64 AU) to beyond the orbit of Mars, (at aphelion of 1.90 AU). It has an inclination of 3.5 degrees to the ecliptic and has an orbital period of 1.4 years. The circumstances of discovery were fortuitous since this small body makes a favorable approach for observation to the Earth only once every ten years. 1988 EG has been observed over a two-month period which ensures the asteroid's recovery with the use of large telescopes in mid-1990 and the spring of 1991.

The most recent discovery, Amor asteroid 1988 PA has been observed for 2 months. A preliminary assessment suggests that with its small orbit, modest eccentricity, and a low inclination, it ranks among the first dozen or so mission candidates with low delta V requirements presently available for future spacecraft missions.

Solar System Studies
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It has been known for over a decade that methane frost is a major surface constituent on Pluto. Recent observations suggest that the surfaces of these two objects are quite different with most, if not all, of the methane frost probably residing on Pluto.

The presently underway mutual eclipse series provides us with an opportunity, not to be repeated for over a century, to determine compositional differences between Pluto and Charon and a crude distribution of methane on the surfaces of these bodies. By observing the variation in near infrared color at wavelengths particularly sensitive to the presence and absence of methane (at $2.0\ \mu\text{m}$ and $2.2\ \mu\text{m}$) during a mutual eclipse event, it is possible to infer the crude distribution of methane on the surface of the occulted body. The spatial resolution achievable using this technique is much greater than can be achieved even by using the Hubble Space Telescope.

In 1988, Matthews, Soifer and Tedesco (JPL), were assigned two half nights on the 200-inch telescope to observe events of Pluto occulting Charon and Charon occulting Pluto. During both events, the southern hemispheres of the bodies were occulted. Excellent data was obtained during both events. These data are currently being analysed to determine if any variation can be detected in the surface coverage of methane on the surface of Pluto and Charon, however, it is clear that no dramatic variations in color, indicative of changes in the surface coverage, were detected.

In another Solar System program, Matthews and Soifer observed another occultation by the Neptune system of a background star at $2.2\ \mu\text{m}$ using the 200-inch telescope. These occultations are used to search for the arc rings previously detected in stellar occultations by Neptune. The rate of occurrence of an arc ring occulting the star is about one in ten events. In the July 88 event no ring occultation occurred.

Asteroid and Comet Flux in the Neighborhood of the Earth

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Subject Heading: Solar System

Significant advances in our knowledge and understanding of the flux of large solid objects in the neighborhood of Earth have made in the last ten years. We present here our best estimates of the collision rates with Earth of asteroids and comets and the corresponding production of impact craters.

Approximately 80 Earth-crossing asteroids have been discovered through May 1988. The rate of discovery increased to 8 per year in 1986 and 1987, more than double the previous 10-year average. As shown by this high rate, the discovery of Earth crossers is far from complete. Among 42 new Earth-crossing asteroids found in the last decade, two-thirds were discovered from observations at Palomar Observatory, and 15 were discovered or independently detected in dedicated surveys with the Palomar 46-cm Schmidt. On the basis of these latter observations and 6 discoveries made in a prior survey using the 46-cm Schmidt, we estimate that the population of Earth crossers brighter than absolute V magnitude (H) of 17.7 (diameter typically about 1 km) is about 1100. The estimated populations of each orbital type, based on the proportions of known objects brighter than mag 17.7, is as follows:

	Number Discovered	Percent Discovered	Estimated Population
Atens	4	(5)	80 $\pm$ 50
Apollos	36	5.1	700 $\pm$ 300
Earth-crossing Amors	15	(5)	300 $\pm$ 150
Total Earth crossers	55	5	1080 $\pm$ 500

Probabilities of collision with Earth have been calculated for about two-thirds of the known Earth-crossing asteroids by the method of Shoemaker et al. [1]; the mean of the calculated collision probabilities is 0.49 per 100 million years. When multiplied by the estimated population of Earth crossers to magnitude 17.7, this yields an estimated present rate of collision with Earth of 5.2 ± 2.5 per million years. This estimate is about 65% higher than that reported in [1], owing chiefly to the discovery in the last 10 years of several asteroids with unusually high probabilities of collision. When improved data on the proportion of S (bright) and C (dark) asteroids, the distribution of impact speeds, and the theoretical distribution of angles of impact are taken into account, we estimate from the above collision rate that the production of asteroid impact craters larger than 10 km in diameter is 1.6 per million square km per 100 million years, somewhat lower than that given in [1] and [2].

Present evidence indicates that the discovery of Earth-crossing asteroids is essentially complete at $H=13$ (diameters about 8 km), close to the magnitude

of the brightest known objects. Because the completeness of discovery declines for fainter objects, the magnitude-frequency distribution of the population can only be inferred from indirect evidence. For Earth crossers fainter than mag 15 (diameters about 3 km), the slope of the magnitude-frequency distribution is assumed to be similar to that of main belt asteroids. If so, the frequency evidently drops precipitously for objects brighter than mag 15. In this model, the collision rate with Earth of Earth-crossing asteroids with diameters greater than 3 km is about 3 per 10 million years; the collision rate of asteroids roughly 8 km in diameter and larger is about 5 per billion years.

Spectrophotometric data obtained chiefly in the last decade show that the large majority of observed Earth crossers are similar to asteroids found in the inner part of the main belt. The combination of asteroid-asteroid collisions in the main belt, resonant perturbations of the orbits of collision fragments, and further perturbation of asteroid fragments by encounters with Mars appears adequate to replace losses of Earth-crossing asteroids due to collisions with planets as well as ejection from the solar system. The population of Earth crossers probably has remained steady within about $\pm 5\%$ through most of the last 3 billion years [3].

The number of discovered Earth-crossing comets is more than 4 times greater than the number of known Earth-crossing asteroids, but reliable data on the sizes of comet nuclei are sparse. Photographic observations of comets, obtained when they were relatively far from the sun, and the record of comet discoveries have been used to estimate the magnitude-frequency distribution and flux of the nuclei [4]. The near-Earth flux is found to be dominated by long period comets. After correcting the observations for the presence of unresolved coma, the estimated present rate of collision with the Earth of comet nuclei brighter than absolute B magnitude 18 is about one per 10 million years.

Several lines of evidence suggest that the albedos of comet nuclei generally are very low; this inference has been confirmed from spacecraft images of the nucleus of periodic comet Halley. Adopting a geometric albedo of 0.03 in the B band [4], we calculate the diameter of comet nuclei to be 2.5 km at absolute B magnitude 18 and 10 km at mag 15. At the rms speed of 57.7 km sec^{-1} , found for long period comets, and a typical angle of impact of 45° , comet nuclei of B magnitude 18 are estimated to produce craters 40 to 50 km in diameter, if their densities are in the range of 0.5 to 1.2 gm per cubic cm.

At the present comet flux, the estimated rate of collision with Earth of comet nuclei greater than 10 km diameter is once per 100 million years, and the corresponding mean rate at which these objects pass the Earth at a distance of 4.67 million km (0.0312 AU), the miss distance of comet IRAS-Araki-Alcock (1983 VIII), is about once per 200 years. The mean diameter of the elongate nucleus of IRAS-Araki-Alcock, determined from radar and infrared observations, is 9.3 km [5]. We conclude that the close approach of this large comet, during the 20-year period in which the radar observations of its nucleus could have been made, either was a stroke of luck (probability ~ 0.1) or our estimate of the present flux of comets about 10 km in diameter is conservative.

The flux of comets almost certainly has been highly variable over late geologic time, owing to the random perturbation of the Oort comet cloud by stars in the solar neighborhood. Monte Carlo studies suggest that surges in the near-Earth flux from 3 to more than 30 times the mean background occurred at typical intervals of a few tens of millions of years. The majority of comet impacts probably occurred during these surges or comet showers.

The record of terrestrial impact craters and impact glass suggests that a mild comet shower may have occurred at 35 million years ago, and a weak shower may have peaked at about one million years ago [6]. On the basis of bounds on the total crater production set by the crater record of the Moon, we suggest that the present comet flux is about twice the mean background for the last billion years. During the last few hundred million years, the mean rate of collision with the Earth of 10-km-diameter and larger objects capable of producing craters larger than ~150 km in diameter may have been about 1 to 2 per 100 million years. Production of these giant craters probably was dominated by comet impact.

Our best estimate of the production of impact craters on Earth over the last 100 million years is as follows:

	Crater Diameters						
	>10 km	>20 km	>30 km	>50 km	>60 km	>100 km	>150 km
Asteroid impacts	820	180	73	10	4.5	0.3	0
Comet impacts	(270)	60	24	8	5.3	1.7	1
Total crater production	(1090)	240	97	18	10	2	1

The uncertainty to be attached to each of the above figures is at least a factor of 2. The estimated total cratering rate to 20-km crater diameter is 4.7 ± 2 per million square km per billion years, which is very close to the rate of 5.4 ± 2.7 per million square km per billion years estimated by Grieve [7] from the geologic record of impact for the last 120 million years. The mean time interval between formation of craters about 100 km diameter is comparable with the interval between major mass extinctions of species.

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STARS

Multicolor CCD Surveys for Faint Quasars

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Subject Heading: Galaxies and Quasars

Anderson and Schechter (MWLCO), in collaboration with Windhorst (ASU) and Koo (UCSC), are conducting surveys for very faint quasars. Using the Four Shooter on the Palomar 5m, deep multicolor CCD images are taken through Johnson B and Gunn g, r, and i filters. These multicolor images allow for the selection of quasar samples to a magnitude as faint as $B < 24.5$. This multicolor selection approach is similar to the photographic technique recently used by Warren et al. (1987) to select several quasars with redshifts $z > 4$. The multicolor technique, however, can be used to select "complete" quasar samples over a very wide redshift range. Normal stars occupy a small, well-defined volume in multicolor space, while quasars, having power-law continuous spectra and emission lines, occupy regions in the multicolor space which are far from the stellar sequence. A primary limitation of the use of photographic plates is the difficulty in obtaining high photometric accuracy at very faint magnitudes: photometric errors artificially broaden the intrinsic "width" of the stellar sequence in multicolor space, making it increasingly difficult to separate quasars from stars. CCD's, on the other hand, are well suited to achieving high photometric accuracy to quite faint magnitudes. The Four Shooter (an imaging device incorporating four, 800X800 pixel TI CCD's) attached to the Palomar 5m is an ideal instrument for the faint quasar surveys because it affords large areal sky coverage ($8.5' \times 8.5'$), as well as the requisite photometric accuracy.

Initially, Anderson and Schechter imaged two fields with the Four Shooter to $B < 22.5$. One of these fields overlaps with the Selected Area no. 57 field (hereafter, SA 57) previously surveyed (photographically) for faint quasars by Koo, Kron, and collaborators, (e.g., Koo and Kron 1988). This initial Four Shooter survey in SA 57 has been used as a test-field to investigate and calibrate the utility of accurate, multicolor CCD photometry in distinguishing quasars from stars. Results from this field confirm the viability of the approach, and a preliminary report on this work is in press (Anderson and Schechter 1989). The second field surveyed to $B < 22.5$ will provide a new, additional sample of faint quasars. This second field was also previously

Speckle Interferometry of Protostars
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Subject Heading: Stars

The planets and other small bodies in the Solar System condensed from a disk of gas and dust encircling the Sun in the first few ten million years or so of its early life. The same process is occurring throughout the Galaxy around newly born stars today, and by observing the conditions surrounding these stars, we gain insight into the circumstances giving rise to the formation of our own planetary system. In fact, it is only from the study of other young stars that we can hope to understand the structure of the primitive solar disk.

