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A SUMMARY OF ONGOING WORK AT THE KECK TELESCOPE ON GRAVITATIONAL LENSING AND ON DISTANT GALAXIES

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ABSTRACT I present a summary of recent scientific projects relevant to the areas being discussed at this conference that have been or are in the process of being carried out at the Keck telescope by astronomers from the California Institute of Technology. Note that in most cases these are team projects, and many people are involved. Among the highlights thus far in the area of gravitational lensing are the detection of an emission line in the lens B0218+357 implying, if its identification as MgII is correct, a redshift of 0.95, and the detection of a redshift of 0.53 for one of the arcs in the X-ray emitting cluster of galaxies MS 0440+0204. Highlights in the area of distant galaxies include the deepest published optical and infrared counts, reaching to $K = 24.5$ mag and to $R \approx 27$ mag. The first results from a redshift survey of faint field galaxies which will eventually reach to $K \leq 20$ mag are also shown.

INTRODUCTION

In this paper I present a summary of recent scientific projects relevant to the areas being discussed at this conference that have been or are in the process of being carried out at the W.M.Keck telescope by astronomers from the California Institute of Technology. Note that in most cases these are team projects, and many people are involved. For each area, I will indicate the people on the team, the overall goal, and the progress achieved thus far.

GRAVITATIONAL LENSING

The people involved in this effort are R.Blandford, J.Cohen, G.Djorgovski, G.Neugebauer and T.Soifer, as well as C.Lawrence, I.Smail and D. Hogg. We have been observing systems in the infrared, where the key issue is the morphology, and where seeing of 0.4 arc-sec has been achieved. In the optical, although some direct imaging work has been done, we are concentrating on systems where the redshift of the lens or of the lensed object is not yet known, and is needed to complete the physical model of the lensing system.

In B0218+357, the smallest known Einstein radio ring, the redshift of the lensed source was unknown. We have found a single emission line, which we believe to be the 2800Å line of MgII. If this identification is correct, the redshift is 0.95. We are of course trying hard to find additional emission features.

MS0440+0204 is a cluster of galaxies with high X-ray luminosity with $z = 0.19$ studied by Luppino et al (1993). They found several bright arcs, but did not attempt any spectroscopy. We have obtained a redshift of $z = 0.53$ based on the detection of 3 emission lines for the brightest of these, Arc 1 (in Luppino et al's nomenclature).

In MG0414+0534, a dusty gravitational lens, Lawrence, Cohen, and Oke (1995) have unfortunately demonstrated that the absorption feature previously believed to arise in the lensing galaxy is in fact absorption from several complexes of FeII lines at a redshift near that of the quasar. This means that the redshift of the lens in the system remains a mystery.

There is also a paper reporting the discovery with observations made at the Keck telescope of several arcs in the cluster of galaxies Abell 2219 (Smail et al 1995), as well as a more detailed model for the bright IRAS source FSC10214, which may be lensed. New optical and infrared spectroscopy are given in Soifer et al (1995).

FAINT GALAXY COUNTS AND SPECTROSCOPIC SURVEYS

The complex question of how galaxies formed is one at the core of current efforts in observational cosmology. There have been many exciting results as this issue has been pursued over the years, with the apparent excess of faint blue galaxies (Tyson 1988) being one of the most interesting. Other related issues include whether galaxy morphology changes as one looks back in time, whether one can detect the effect of galaxy mergers, how and why do mean galaxy colors vary with time, and whether one can constrain the large scale geometry of the universe.

The way one normally pursues such issues is to survey faint field galaxies, and try to model the results with a particular cosmological model and with a particular choice of galaxy evolution. There are many groups, with many different strategies, engaged in these efforts. Many aspects of this subject are discussed in the recent review by Koo & Kron (1992).

The easiest thing to do is to count galaxies, because a relatively small investment in telescope time is required. The large aperture of the Keck telescope, the accuracy (at least most of the time) of its mirror support system and tracking system, and the good seeing prevalent at Mauna Kea mean that imaging to astonishingly faint magnitudes levels becomes possible. Deep counts in the infrared reaching to $K = 24.5$ mag from frames taken with the Near Infrared Camera have already been published for 3 fields (Soifer et al 1994, Djorgovski et al 1995), and at present data such for a total of 5 fields have been obtained and reduced.