Beckwith, Koresko, Matthews, and Neugebauer began a program to image the circumstellar regions around newly born stars using the technique of infrared speckle interferometry. The goal is to obtain infrared pictures of about a dozen nearby stars with enough resolution to see structure at scales corresponding to the size of the outer Solar System, approximately 100 AU. At the distance of even the closest objects, 100 AU corresponds to an angle less than 0.5 seconds of arc, an angle blurred by the Earth's atmosphere in a process known as "seeing", and the resolution enhancement provided by speckle interferometry is necessary to carry out the program.

The first infrared speckle observations made in 1987 December achieved an angular resolution of 0.2". Figure 1 shows the binary star ω Leo clearly resolved into distinct components. The separation of the two stars is 0.3", much smaller than the 1" seeing during the observations. The 200 inch telescope provides an exceptionally stable environment with good quality optics which should make it possible to refine the resolution to 0.1" with somewhat modified instrumentation.

Figure 2 is a one dimensional image of BN Orionis, a protostar in the Orion nebula. Light from the star itself is a central maximum which extends above the top of the figure. A pedestal of emission extends from the base of the central source approximately 0.5" on either side of the star. This pedestal is light reflected by small particles, particles which may be orbiting the star or falling onto a disk of the sort giving rise to planetary formation. The region seen in this figure is approximately 500 AU across, roughly five times the diameter of Pluto's orbit.

BN Orionis is one of a dozen stars which the group will observe using the speckle imaging technique. Future observations will combine a series of the one-dimensional images shown above to create a complete two-dimensional picture by a process called tomography. From the two-dimensional light distributions, the distributions of small particles may be calculated and compared with theories for disk formation, such as was done for the widely publicized star β Pictoris by Smith and Terrile (1984).

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Figure 1: A one-dimensional speckle reconstructed image of the binary star ω Leo at $2.2\ \mu\text{m}$ made during a period of $1''$ visual seeing using the 200 inch telescope in December 1987. The horizontal scale is labeled in seconds of arc; the vertical scale is labeled in arbitrary units. The separation of the stars is $0.3''$; the angular resolution achieved here is $0.2''$.

Figure 2: A 1D speckle reconstructed image of BN Ori at $2.2\ \mu\text{m}$ using the 200 inch telescope in December 1987. The vertical scale is expanded to saturate the unresolved central star and show the asymmetric halo which extends $0.5''$ to the southeast (left side of plot). The visual seeing was $\sim 1''$. The resolution of $0.24''$ was limited by the relatively large slit used for the observations.

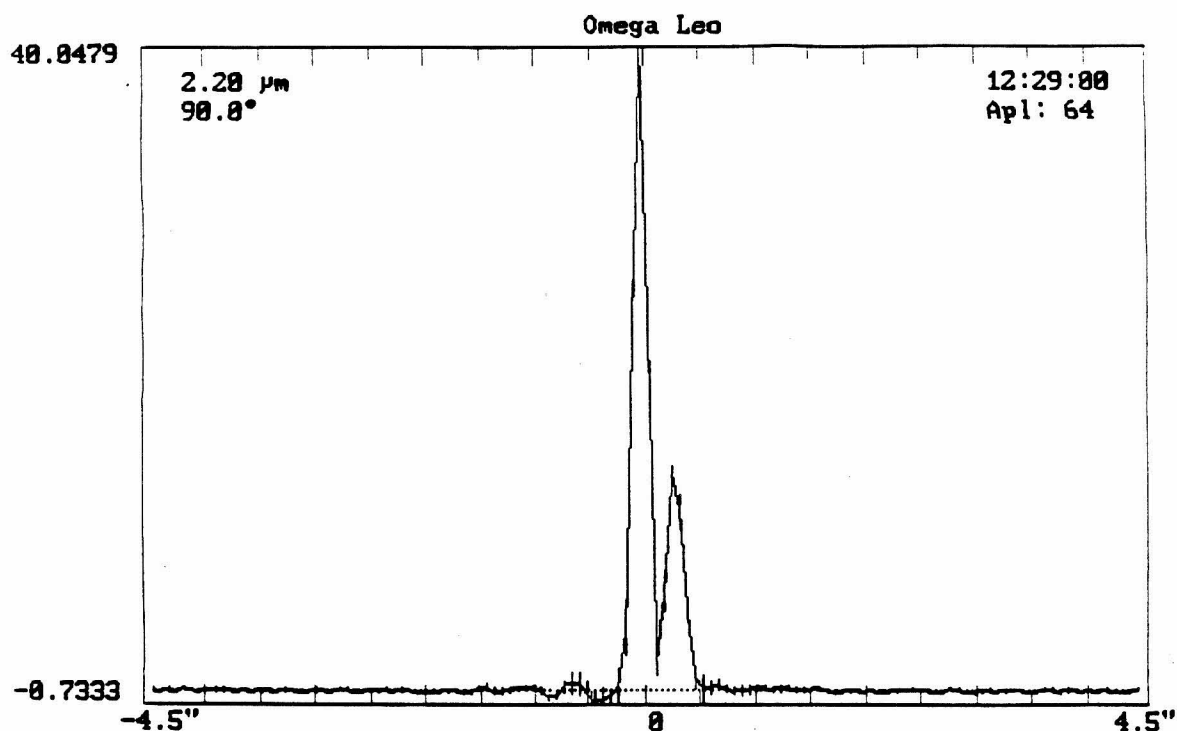


Figure 1: A one-dimensional speckle reconstructed image of the binary star ω Leo at 2.2 μm made during a period of 1" visual seeing using the 200 inch telescope in December 1987. The horizontal scale is labeled in seconds of arc; the vertical scale is labeled in arbitrary units. The separation of the stars is 0.3"; the angular resolution achieved here is 0.2".

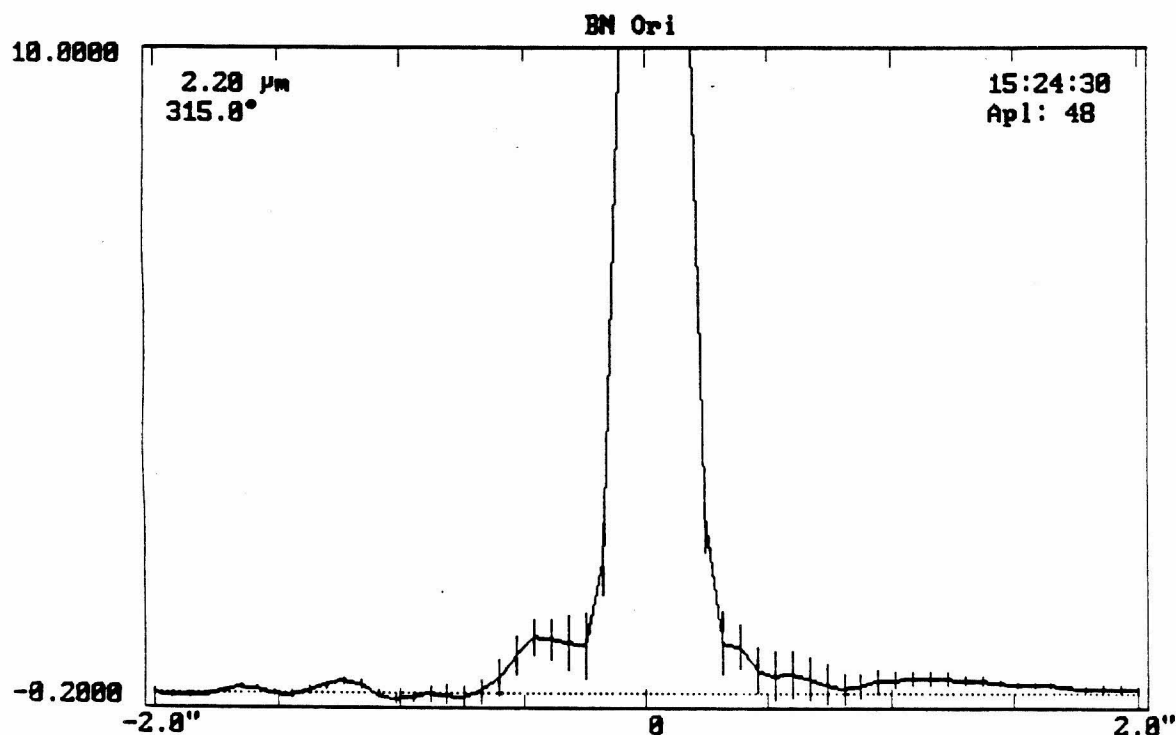


Figure 2: A 1D speckle reconstructed image of BN Ori at 2.2 μm using the 200 inch telescope in December 1987. The vertical scale is expanded to saturate the unresolved central star and show the asymmetric halo which extends 0.5" to the southeast (left side of plot). The visual seeing was $\sim 1''$. The resolution of 0.24" was limited by the relatively large slit used for the observations.

Geometry of the Shell of Nova DQ Her 1934

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Subject heading: Stars

Nova explosions are believed to arise by mass transfer in binary systems where one of the components is a white dwarf which has exhausted its hydrogen. The accreted mass from the second component is hydrogen rich, and it builds up on the surface of the white dwarf, gradually compresses, and if hydrogen burning ignites in a degenerate region, a nova explosion results. This explosion is inherently spherically symmetric, and most nova shells (the shell being the gas blown away during the explosion) appear circular when projected onto the plane of the sky.

Nova shells which are spatially resolved are of great interest because they can be used as distance indicators to the novae themselves via an expansion parallax. For nearby novae in our own galaxy, the objects are sufficiently close that the shells can sometimes be resolved. Such objects are used to calibrate a relationship between the nova luminosity at maximum light and the rate of decline from maximum light. This relationship is in turn used to determine distances to nearby galaxies, since novae are much brighter than Cepheids, and can be detected out to the distance of the Virgo cluster.

In all previous work on the calibration of the maximum luminosity - rate of decline relationship using the expansion parallax of nova shells (including my own, see Cohen 1985), the assumption has been made that the shells are spherical and are uniformly expanding. A careful check of this assumption was made this year for the bright and relatively large shell of nova DQ Her 1934. Many exposures of DQ Her 1934 were taken with the Double Spectrograph at the 200-inch Hale telescope, moving the slit slightly between each exposure so as to cover the entire extent of the shell. The results are a confirmation of the hypothesis of Mustel and Boyarchuk (1970) - the shell is in fact a prolate ellipsoid. A proper geometric model of the shell gives a distance 15% larger than does the simple spherical assumption, a significant change.

Having demonstrated that the non-sphericity of nova shells must be taken into account, future work will concentrate on trying to construct such complete geometric models for a few

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more well resolved nova shells so that the calibration for extragalactic distances based on nova luminosities and light curves can be refined.

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Abundance Variations in Globular Clusters

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subject heading: stars

Judith Cohen (Caltech) and Roger Bell (University of Maryland) have been collaborating on a program to study abundance variations in globular clusters together with Matthew Lehnert, a graduate student at the University of Maryland. Globular clusters are large ensembles of stars in the halo of our galaxy which formed together and which are normally held to be chemically identical. In recent years it has become apparent that some elements formed by nucleosynthesis in the stellar interior in the course of normal stellar evolution are mixed to the surface of the stars. These produce the widespread variations in the abundance of C, N, and O seen among stars in a given globular cluster. However, there have been persistent claims of variations in the heavier elements, which could not have been produced by the normal course of stellar nuclear burning, stellar evolution, and convective mixing, and which therefore must represent primordial variations in the chemical composition of the gas out of which the globular cluster condensed.

The goal of this effort is twofold. First we are trying to determine if in the particular two clusters we are examining (M13 and M22) there are in fact variations among the heavier elements that cannot be explained by canonical models of stellar evolution. If these variations are in fact real, are they correlated with evolutionary stage of the stars? Were such a correlation to be observed then one would infer that the abundance variations are the result of stellar evolution and mixing, and it is the models and mixing theories which are defective. The approach to the second problem has been to pick pairs of stars, one on the normal giant branch (i.e. a star which is burning hydrogen in a thin shell) and one in a later stage of evolution burning helium in a thin shell called an asymptotic giant branch star. Careful comparison between the pairs of stars should tell us how much mixing can be attributed to the normal processes of stellar evolution.

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Very high spectral resolution and high precision spectra are required for this effort. These have been obtained with multiple long exposures with the Double Spectrograph on the 200-inch Hale telescope. The results thus far are as follows: for the first cluster we are looking at (M13) there is no sign of variations in any elements heavier than C, N, or O. In particular, the Ca and Fe abundances are constant from star to star over the sample of ten stars with a dispersion about the mean of 0.08 dex for Ca and 0.04 dex for Fe, which can be attributed to the uncertainties in the abundances. These represent the most precise abundances available to date for globular cluster stars. For the stars in M22, however, there are apparent variations in Ca and Fe which are correlated and which correlate with the variation in CH and CN band strengths. The dispersion in Ca abundance for the ten stars in M22 for which we have spectra is 0.20 dex, while the dispersion in Fe is 0.11 dex, which is larger than the uncertainty in the determination.

The issue is complicated by the strong possibility of variations in interstellar reddening across M22. There the mean reddening is $E(B-V) = 0.36$ mag. A set of photoelectric photometry by Crocker (1988) as well as our color-magnitude diagrams constructed for small areas around each of the ten stars in the sample show variations in reddening which exceed 0.10 mag from one part of the cluster M22 to another. Even worse, the reddening appears to be locally variable (i.e. even the color-magnitude diagrams of the small patches around each sample star show a larger width in color for the principal sequences such as the subgiants, turnoff stars, and giant branch). These reddening variations will be taken into account in a further analysis of the data.

The Binary Millisecond Pulsar System 1957+20

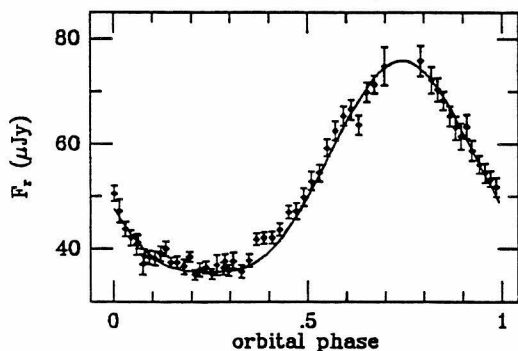
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Subject Heading: Stars

Pulsars (rapidly spinning neutron stars) are one of the possible end stages of stellar evolution, and from the astrophysical viewpoint, perhaps the most interesting and observationally the richest. The current theoretical understanding is that some pulsars are “born twice”: after their initial, normal pulsar spindown, and if the neutron star has a normal binary star companion, it can accrete material from it, spin up, and reappear as a millisecond (ms) pulsar. There are several ms pulsars now known, some in binary systems, and some single: the mystery of their missing companions was a substantial problem for the theory. This scenario got a dramatic confirmation, and the solution of the missing-companion puzzle, in the recent discovery of the binary system 1957+20 (Fruchter *et al.* 1988), in which an ms pulsar has a low-mass companion, which is being ablated by the pulsar beam. The mass of the companion is now only about 20 Jupiter masses, and thus it can be regarded as the first definitive extrasolar planet (albeit it started as a star). The side of the unfortunate companion facing the pulsar should be ablaze, being heated by the pulsar beam, and thus be optically detectable. The optical counterpart has indeed been discovered by Kulkarni *et al.* (1988). The studies of this system can provide crucial insights in the formation and transformation of pulsars and x-ray binaries, and to probe *in situ* the relativistic pulsar wind.

First, we obtained a detailed light curve of the system, shown below. Our data indicate that the originally proposed counterpart is a blend of the real pulsar companion, and an unrelated background star (resolved in our good-seeing images). From our photometry and simple theoretical modeling, and with reasonable estimates of the distance and extinction to the system, we were able to constrain the physical parameters of the companion: photospheric temperature $T_{eff} \simeq 4500^\circ$ K, radius $\sim 10^5$ km, and for its physical state, degenerate hydrogen or solar composition dwarf. The asymmetry of the light curve indicates presence of ablated material accelerated away from the companion.



Light curve (data points) of the PSR 1957+20 system, expressed in linear flux units, plotted *vs.* the orbital phase, derived from the radio observations. The minimum (phase 0.25) corresponds to the pulsar eclipse, when the cold side of the companion is facing us, and the maximum (phase 0.75) is when the heated side is seen face-on. The solid line is our theoretical model for the companion, and the observed asymmetry is due to the swept material (its “cometary tail”). From Djorgovski & Evans (1988).

We then obtained spectra of the system. The companion shines in the continuum light, but there is a clear detection of an $H\alpha$ nebulosity (discovered independently by Kulkarni & Hester), due to the interaction of the pulsar’s jet with the interstellar gas.

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THE INFRARED EXCESS OF G29-38: A BROWN-DWARF OR DUST?

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Subject Heading : Stars

Brown dwarfs are hypothetical bodies with masses which lie in the range between stars and planets ($10^{-1} - 10^{-3} M_{Sun}$). They are too light to ignite thermonuclear burning (i.e. less than $0.08 M_{Sun}$), and therefore they do not qualify as stars. Although brown dwarfs cannot release energy through hydrogen fusion, they will glow in the infrared because they can release gravitational energy as they contract. Finding a brown dwarf would be extremely significant, and the study of such objects would answer important questions such do they contribute to the dark matter in the galaxy, and what is the structure of substellar dwarfs below the hydrogen burning mass limit.

The discovery that the white dwarf G 29-38 has substantial infrared excess emission above what is expected from a single star is the first important result of a survey designed to find cool companions of young white dwarfs (Zuckerman and Becklin 1987a). Previously Zuckerman and Becklin (1987b) had measured the infrared colors of white dwarfs in the young Galactic clusters the Hyades and the Pleiades, and found that none showed excess emission, and so G29-38 is most unusual. The infrared color temperature of the excess is $\approx 1,200 K$, and the emitting area corresponds to a radius of $\approx 7 \times 10^9 cm$ or 0.1 solar radii, which makes G29-38 an excellent candidate for a white dwarf brown dwarf binary system.

The hypothesis that the infrared excess is due to a low mass companion remains viable in the light of new data in the form of infrared spectroscopy and imaging (Togunaga *et al.* 1988), and a detailed study of the spectrum, carried out by Greenstein (1988). But the possibility that the emission is due to many small solid particles or dust grains rather than a single body has not yet been entirely ruled out.

G29-38 is a type of variable star known as a ZZ Ceti star. These stars have periods in the range 200 – 1000 s and a variability in brightness of up to 30 %. G29-38 (ZZ Psc) is one of the brightest and largest amplitude ZZ Ceti stars, a fact which suggests that searching for variability of the infrared excess may be a way to rule out the presence of dust. If the excess emission is due to dust grains heated by the white dwarf, then the dust temperature will respond to optical variations causing a detectable change in the excess at $2.2 \mu m$.

G 29-38 was observed twice in July 1988 at the Hale 5-m telescope. Simultaneous optical ($0.45 \mu m$) and infrared (1.3 and $2.2 \mu m$) photometry was obtained and recorded approximately every 100 s so that variability and periodic behavior could be studied. Figure 1 shows the optical and infrared light curves from July 04 1988. Data at $2.2 \mu m$ was also taken at $10ms$ time resolution — (Figure 2) The optical light curve of G29-38 clearly shows variability, with peak to peak range of 25 %. Variations are seen on a time scale of about 1000s, the pulse shape is irregular, and no clear periodicity is apparent. Variability is also seen at a wavelength of $1.3 \mu m$. The amplitude of the variations is less, $\approx 7\%$ peak to peak, and figure 1 suggests that the variation at $1.3 \mu m$ and $0.45 \mu m$ are correlated. Significant changes in the brightness at $2.2 \mu m$ are seen with a peak to peak amplitude of about 15%. These variations do not appear to be correlated with either $0.45 \mu m$ or $1.3 \mu m$, and the timescale for the variations is faster than the sampling interval. The high time resolution $2.2 \mu m$ data confirm the presence of rapid variability with a peak to peak amplitude of $\approx 20\%$ at this wavelength.

To search the light curves for periodic variations we used a mathematical tool called a periodogram. A periodogram is identical to estimating the harmonic content of a data set by fitting sine and cosine functions to the data. The periodogram for the optical light curve shows the previously known 10 minute period, which led to the classification of G29-39 as a ZZ Ceti variable. At $1.3 \mu m$ exactly the same behavior is seen, while at $2.2 \mu m$ no 10 minute period is seen. At $2.2 \mu m$ the light from G29-38 is dominated by the cool component and therefore this seems to be evidence that the cool component is not effected by changes in the brightness of the white dwarf, ruling out dust.

Although the $2.2 \mu m$ photometry shows no evidence for a 10 minute period there are very strong signals with periods of 3 and 4.5 minutes which are not seen in the optical! We have compared the strength of the 10 minute period at optical and infrared and find excellent agreement, making the presence of faster variation which is seen at only $2.2 \mu m$ even more mystifying.

To understand what is going on we have to look at the white dwarf star in detail. The optical brightness variations of ZZ Ceti stars such as G29-38 are thought to be due to pulsations on the surface of the star. These pulsations do not change the radius or shape of the white dwarf significantly but cause oscillating hot and cold patches to move across the surface. The patches form a regular pattern similar to the construction of a soccer ball.

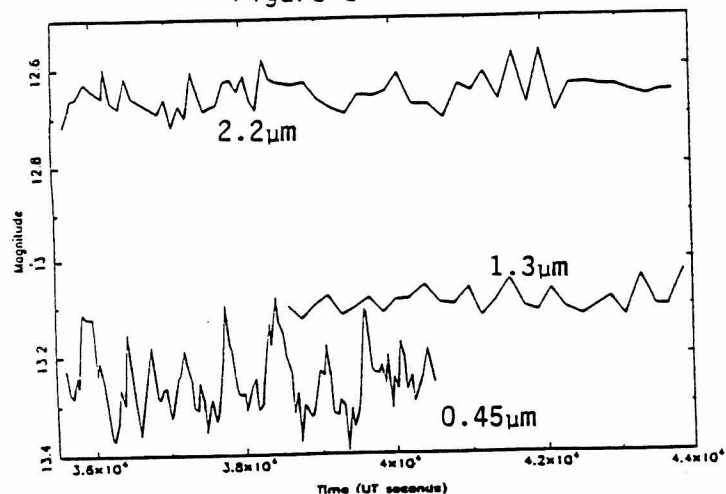
According to theory, the pulsation pattern for the 10 minute period will have an asymmetric distribution about the equator. In the simplest mode the northern hemisphere will be alternately hot and cold, out of phase with the southern hemisphere. The most likely distribution of dust is similar to Saturn's rings, a thin disk. Dust in such a ring alternately heated by the emission from the northern and southern hemispheres so there is no net change in the brightness at $2.2 \mu m$ with a 10 minute period. The temperature pattern for the faster 3 and 4.5 minute periods is most likely *symmetric* about the equator and therefore any dust in a ring will warm up and cool down in phase with the temperature variations on the surface giving an observable signal at $2.2 \mu m$. No optical variations are seen because if the pole is tipped anywhere between 50—70 degrees to the line of sight the 3 and 4.5 minute pulsations cancel out when viewed from a great distance. In conclusion the data on the variability of G29-38 is best explained if the infrared excess is due to a ring of dust heated by the white dwarf, rather than by a brown dwarf companion.