Djorgovski et al (1995) describe the infrared counts obtained to date and provide a comparison with the models after 3 fields were completed. the status of the infrared counts. Figure 1a of this paper shows the counts of various groups from 10 mag $< K <$ 24.5 mag, while Figure 1b shows the faint end of the counts and compares them to various models for galaxy evolution with various assumptions about the global geometry of the universe. There is one arbitrary normalization constant, namely the total number density in some particular magnitude range. Note that the models do not strongly diverge from each other until $K > 22$ mag, i.e. the last two magnitudes of the counts are providing essentially all the discrimination between models.

At optical wavelength, Smail et al (1995) report on counts from several R images taken under conditions of very good seeing (FWHM $\approx$0.6 arc-sec) with LRIS totaling about 3000 sec in exposure. These data reach to $R \approx 27$ mag. The extremely high galaxy density, equivalent to 3 x 10^9 galaxies in the observable Universe, and the small intrinsic sizes of the galaxies are both surprising and challenging for cosmological models.

The group of people involved in this effort includes R.Blandford, J.Cohen, G.Djorgovski, G.Neugebauer and T.Soifer, as well as I.Smail, D.Hogg, J.Larkin, M.Pahre, L. Yan, and several other graduate students.

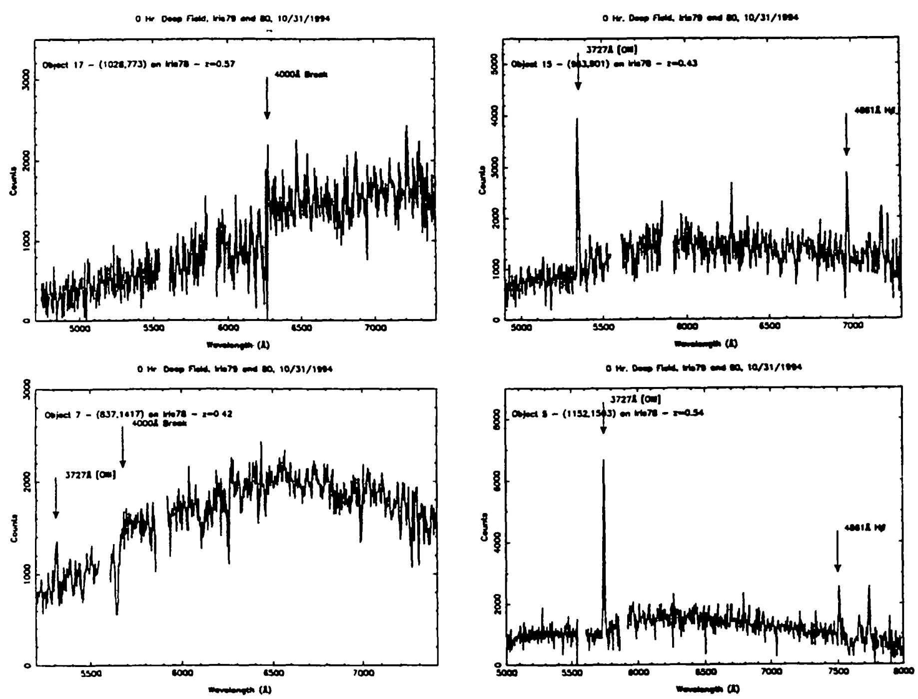

Fig. 1. Representative spectra of four distant galaxies obtained with LRIS on the W.M. Keck ten–meter telescope are shown. The total exposure time is 6000 sec. ADC counts are plotted as a function of observed wavelength, excluding the region around the very strong 5577Å night sky emission line.

The big payoff in this field comes from surveys where galaxy redshifts are measured, which requires much more telescope time. Now that multi-object spectrographs are available on most large telescopes, there is a lot of activity in this area. Ignoring efforts concentrating on the local universe, such as the Center for Astrophysics surveys (see Thorenstein et al 1995, and references therein), there are surveys with non-filled areas (such as pencil beam surveys), including those of Kirshner et al (1990), and there are several groups working on large scale surveys of faint galaxies. The British group (see Glazebrook et al 1995 and references therein) and the group at the University of Hawaii (see Cowie et al 1994 and references therein) are among the most active.