This explanation makes predictions about the variability of the excess as a function of wavelength, and new phenomena, such as the polarization of the light at $2.2 \mu m$. We hope to make future observations which will test these predictions

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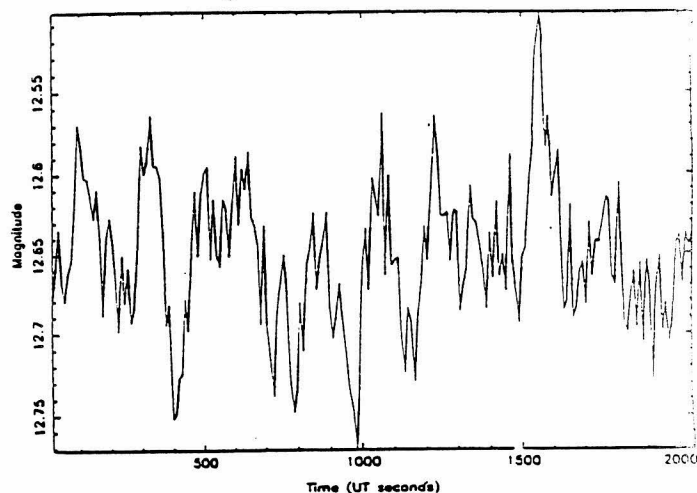
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Figure 1



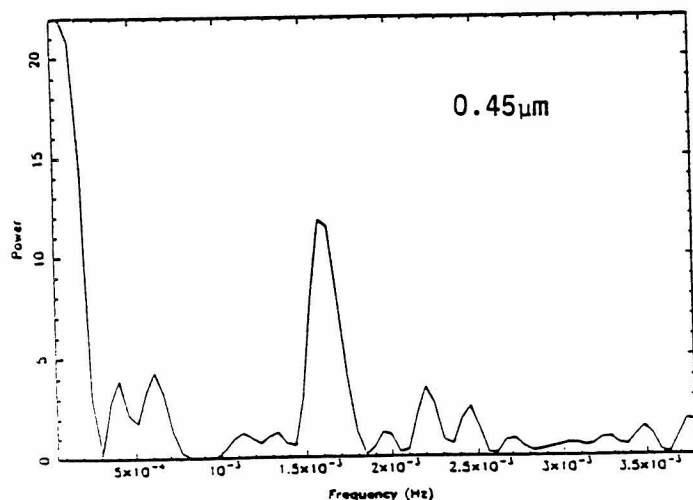
Simultaneous optical ($0.45\mu\text{m}$) and infrared (1.3 and $2.2\mu\text{m}$) light curves for G29-38

Figure 2



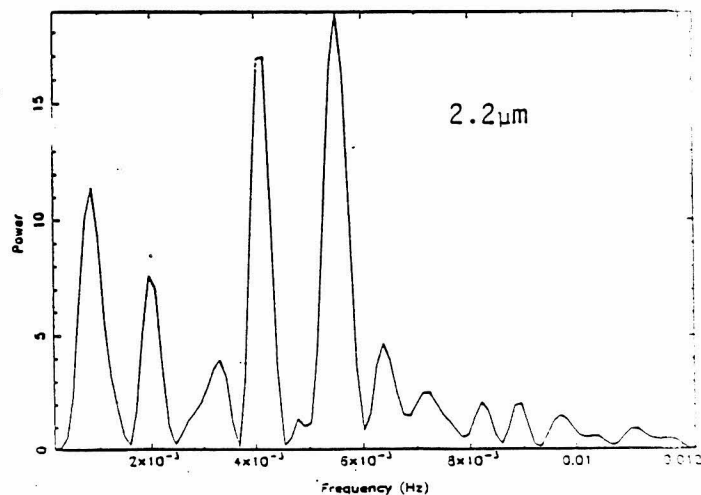
The $2.2\mu\text{m}$ light curve of G29-38 from the "high speed counter".

Figure 3
White Dwarf



The periodogram for the optical data shows a strong signal with a frequency of $1.6 \times 10^{-3} \text{ Hz}$, which corresponds to a period of 10 minutes.

Figure 4
White Dwarf



The periodogram for the infrared $2.2\mu\text{m}$ data shows no 10 minute period, but newly discovered signals with 3 and 4.5 minute periods. These variations found only in the infrared indicate that the excess emission is probably due to dust.

PULSARS and BLACK HOLES

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Coinvestigators: J. Hester, S. Djorgovski, H. Johnston, J. Oke

Subject Heading: Stars

The birth and evolution of neutron stars is one of the most exciting areas in modern astrophysics. Neutron stars are the remnant stars of stars more massive than about ten times that of the sun. As their name implies, neutron stars are made of up of neutrons. These are amongst the densest objects in the Universe. Neutron stars beyond a mass twice that of the Sun collapse and become black holes. Pulsars are rotating, highly magnetized neutron stars which emit pulsed radiation and a A pulsar can be regarded as a giant electrical generator converting its rotational energy into acceleration of electrons and positrons. Neutron stars offer a wonderful natural laboratory to study many kinds of physical phenomena that cannot be studied in the laboratory: physics of ultradense matter, verification of general theory of relativity and physics of dense plasma and intense magnetic fields.

This year has been a particularly exciting year. Using radio telescopes, our group discovered a 40 ms radio pulsar in the confines of the bizaare supernova remnant CTB 80. This is the fifth pulsar-supernova remnant association known to us. The discovery of this pulsar demonsrtates that not all pulsars need be born with large magnetic field strengths. Immediately following the discovery we made several observations of this unusual pulsar at Palomar: spectroscopy of the nebula and searched, with no success, for optical and IR pulsations as well as an optical synchrotron nebula. Our optical observations showed that bulk of the pulsar spin down energy is used to power the nebula that surrounds it.

The pulsar in CTB 80 made us realize that an active pulsar can drive a nebula that is most easily detectable in optical emission lines. Consequently we started a mini-survey of all active pulsars with the hope of discovering additional such nebula. We were pleasantly surprised when we discovered a nebula surrounding the 1.6 ms, binary eclipsing pulsar (see below; Figure 1). This is the first detection of a nebula around an ancient pulsar. Theorists are excited about this discovery since these nebula constitute a new class of nebula.

This year, a group at Princeton announced the discovery of PSR 1957+20 – a 1.6 ms pulsar which is eclipsed every 9 hours. The companion is believed to be a 0.02 solar masses degenerate object. The stream of high energy electrons and positrons emanating from the pulsar impinge on the companion, heat it up and drive a wind off the surface. The companion is expected to boil away to oblivion in 100 million years leaving a solitary rapidly rotating pulsar. Our Palomar observations showed that a possibly variable faint star coincided with radio pulsar. This was subsequently shown to be the ablating companion.

A0620-00, a system which underwent a nova explosion in 1976, is now considered the best case for a galactic black hole. The system consists of a K dwarf star and an unseen companion. The companion was inferred to be a black hole of mass greater than 4 solar masses and perhaps 7 solar masses from radial velocity studies by a group from the Center for Astrophysics. We observed the K star with much better signal to noise ratio and confirmed the earlier claim. In addition, our data showed that the emission lines show systematic changes with the orbital phase of the system. The emission lines arise in the accretion disk surrounding the black hole. Our analysis of the emission lines suggest that the mass of the black hole is probably as high as 25 solar masses! This is much more massive than is expected from stellar evolutionary models.

Our success of detecting nebula in emission lines of ionized species show that the optical technique is a powerful way to discover more of these interesting objects. We will continue our search for more pulsar driven wind nebulae from Palomar as well as Las Campanas. More detailed

observations are needed of the ablating companion around PSR 1957+20. Theoretically optical pulsations are expected from the 1.6 ms pulsar and we hope to look for these pulsations. Just this year a new X-ray nova very similar to A0620-00 took place. It is most likely that it too houses a black hole. We will observe this new system as well as continue our study of A0620-00 in order to better define the mass of the black hole.

Investigations in Asteroseismology

Principal Investigator: Ken Libbrecht
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Subject Heading: Stars

In 1987-8 Libbrecht continued his endeavor to measure short-period, small amplitude acoustic oscillations in main-sequence stars. The motivation for this project comes from the sun, where millions of low-amplitude (< 20 cm/sec/mode at the solar surface) oscillation modes are now routinely observed, and the measurements are being used as a helioseismic probe of the sun's hidden interior. One of the biggest remaining questions concerning the sun's oscillation modes is how the modes are excited to their observed amplitudes. From the work of Goldreich and Kumar at Caltech it is thought that the modes are stochastically excited by turbulent convection in the sun. However, convection is poorly understood theoretically and therefore so are the sun's oscillations. If one could measure similar oscillation modes on other stars, which have qualitatively different convection zones, then this could lead to a considerable increase in our understanding of the physics of convection in general. Note this has some earth-bound applications, since the generation of acoustic waves by turbulence is sometimes referred to as airport noise.

The approach most likely to yield a detection of solar-like oscillations in other main-sequence stars is that of precision radial velocity measurements. Such measurements at Palomar were made using the coude spectrograph, combined with an iodine absorption cell in the beam to impress a stable reference spectrum onto the stellar spectrum. Observations were made of Procyon, which was thought to be a good candidate, for several good nights, and although no oscillations were found, an upper limit of 1 m/sec/mode was derived. Since the Palomar observations, a heroic run by a French group (a nearly continuous timeseries combining 4 nights from the 4-meter CFHT in Hawaii with simultaneous data from the other side of the globe—7 nights at the 6-meter Zelentchuk telescope in Russia) lowered this limit even further. This is beginning to suggest that Procyon is probably a poor candidate star, reflecting the fact that we don't know much about the excitation mechanism for solar-like oscillations.

Where this branch of asteroseismology goes from here is not clear, but it is likely that some improvements in the observational techniques and equipment will yield an additional factor of five or more improvement in sensitivity, which will allow us to finally detect these oscillations.

In an effort to prove that the technique of precision radial velocity measurements is a sound one, Libbrecht also made observations of the magnetic Ap star Gamma Equulei, which is known to exhibit photometric oscillations at the very low level of 0.06 percent (peak-to-peak). Several good nights of data were obtained in August 1987, and indeed the star showed oscillations in radial velocity at the level of 40 m/sec (peak-to-peak). Such oscillations were well above the noise background in the data, and these observations were only the second time that velocity oscillations were measured in an Ap star. As an added bonus, the high signal-to-noise revealed that two modes of oscillation were excited in the star, which allowed a measurement of the fundamental frequency spacing between the star's oscillation modes. This frequency spacing is directly related to the structure, particularly the radius, of the star.

The Radii and Luminosities of Long Period Cepheids

Principal Investigator : Jeremy Mould

Division of Physics, Math, & Astronomy, Caltech

Co-Investigators :

Robert Coker, Barry Madore, J. B. Oke, Alain Picard

Division of Physics, Math, & Astronomy, Caltech

and

John Huchra and David Latham

Harvard Smithsonian Center for Astrophysics

Recent improvements in the strength of the cepheid period luminosity relation lend emphasis to the fundamental problem of calibrating the relation. The prospect of detecting cepheids with Space Telescope in a much larger sample of galaxies than have been studied to date gives this project some priority. Most important for the problem of the distances of these galaxies are the cepheids with periods longer than 10 days.

Most such cepheids in the Galaxy are so distant that there is little prospect of reliable trigonometric parallax measurement in the near future. The remaining options are the use of cepheids in open clusters, the use of cepheids in the Large Magellanic Cloud, and the physical determination of cepheid radii following the Baade Wesselink method. It seems worthwhile to pursue all of these options.

In principle, the Baade Wesselink method is straightforward: integration of the radial velocity curve gives the dimension of length, or more exactly, the radius change as a function of phase. This dimension can also be monitored via the luminosity and effective temperature. It is then possible to solve for the stellar radius, and finally the distance.

In this project spectrophotometry was carried out at Palomar Observatory. The radial velocities for the cepheids were obtained on the 61-inch Wyeth reflector at Oak Ridge Observatory, at the 60-inch Tillinghast reflector at The Whipple Observatory and at the Multiple Mirror Telescope. From 1987 to 1988 we monitored the radial velocity and spectral energy distributions of a number of cepheid variables with periods of 10 days or longer. We have submitted a paper examining how the data can be used following the Baade Wesselink formalism to estimate the radii of cepheids and their luminosities. We conclude that the precision of the velocities obtained in this project is such that the dominant source of error is now the data on temperature variation. With the present data the radius of VX Per is $90 \pm 30 R_{\odot}$ and the radius of SZ Cas is $40 \pm 10 R_{\odot}$. A precision of 15K in measuring temperatures is required to reduce this error to 10%. This is beyond the limits of the type of spectrophotometry obtained in this program, but may be within the capabilities of optical/IR V-K photometry.

Absolute Spectrophotometric Calibrations

Principal Investigator: J. B. Oke

Subject Heading: Stars

Some spectrographic observations of stars and galaxies must be calibrated in an absolute way so that the actual amount of energy received at the earth is known. This is done by calibrating a few selected stars against the single star Vega which in turn has been compared with standard laboratory radiation sources. For the past two years Oke has been calibrating a group of about 20 stars which will be used both by large ground-based telescopes and by the Hubble Space Telescope when it is in orbit. Oke has calibrated the stars from the ultraviolet at 3200 Å to nearly 10,000 Å in the infrared. The calibration in the ultraviolet between 1150 Å and 3200 Å has been done using mainly the International Ultraviolet Explorer (IUE) satellite. This program which requires the 200-inch telescope and extremely clear skies has now been completed and the final absolute calibrations are being assembled.

Studies of Young Stellar Objects

Principal Investigator: S. E. Persson

Co-Investigator: Fred Hamann

Mount Wilson and Las Campanas Observatories

Subject Headings: Stars

One of the premier problems in astronomy is understanding the formation and early evolution of the sun and earth. Because the sun and solar system are already middle aged (born roughly 4.5 billion years ago) and carry only fossils of their early lives, we look to nearby sites of current star formation for clues to their origin. Recent work in this field reveals that the necessary precursors to planetary systems, namely dense disks of gas and dust around young stars, are a common and natural product of the star forming process. The sun, like all stars, condensed out of a dense interstellar cloud under the weight of its own gravity. As a cloud core collapses, it cannot dissipate its angular momentum fast enough to allow strictly spherical infall; with the result that a rotating disk forms around the central protostar. As the disk accretes additional material onto the surface of the protostar, its rotational energy is converted to heat, and a turbulent, highly ionized boundary layer is created. Sometime during this phase, by processes not yet understood, the disk and protostar combine to produce a strong, supersonic, and often very collimated wind, which reverses the collapse and contributes to the eventual destruction of the disk. The strong winds also dominate the global cloud dynamics and can trigger further star formation. These energetic phenomena produce spectral emission lines from the gas ions, whose strengths and velocity broadened shapes provide useful diagnostics. Our work at Palomar Observatory primarily involves measuring the ionic line spectra of YSOs to extract more detailed information about the geometry, dynamics, densities, and temperatures of the material in the inner circumstellar regions. The continued support of existing facilities at Palomar, as well as the development of new state-of-the-art instruments, is essential for this research.

Recently, a large population of YSOs was discovered which appear not to have significant disk material around them. Some of these objects are much younger than the oldest known disk-containing objects. This implies a range in disk survival times from a few million to a few hundred million years; probably dependent upon the conditions in the cloud core when collapse began. Establishing disk lifetimes is important for understanding the feasibility of planet formation. We are beginning a program to quantify the amount of disk material around YSOs of various ages by measuring the relative strength of several spectral indicators.

Also essential to the planet formation problem is determining the densities and temperatures at different radii in the disk. From the spectral lines we measure, and the known thermal energies needed to produce them, we have been able to make rough estimates of the range of densities and temperatures present, but we can only speculate on where these conditions exist. For example, in a large number of young stars we find a peculiar pattern in the emission lines of singly ionized calcium. We interpret this as resulting from similar *vertical* temperature variations in their disks. If correct, this favors an internal heat source, such as is expected from viscous heating of disk material as it spirals in toward the star. A better understanding will require detailed computer simulations of the disk/star environment. In a recent collaboration, S. E. Persson and G. J. Ferland

had great success in applying computer simulations to similar problems in the study of distant galaxies. These calculations balance the energy added into the disk, such as from accretion heating or from the absorption of light from the central star, against the energy radiated away as reprocessed light. In the future, we will begin comparing measurements of disk radiation with new results of these calculations to determine how and where the gas is heated near young stars.

Another aspect of our work at Palomar involves taking digital pictures of young star/disk systems in infrared light, and comparing these with ultra-high resolution visible light images of the same objects obtained with the Hubble Space Telescope. The Space Telescope pictures will map the dust distributions via reflected light from the central star, while the Palomar infrared pictures will measure emission arising directly from the dust (disk) itself. By taking these multi-'color' pictures of young stars of various ages, and comparing them with our spectroscopic data, we hope to assess the frequency with which disks form, and follow the evolution of disks through the planet building phase.

Hot white dwarfs and OB subdwarfs

One of the white dwarf-red dwarf common proper motion pairs observed as part of the gravitational redshift programme was the system G191-B2A/B. The white dwarf, also known as EG 247, is the hottest known DA-type degenerate, and the 1Å resolution 200-inch spectra suggested a rather unusual $H\alpha$ profile. Subsequent observations with the echelle spectrograph on the 60-inch telescope at Palomar, giving a resolution of $\sim 0.2\text{\AA}$, revealed previously unsuspected narrow emission within the core of this line.

With no infrared excess, this feature cannot be attributed to a close companion, while the absence of spatially extended emission rules out a remnant planetary nebula. Nor is the line core likely to arise from a stellar wind, such as is observed in some hot subdwarfs, since the mean velocity (relative to the system as a whole) is only $\sim 20\text{ km s}^{-1}$, while the equivalent width indicates a velocity dispersion of only $\sim 30\text{ km s}^{-1}$. Indeed, the observed redshift agrees well with that observed for high excitation ultraviolet lines of C IV, N V and Si IV that in other white dwarfs are known to originate in the stellar photosphere. The implication is that the velocity difference relative to the distant K-dwarf companion arises from the Einstein redshift, and that the emission originates at or near the stellar photosphere.

The existence of emission line cores in Ca II lines in main sequence stars is well known and is due to a temperature inversion in the stellar atmosphere, with a high temperature chromosphere overlying lower temperature layers. Since making the G191-B2 observations, echelle spectra have been obtained of a number of hot O and B subdwarf stars, compact stellar cores evolving towards the white dwarf cooling tracks. All of the sdO stars observed also exhibit $H\alpha$ emission cores, and the implication is that some kind of temperature inversion is also present in these stars.

A clue to the possible origin of this phenomenon is given by the fact that none of the sdB subdwarfs nor any of the cooler DA dwarfs observed have $H\alpha$ emission. The sdO subdwarfs appear to have atmospheres that are substantially more helium-rich than the sdBs. The latter are thought to have evolved along the extended horizontal branch into the white dwarf domain, rather than via the asymptotic giant branch and planetary nebula tracks. Similarly, the He/H ratio in the surface layers of DA atmospheres decreases with decreasing temperature as He moves inward through gravitational settling. Wesemael has computed pure-He NLTE model atmospheres which show a temperature inversion in the outer layers, with the heating arising from the overpopulation of the ground He II state. A similar effect occurs in main sequence OB stars. Relatively little theoretical work has been devoted to this question and it is likely that further observation of the variation of the emission line strength with position in the H-R diagram will probe both the densities and composition of the outer layers of these stars, and the evolution of these characteristics with time.

I. Neill Reid

Stars

I. Neill Reid

Einstein redshifts and white dwarf masses

Most single, intermediate mass ($1 \leq \frac{M}{M_{\odot}} \leq 7$) stars end their evolutionary careers as degenerate white dwarfs. Thus the masses of these remnants can be used to set constraints on stellar evolution both on the core-helium burning and on the double shell burning (asymptotic) giant branch - in particular on the mass loss rates and the return of processed material to the interstellar medium during these phases. In addition, these observations can be used to check theoretical mass-radius relations for white dwarf stars and, combined with the white dwarf luminosity function, can be used to estimate the total mass locked up in remnants in the galactic disk.