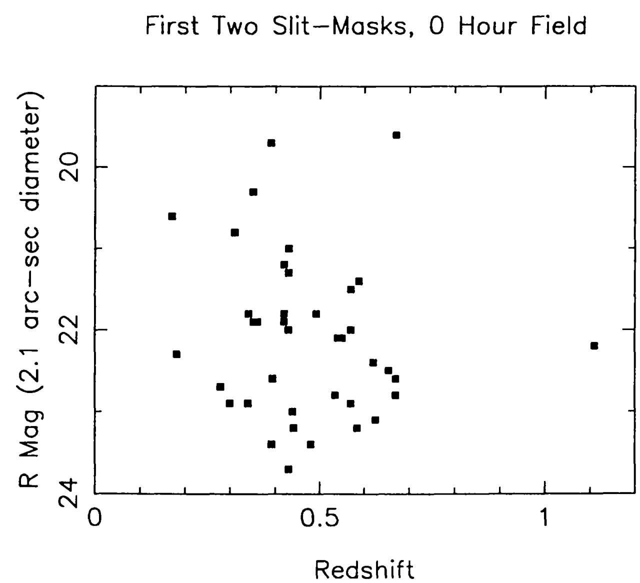

Fig. 2. The redshift as a function of R magnitude inside a 2.1 arc-sec diameter aperture is shown for those galaxies in the first two slit-masks of the 0 hour field of the Caltech deep spectroscopic survey of faint field galaxies. The multi-slit spectra were taken with the LRIS on the W.M. Keck telescope.

The Caltech deep spectroscopic survey of faint field galaxies is concentrating on a single field and all redshifts come from LRIS multi-slit images. The sample is defined by the cutoff $K = 20$ mag, and is based on 2.2μ images obtained with the Palomar 60–inch telescope. This effort showcases the multi-slit mode of operation of LRIS, where spectra of up to 35 objects can be obtained simultaneously. In the field we are currently working on redshifts for the "brighter" galaxies have been obtained, and Figure 1 shows representative spectra of four distant galaxies obtained with the LRIS on the Keck telescope. These illustrate the range of galaxy type seen, from pure absorption spectra to those totally dominated by emission lines with essentially undetectable continua. A surprisingly large fraction of the galaxies fall into this latter group.

Figure 2 versus magnitude for the 40 "bright" objects in that field whose redshifts have been determined obtained from the first 3 multi-slit masks analyzed here. The median R magnitude (in a 2.1 arc-sec diameter aperture) is about 22 and the median redshift is about 0.45. Note that this is the "bright" part of the sample.

Completion (with perhaps 10% of the objects without redshifts) of the full sample of 155 objects in this strip 2 x 8 arc-min is expected to occur this summer. The divergence between the various types of models increases rapidly at fainter apparent magnitudes and larger redshifts, a fact well known to any student of observational cosmology, so extending this type of survey even deeper is critical. That is what we are in the process of doing.

MY PERSONAL PROGRAMS

Although not all of these are relevant to the topic of this meeting, I can't resist showing you some of the data from my personal research programs now underway at Keck.

My graduate student Lin Yan and I have written a paper on cooling flows. We searched for the [FeX] line at 6574Å in the central regions of two massive clusters of galaxies where X-ray observations indicate the presence of a cooling flow. We did not detect any [FeX] emission in either Abell 1795 or in Parkes 0745–191. Our upper limits in both clusters are about a factor of 10 better than the previous measurements. Full details, and a discussion of how these data can be used to constrain models for cooling flows, can be found in our paper (Yan and Cohen 1995) which will be published in the Nov. 20, 1995 issue of the Astrophysical Journal.

As many of you know, I have been interested in globular clusters for a long time. The combination of the LRIS on the Keck telescope is a perfect one for reaching the extensive globular clusters around the central massive ellipticals in the Virgo cluster, and I have been working on this for the past year or so. I now have spectra taken with 8 multi-slit masks encompassing about 200 globular clusters. Figure 3 shows the spectra of 4 typical objects in the region of the Mg triplet. The spectra are beautiful, and should yield not only abundances and kinematic data for the globulars, but also such for the inner part of the halo of M87 itself. There should also be strong constraints on any age differences among the clusters in the M87 population. I'm looking forward to finding enough time this fall and winter to finish the analysis for this project.