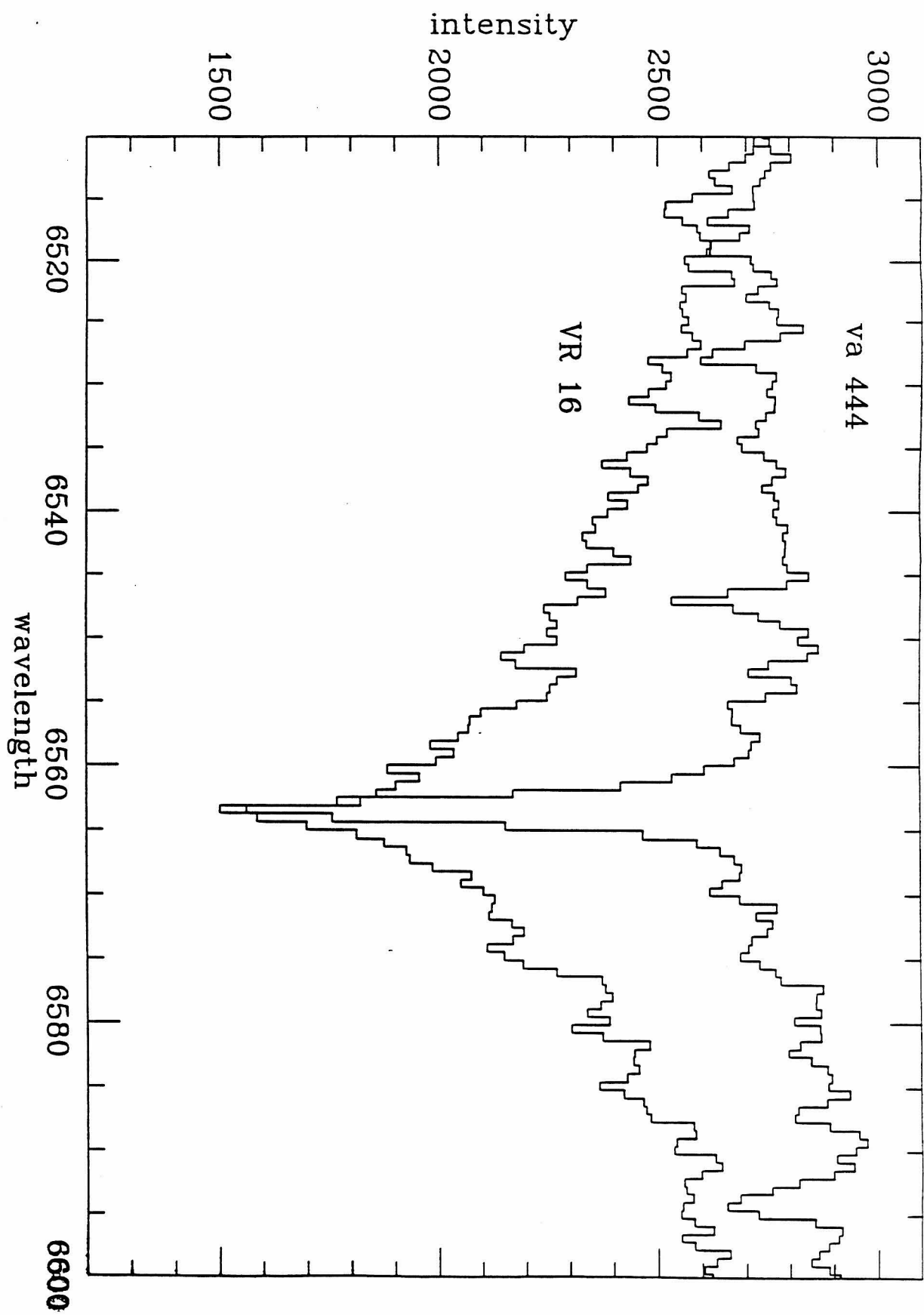
Few degenerates, however, have well determined mass estimates, and there is some controversy over both the mean mass and the dispersion in mass, with one school favouring $\langle M \rangle \sim 0.5 \pm 0.1 M_{\odot}$ (Weidemann, 1987, *Astr. Ap.* 188, 74), while the second proposes $\langle M \rangle \sim 0.75 \pm 0.25 M_{\odot}$ (Shipman & Sass, 1984, *Ap. J.* 235, 177). N. Reid, working in collaboration with G. Wegner (Dartmouth College), is currently using gravitational redshift measurements to investigate this question.

White dwarf stars are very compact objects, with radii of $\sim 1\%$ that of the Sun and, as a consequence, surface gravitational fields that are 10,000 times the solar field. This high gravitational field leads, through the principle of equivalence, to a significant redshift in the wavelength of the emitted radiation. If this gravitational redshift, also known as the Einstein redshift, can be measured, and the radius computed from the luminosity (which requires measurement of the distance) and the surface effective temperature (from model atmospheres), then the mass follows in a straightforward manner. Accurate radial velocity measurements can be obtained for hydrogen line (DA) white dwarfs, since the broad Balmer lines have sharp non-LTE cores - especially $H\alpha$ (figure 1). The trick lies in separating the gravitational redshift from the line of sight motion of the star. The last can be achieved by selecting degenerates which either form wide binaries with main sequence stars (which have negligible gravitational redshift) or which are members of open clusters, and hence have known radial velocities.

To date spectroscopic data have been obtained of 21 degenerates, including seven stars that are members of the Hyades cluster. Most of these observations were made using the double spectrograph on the Hale 200-inch telescope, but seven of the brighter stars were also observed in May 1986 using the Isaac Newton Telescope on La Palma. Figure 1 shows spectra in the region of $H\alpha$ for one of the Hyades white dwarfs, VR 16, and ν 444, a G-type cluster member. The gravitational redshift is clearly evident in the offset between the narrow main-sequence star line and the core of the white dwarf line.

Considering first the field stars, the redshift varies from ~ 17 to 40 kms^{-1} , corresponding to masses in the range 0.39 to $1.19 M_{\odot}$, with the individual estimates uncertain typically $0.1 M_{\odot}$. The mean mass is $0.60 M_{\odot}$, in good agreement with the $0.58 M_{\odot}$ found by Koester (1987, *Ap. J.* 322, 852) in a similar survey (which includes several of the stars in the Palomar sample). The dispersion in the Palomar/La Palma sample is $\sim 0.24 M_{\odot}$, rather than the $0.11 M_{\odot}$ of Koester's sample, although most of this increased dispersion stems from the two stars with masses of more than $0.8 M_{\odot}$. The individual stars map out a relation that is in broad agreement with the shape of the expected mass-radius relation, but offset to larger radii at a given mass. Koester has suggested that this arises from the hydrogen content in the photosphere.

The Hyades stars have a significantly higher mean mass than the average of the field stars. Averaging all seven gives $\langle M \rangle \sim 0.65 \pm 0.14 M_{\odot}$, while excluding HZ 14 ($M \sim 0.39 M_{\odot}$) gives $\langle M \rangle \sim 0.69 \pm 0.08 M_{\odot}$. This is not unexpected, since the Hyades cluster is only $\sim 10^8$ years old, considerably younger than most stars in the galactic disk. Thus the Hyades white dwarf stars are descended from stars more massive than $2.2 M_{\odot}$, while the field progenitors were, with a few exceptions such as Sirius B, of lower mass. Thus our results for the Hyades degenerates suggests that $\sim 2 M_{\odot}$ main sequence stars lose at least $1.4 M_{\odot}$ of material as red giants and planetary nebulae. This is rather more than predicted by standard models.



The Milky Way Galaxy

On the nature of Eggen's non-disc stars

One of the many recent investigations of local galactic structure is Eggen's photometric survey of all known proper motion stars with $\mu > 0''.5$, $V < 15.1$ and $\delta < +30^\circ$ (Eggen, 1986, Astr. J. 92, 393, and refs. within). Eggen has used broad (UBVRI) and narrow (uvby β) band photometry to calibrate luminosities and abundances, deriving space motions from radial velocities and proper motion data, and classes stars as disc and non-disc from the orbital eccentricity (ϵ) - $[\text{Fe}/\text{H}]$ distribution. (The orbital eccentricity is calculated using the Eggen, Lynden-Bell and Sandage (1962, Ap. J. 136, 748) Galaxy model.) Eggen argues for a discontinuity between disc and halo at $\epsilon \sim 0.5$, corresponding to $P([\text{Fe}/\text{H}]) \sim -0.6$, and assumes that all stars in his sample with $\epsilon > 0.5$ are metal-poor halo stars.

Under this definition of the halo (or non-disc) population, Eggen calculates the luminosity function using the V_{max}^{-1} method, deriving a distribution similar to the disc luminosity function, but with a halo-to-disc ratio of ~ 0.008 . This compares with the ~ 0.002 number ratio derived by Bahcall and Casertano (BC - 1986, Ap. J. 308, 347). As Eggen points out, the two density estimates rest on stellar samples defined using different criteria, with BC using a kinematic model of the halo to match the number of high velocity ($V_{\text{tangential}} > 160$ to 250 km s^{-1}) subdwarfs that are observed, as compared with Eggen's orbital eccentricity criterion. BC show that the stars of highest velocity are consistent with a "standard" halo model - low rotation ($V_\odot \sim -150 \text{ km/sec}$) and high velocity dispersions ($\sigma_r = 140 \text{ km/sec}$, $\sigma_\theta = 100 \text{ km/sec}$, $\sigma_z = 75 \text{ km/sec}$). BC suggest that the remaining stars are disc stars, drawn from the high velocity tail of the distribution, which shape, they point out, is not well known - simply through the paucity of such stars in the vicinity of the Sun. If this is the case, then, knowing the selection effects that enter into the construction of Eggen's catalogue, we can use the proper motion sample to better examine the properties of the high velocity disc. Alternatively, these "extra" stars could represent an intermediate population - perhaps a high angular momentum, bulge related population.

We have obtained echelle spectra of an area-complete sample of these proper motion stars, observing all stars with $M_v < 8.5$ and $\delta < -25^\circ$, including both those stars classed as disc and as non-disc. Our analysis is as yet very incomplete, but the spectra do indicate that the non-disc stars span a considerable range of metallicity, from near-solar to $[\text{Fe}/\text{H}] < -2$. Whether the stars form any coherent subgroups is not yet clear.

I. Neill Reid

CHEMICAL COMPOSITION OF GLOBULAR CLUSTER STARS

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Subject Heading: Stars

Stars in globular clusters provide a test bed for theories of stellar evolution because within a cluster all stars were formed at the same time with nearly the same chemical composition. Stellar models which endeavor to predict accurately the luminosity and radius of evolving stars in globular clusters must be calculated with the initial assumption of the stellar mass and its composition. The initial composition must be inferred from the current composition of globular cluster stars rather than derived from some sort of grand principle or a model of the early evolution of our Galaxy prior to the isolation of the material that later became the globular cluster.

The digital computer can then produce stellar models and follow the changing conditions within the star as its hydrogen is transformed into helium and the star becomes a red giant. During this process the star develops a large outer convective zone that mixes the surface material with matter that was formerly quite deep in the stellar interior. This mixing brings to the surface the products of the nuclear reactions. Hence, the observed composition of the surface material reflects both the nature of the original composition of the star and the modification due to nuclear reactions and mixing. The key elements whose abundance relative to hydrogen needs to be obtained are helium, carbon, nitrogen, oxygen and iron, the last of which represents all the medium weight elements from sodium through zinc. In addition we need to know the $^{12}\text{C}/^{13}\text{C}$, i.e., the isotopic ratio of carbon, which may be grossly effected by nuclear burning.

Starting in 1987 and continuing in 1988 Wallerstein and Oke have been observing stars in various globular clusters with the 200-inch telescope and both the coude and cassegraine double spectrographs to obtain the abundances of these elements.

The helium abundance is the most difficult parameter to measure because in globular clusters the only red giants to show helium lines are the Cepheids. Fortunately, Wallerstein and Oke obtained spectra of the star W Virginis which is not actually a member of a globular cluster but is brighter than any globular cluster Cepheid and similar in many ways to Cepheids in typical globular clusters. an analysis of the hydrogen and helium line profiles by Wallerstein and Raga (University of Washington) using shock wave theory to explain the excitation of the hydrogen and helium lines reveals a He/H ratio of 0.20 by number which may be compared with 0.08 for unevolved stars of similar age and metal abundances.

For the globular cluster stars Wallerstein and Oke have made a major effort to learn the carbon, nitrogen, and oxygen abundances in the cluster M13 which previous work showed to include at least one red giant with drastically reduced oxygen as compared to other red giants in the same cluster. During 1987 and 1988 they obtained high dispersion spectra of 6 stars in M13 for O I, CN, CH, and NH features. As part of the same program they observed stars in M22 and M4 for CH and will combine that data with data obtained in the O I and CN regions by Wallerstein at Cerro Tololo.

As a start in obtaining similar data for three clusters at very large distances from the galactic center Wallerstein and Oke used a five night run in June 1988 to obtain spectra in the CH region of stars in NGC 6229, NGC 7006, and NGC 7492. These clusters all show only moderate metal deficiencies despite the fact that they are located far out in the Galactic Halo. In addition they show differing horizontal branch morphologies with NGC 7006 showing a strongly red horizontal branch and the other two clusters showing much bluer horizontal branches. One of the causes of this difference may be a difference in abundances of carbon, nitrogen, and oxygen even if the metal abundances are the same. NGC 6229 is specially interesting because its star density is 250 times greater than that of NGC 7492. Hence, it will be possible to compare these clusters to see if a composition difference correlates with the gross difference in initial conditions of cluster formation. Observations planned for 1989 will complete the needed data for these clusters in the O I and CN spectral regions.

INSTRUMENTATION

The Prime Focus Infrared Camera

Principal Investigator: C. Beichman
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Jet Propulsion Laboratory

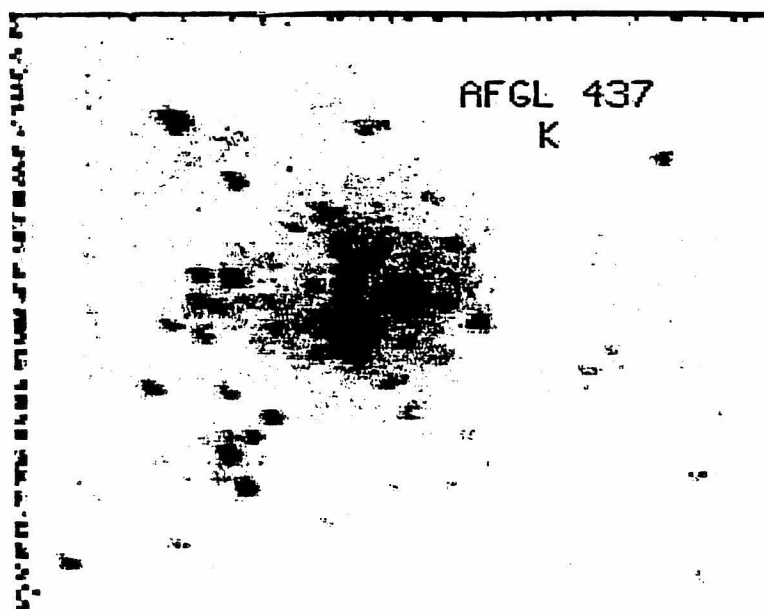
Co-Investigators: T. Gautier (IPAC)
J. Hester (IPAC)
G. Bailey (JPL)
G. Neugebauer (CIT)

Subject Heading: Instrumentation

The advent of array detectors for astronomy is creating a revolution in astronomy more profound than the advent of CCDs for optical astronomy. Until now infrared astronomers were limited to looking at the Universe through single detectors, pinholes a few arcseconds in size. Mapping a large region was a tedious task of pointing the telescope, taking a data point and repeating the process for hours. Now that same task can be accomplished in seconds.

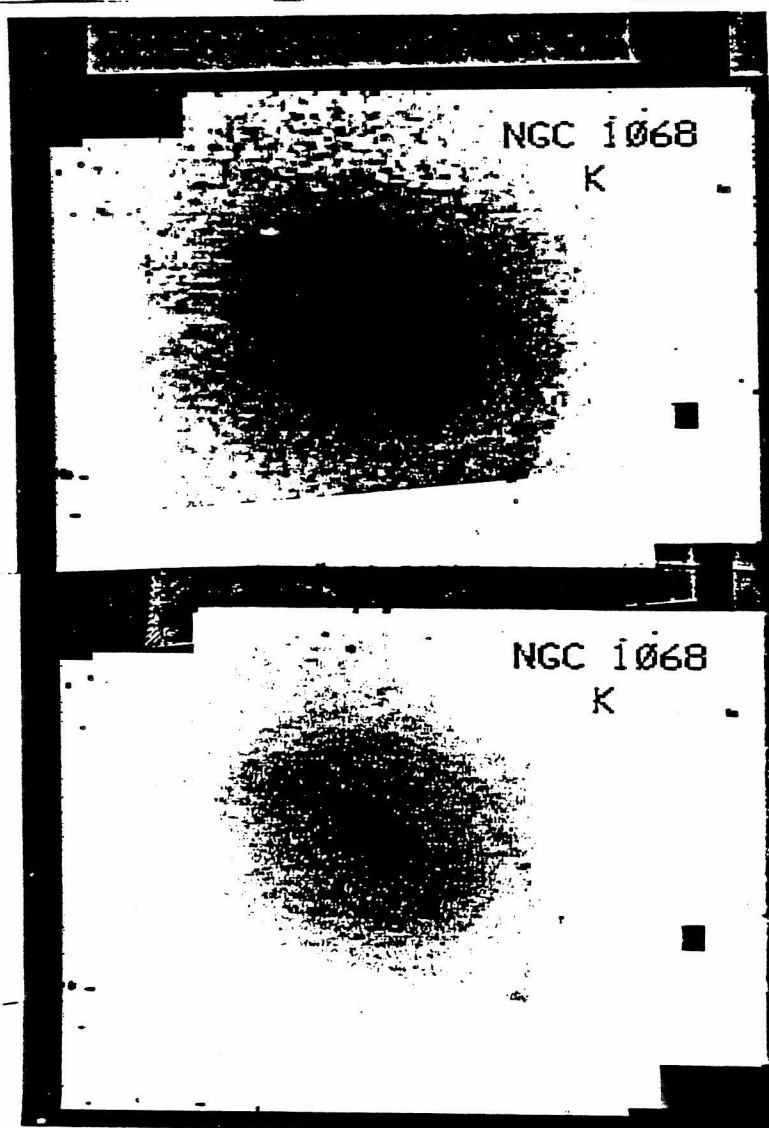
With support from the Caltech President's Fund and the HIRIS project at JPL we have built a camera for near infrared wavelengths that operates at the prime focus of the 5m telescope. The camera utilizes a 128x128 array of HgCdTe detectors sensitive from 1 to 2.5 μm and is optimized for covering large fields of view and low surface brightness features. The pixel size on the sky is 0.8'' which gives a field of view of 90''x90''. The array has a quantum efficiency of 0.25, a read noise of 1500 electrons and negligible dark current. The camera includes a complement of 14 broad and narrow band filters for photometry and imaging in specific spectral lines. The camera was installed on the 5m telescope during the summer and fall of this year and worked very well. The 1 sigma sensitivity limit at 2.2 μm is about 17 mag after a 10 second integration. Observations have been made of star forming regions, supernova remnants and colliding galaxies.

This camera is the first of a series that are planned to take advantage of the rapid advances in array technology. Future plans involve larger format arrays, up to 256x256, and more sensitive devices with read noise as low as 30 electrons. Such devices are well suited for making high spectral resolution images of galactic and extra-galactic objects and for searching for distant primeval galaxies.



AFGL 437
K

A 2.2 μ image of the star formation region AFGL 437, showing many embedded young objects. The image was obtained with the Prime Focus Infrared Camera.



NGC 1068
K

A deep 2.2 μ image of the Seyfert galaxy NGC 1068, showing the outer arm structure.

NGC 1068
K

NGC 1068, with a stretch showing the structure of the inner part of the galaxy, including the barred spiral structure.

Design of the Keck Telescope Alignment Camera

Principal Investigator: Gary Chanan
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Subject Heading: Instrumentation

The Ten Meter Telescope of the W. M. Keck Observatory, now under construction on Mauna Kea on the island of Hawaii, will be the world's largest optical and infrared telescope when it becomes operational early in the next decade. This telescope utilizes a new technology in which the primary mirror is built up of 36 individual hexagonal segments, which fit together to form an essentially continuous single optical surface; in this manner one can attain substantially larger apertures than with traditional monolithic mirrors. The relative positions of the segments are maintained by an active electro-mechanical control system of sensors and actuators, which "freezes" the configuration of the mirror. However, this control system cannot determine exactly where the segments are to be positioned in the first place. This latter task is to be accomplished by means of an alignment camera, which can sense when the intersegment steps are within the tolerance of about one tenth of a wavelength of visible light, or 50 nanometers.

We are currently in the process of developing and designing the Keck alignment camera, based on a series of measurements made at the Palomar 60-inch telescope. [The 60-inch is well-suited to this study because it has a focal length similar to the Keck Telescope, and is equipped with some of the same state-of-the-art detectors -- charge-coupled-devices (CCDs) -- that will be used at Keck.] The alignment camera works by breaking the image of a single star into a number of subimages (one subimage for each of the 84 possible pairs of adjacent segments), and then making use of the fact that images formed by discontinuous segments will be out-of-round. The ultimate sensitivity of the alignment camera (and consequently the image quality of the Keck Telescope itself) therefore depends on how accurately one can measure the out-of-roundness or asymmetry of an image. Quantitatively, we simply measure the fractional difference between the image diameters in two perpendicular directions. In practice, this sensitivity is limited by a number of effects, including "seeing" (the blurring effects of turbulence in the earth's atmosphere), the statistical limitations caused by the starlight arriving in discrete photons, and the finite resolution caused by discrete picture elements (pixels) in the CCD.

We have made an empirical study of how accurately we can measure our above asymmetry parameter as a result of these effects at the 60-inch telescope, including the dependence on such other variables as observing conditions, exposure time, and wavelength of light. We have found that we can reliably make these measurements to an accuracy of 2 to 3%. A computer model of the alignment camera then shows that with this sensitivity, the telescope specification of tenth-wave surface quality should be met. The alignment camera has just passed its formal Critical Design Review, and is now being built.

DIFFRACTION LIMITED IMAGING ON THE HALE 5-M TELESCOPE

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

Coinvestigators: A. Ghez, P. Gorham, T. Nakajima, G. Neugebauer, J. Oke, T. Prince, A. Readhead

Subject Heading: Instrumentation

Perhaps more than any other science, progress in astrophysics is driven by new developments in instrumentation e.g. our view of the Universe changed completely with the advent of radio and X-ray astronomy. Along the same vein, higher angular resolution has resulted in dramatic progress as has been demonstrated by radio astronomers. At optical wavelengths, progress in high angular resolution imaging has been difficult owing to turbulence in the atmosphere. Recognizing the potential gains of high angular resolution imaging we formed, two years ago, a multi-disciplinary group and started a program of instrumentation and algorithm development.

This year we built an interferometer (Figure 1) and outfitted it with a photon-counting detector and observed bright binary stars and asteroids at the prime focus of the Hale 5-m telescope. We tried two different techniques: (1) the Non Redundant Mask (NRM) and (2) the Fully Filled Aperture (FFA). The NRM technique is the optical analog of a multi-antenna radio array and image construction is based on the well known radio technique of "closure phases".

The NRM data was reduced on the Convex C-1 mini supercomputer at Robinson Laboratory and the Caltech Very Long Baseline Interferometry (VLBI) package was used to construct the images. In Figures 2 and 3 we show the synthesized images of two binary stars, β Corona Borealis and σ Hercules. The angular resolution in these maps is quite good: about 50 milliarcseconds. The *dynamic range* or the ratio of the brightest feature to the noise in the map is approaching 100:1. These images show that the highly successful radio technique of closure phases can be imported to optical wavelengths.

At the current time, we are restricted to bright images with the NRM technique (fifth magnitude objects). Improvements in detectors, additional hardware (dispersion corrector) and better understanding in image construction algorithms can perhaps make it feasible to study objects nearly a factor of 100 fainter. Our final goal is to image the cores of nearby active galactic nuclei which, according to conventional theory, are supposed to house an accreting, massive black hole. Over the next year we hope to make progress in these three areas.