One other project I have underway is that of looking for rotation in horizontal branch stars. Following the early work of Ruth Peterson (1985), there has been a hiatus in progress in this field for many years. Now with the high resolution echelle spectrograph (HIRES) on the Keck telescope, it is possible to obtain precise high-signal-to-noise spectra of such faint stars in a relatively short exposure time.

I have HIRES spectra of five horizontal branch stars in M92. Four of the five show detectable rotation, with the maximum value of v_{rot} projected onto the line of sight equal to 60 km/sec. I can't tell yet whether there is a real spread in v_{rot} or whether the distribution is just the result of a random distribution of projection angle. Figure 4 shows about 60Å (part of one echelle order) in the spectrum of M92 XII-1, the M92 horizontal branch star with the highest detected rotation in my sample, versus that of M92 X-22. It is obvious from examining this small part of the spectrum that projected v_{rot} values differ substantially among the stars in this sample and that in some cases v_{rot} is large.

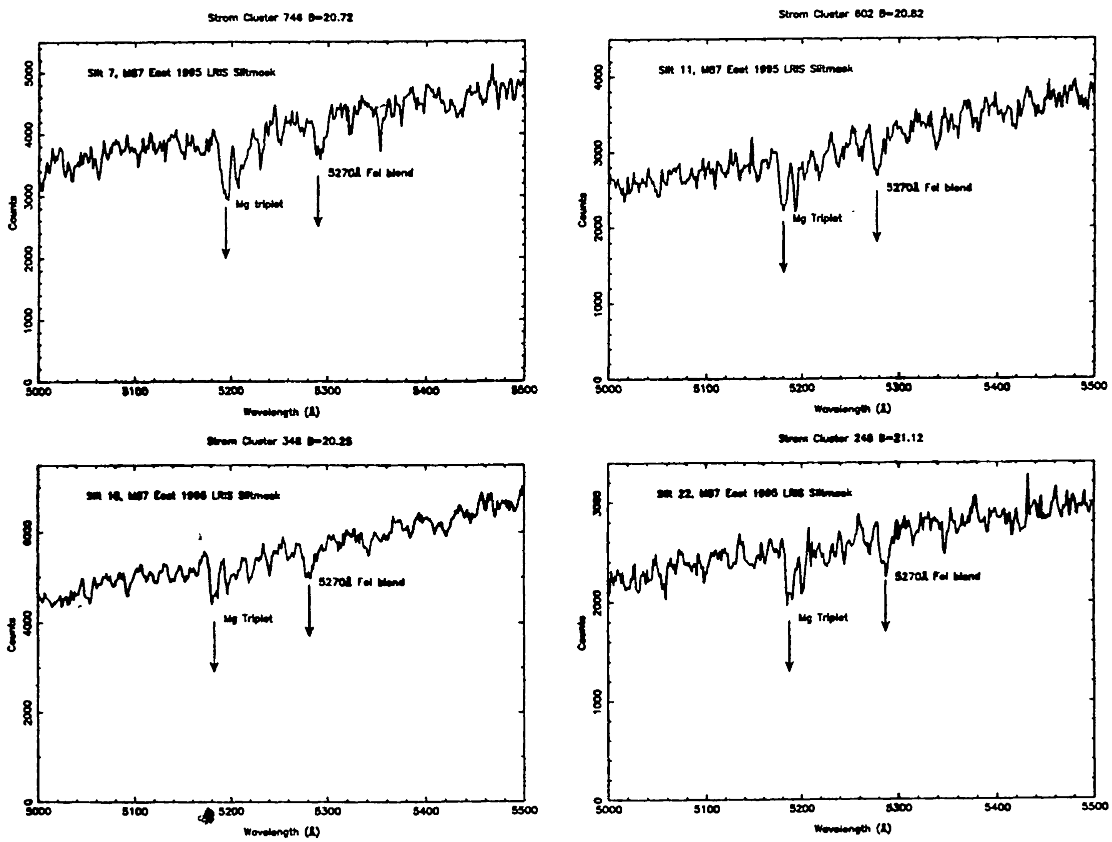

Fig. 3. Spectra of four typical globular clusters in M87 (ADC counts versus wavelength) in the region of the Mg triplet are shown. Some of the most prominent features are identified. These spectra have not been converted to flux units.