Progress of the FFA method has been somewhat slow because it is a relatively new technique and besides requires tremendous computing. P. Gorham has been concentrating on the FFA method and is using Caltech's NCUBE, a concurrent supercomputer to reduce the data obtained so far. Theoretical work done by our group indicate that FFA is expected to be more sensitive than the NRM technique by more than order of magnitude.

Finally, next year we plan to obtain some data at infrared (IR) wavelengths with the new Cassegrain IR camera. There are two reasons why we wish to move into IR: (1) imaging becomes easier as one goes to longer wavelengths and (2) there is tremendously exciting science that awaits any high angular resolution effort at IR wavelengths.

CLAN MAP
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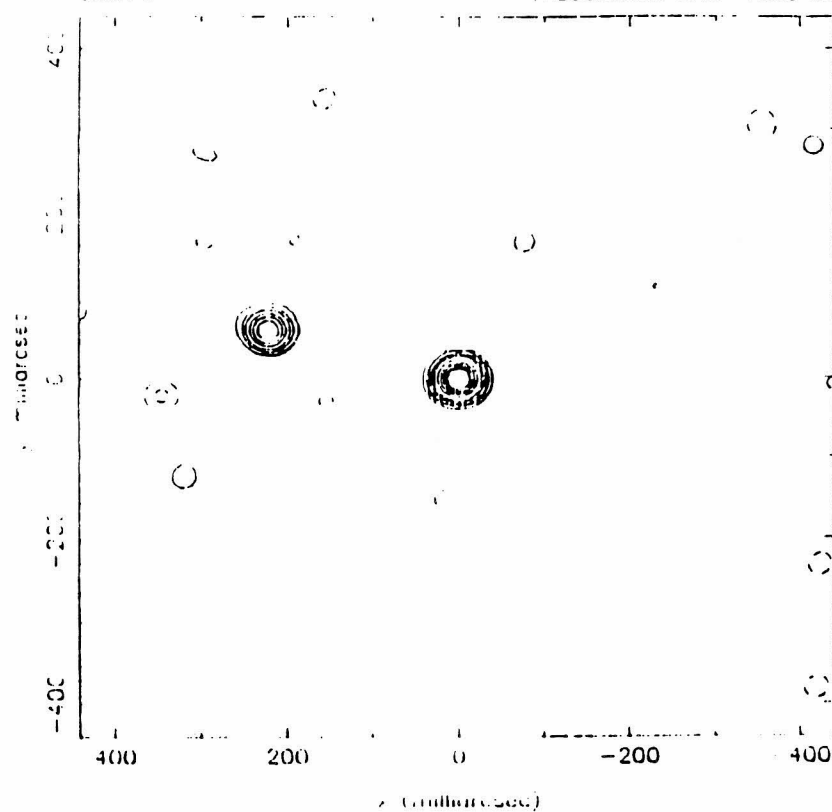


Figure 2

CLAN MAP
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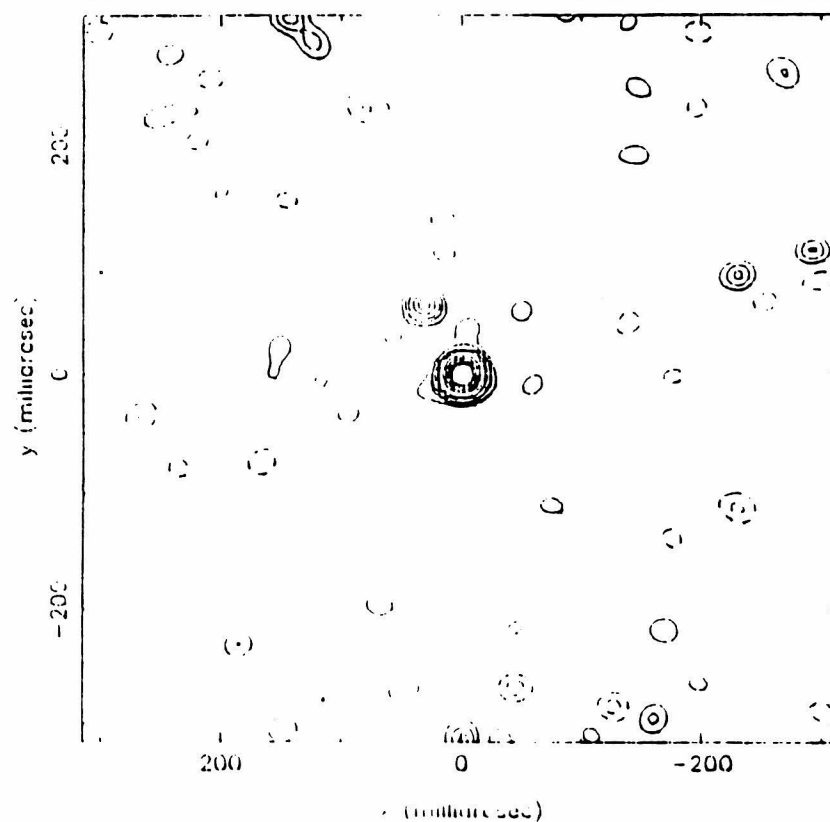


Figure 3

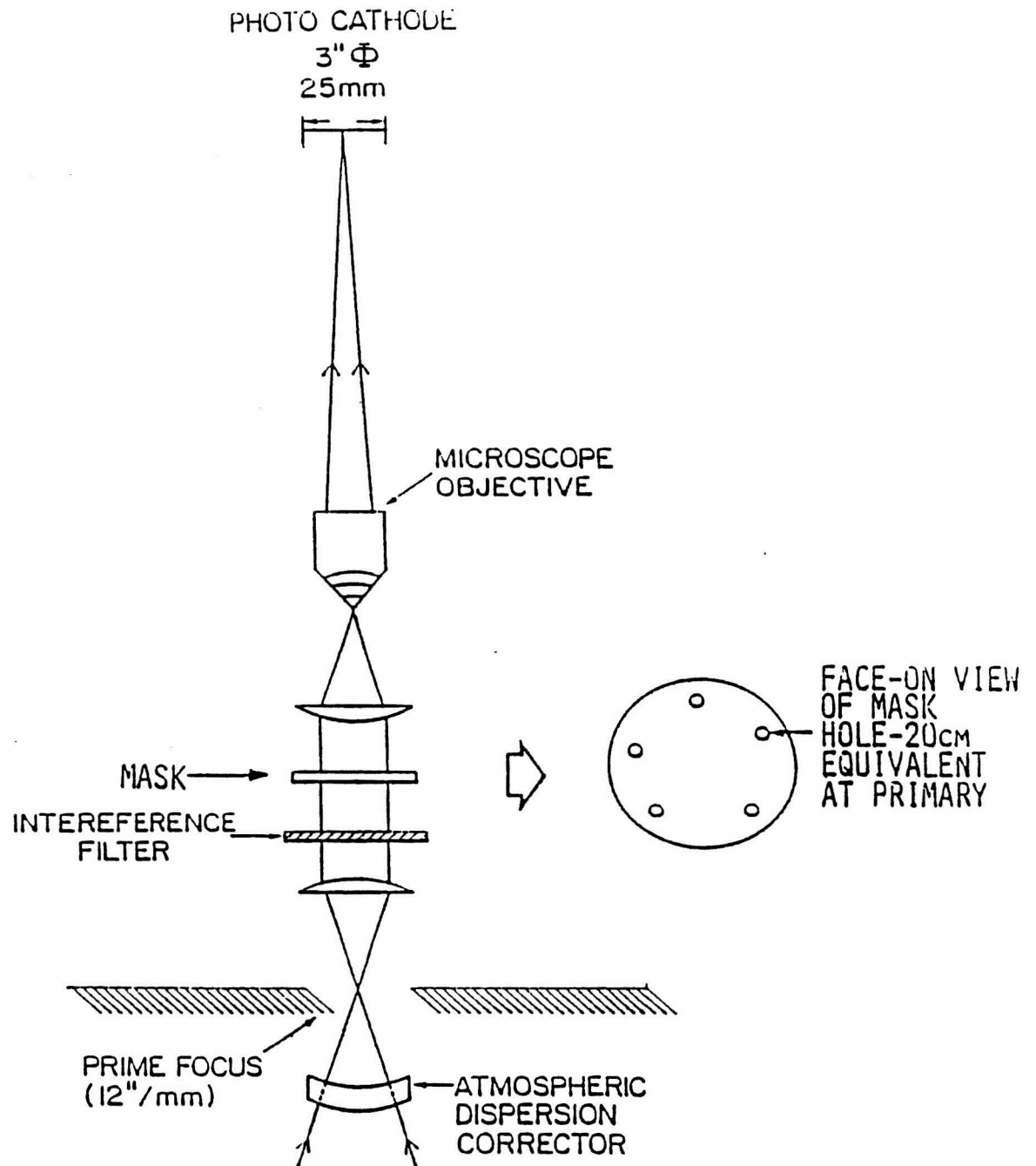


Figure 1

CCD Experiments

Principal Investigator: J. B. Oke

**Co-Investigators: F. Harris
Delong Wang**

Subject Heading: Instrumentation

Virtually all optical observing on the 5-meter and 1.5-meter telescopes at Palomar is done with 800x800 pixel CCDs made by Texas Instruments. These CCDs are excellent devices at visual and near infrared wavelengths but have proved to be very poor in the ultraviolet and blue. A long series of experiments were carried out by Oke, Harris and Delong to extend experiments done at the Jet Propulsion Laboratory by Janesick, for the purpose of improving ultraviolet performance. The nature of the problem was isolated and a solution, soaking of the CCDs in oxygen gas when they are not in use, has solved the problem for some of the CCDs. Two of the CCDs which are needed for ultraviolet work now have quantum efficiencies of 30-45 percent instead of the previous 5 percent. With this kind of efficiency these are the best ultraviolet detectors which have ever been available.

THE SECOND PALOMAR OBSERVATORY SKY SURVEY

Subject Heading: Instrumentation

Work at the 48-inch Oschin Telescope is continuing on the second Palomar Observatory Sky Survey (POSS II), which will consist of 894 fields covering the northern half of the celestial sphere, each field to be photographed on blue, red and near-infrared sensitive emulsions.

In previous years, the telescope was equipped with a new achromatic corrector lens (to provide good images over a broad range of colors), the dark rooms were completely rebuilt and a special building was constructed for pre-exposure treatment of the 14x14-inch glass photographic plates to enhance their sensitivity.

The use of fine-grained emulsions, which are capable of recording sharp images, and the high standards set for the survey have prompted a continuing effort to improve the performance of the telescope and to increase the yield of acceptable plates.

In the past year, for example, the figure of the 72-inch primary mirror was measured using an interferometer and improved by minor adjustments of the mirror support system. The photoelectric autoguider was modified, both mechanically and electrically, to improve its ability to guide the telescope to a high degree of accuracy.

Because of residual astigmatism in the corrector lens, it is essential for the telescope to be correctly focused with a very small margin of error (less than 0.0004 inch) for each exposure. For this reason, a high-precision optical encoder was installed on the focus mechanism. In addition, tests are being conducted to determine the effects flexure and temperature changes have on the focus.

At present, about 250 photographs have been accepted for the survey, leaving about 2,400 yet to be obtained, a task expected to be completed in 1992.

The survey is funded, in part, by grants from the Eastman Kodak Company, the Alfred Sloan Foundation, the National Geographic Society and the National Science Foundation. In addition, a portion of a gift from the Samuel Oschin Foundation has been used for many of the improvements to the 48-inch telescope and its supporting facilities.