Just as have most astronomers these day, I too have been swept up in the brown dwarf mania. Mould et al (1994) presents our effort using the LRIS on the Keck telescope for one proposed candidate for that honor, PC0025+0447. While this is a very late type cool star, it does not show any LiI lines and is almost surely not a brown dwarf.

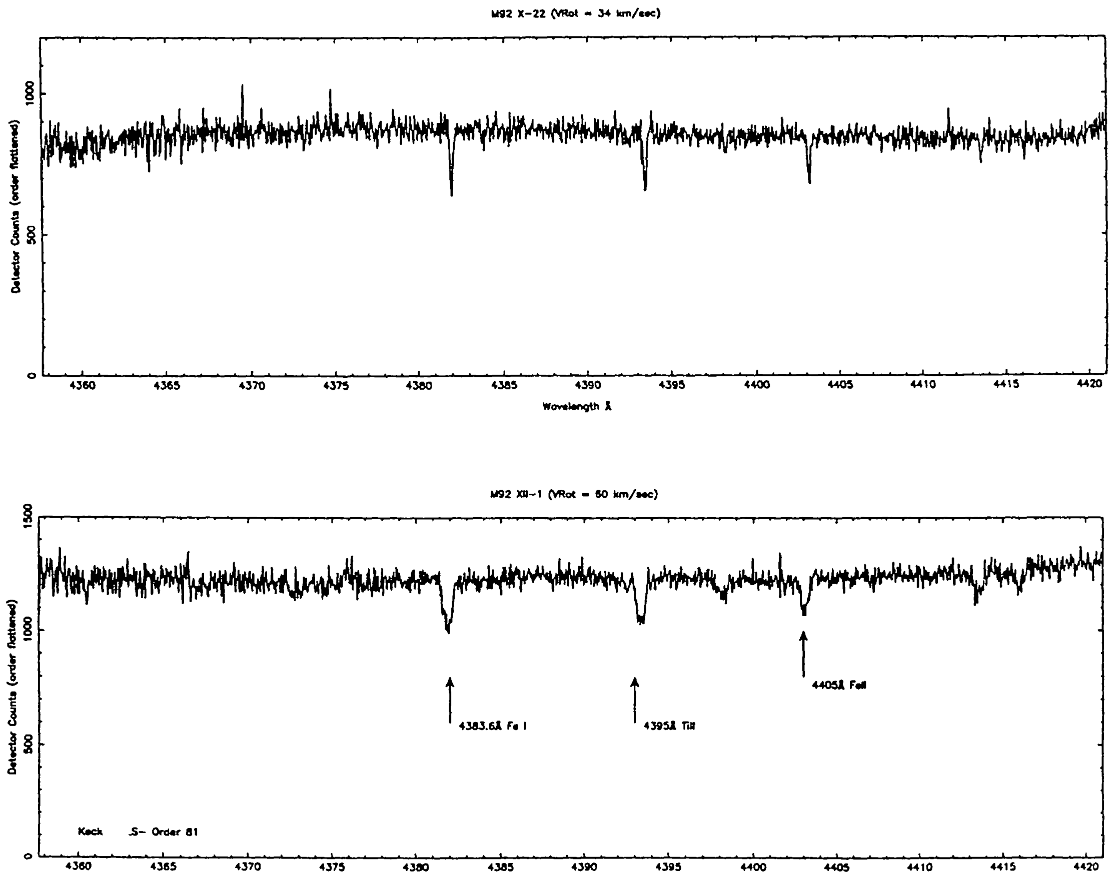

Fig. 4. Part of a single echelle order from the HIRES spectra of two horizontal branch stars in M92 is shown. These spectra have been corrected for the loss in signal as one moves off the center of an echelle order, but have not been fluxed.

CONCLUSION

The Keck telescope is a functioning scientific facility, and there is a lot of exciting work being carried out with it at the present time by many people. I present here a brief summary of but a small part of this large body of work, much of it on the forefront of astronomy and sure to have a big impact in the fields of gravitational lensing and studies of faint field galaxies in the very near future once more of the studies currently underway are completed.

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