12

STEWARD - 1435

FERMILAB
SEP 1 1998
LIBRARY

PREPRINTS of the STEWARD OBSERVATORY

THE UNIVERSITY OF ARIZONA
TUCSON, ARIZONA 85721-0065 U.S.A.

Fermilab Library
0 3560 0097364 4

No. 1435

OPTICAL SPECTROSCOPY WITH A NEAR SINGLE-MODE FIBER FEED AND ADAPTIVE OPTICS

Jian Ge[a], Roger Angel[a], Chris Shelton[b]

NAME	I D No.	M.S.

FERMILAB LIBRARY

1998 SPIE CONFERENCE PROCEEDINGS 3355 ON
OPTICAL ASTRONOMICAL INSTRUMENTATION
IN PRESS

[a]Steward Observatory, The University of Arizona, Tucson, AZ 85721
[b]Keck Observatory, 65-1120 Mamalahoa Highway, Kamuela, HI 96743

Optical Spectroscopy with a Near Single-mode Fiber Feed and Adaptive Optics

Jian Ge[a], Roger Angel[a], Chris Shelton[b]

[a]Steward Observatory, The University of Arizona,
Tucson, AZ 85721 USA

[b]Keck Observatory, 65-1120 Mamalahoa Highway, Kamuela, HI 96743 USA

ABSTRACT

We report on first astronomical results with a cross-dispersed optical echelle spectrograph fed by a near single-mode fiber. We also present on a novel design of a new adaptive optics (AO) optimized fiber-fed cross-dispersed echelle spectrograph. The spectrograph is designed to match with AO corrected images in the optical bands provided by such as the Mt. Wilson 100 inch, Starfire Optical Range 3.5 m AO telescopes. Ultimately, it will be installed at the 6.5 m MMT, when this has high resolution AO correcting the optical spectrum. The spectrograph, fed by a 10 micron fused silica fiber, is unique in that the entire spectrum from 0.4 micron to 1.0 micron will be almost completely covered at resolution 200,000 in one exposure. The detector is a 2kx4k AR coated back illuminated CCD with 15 micron pixel size. The close order spacing allowed by the sharp AO image makes the full cover possible. A 250x125 mm^2 Milton Roy R2 echelle grating with 23.2 grooves mm^{-1} and a blaze angle of 63.5 deg provides main dispersion. A double pass BK7 prism with 21 deg wedge angle provides cross dispersion, covering the spectrum from order 193 to 77. The spectrograph is used in the quasi-Littrow configuration with an off-axis Maksutov collimator/camera. The fiber feeds the AO corrected beams from the telescope Cassegrain focus to the spectrograph, which is set up on an optical bench.

The spectrograph will be used mainly to study line profiles of solar type stars, to explore problems of indirect detection of planets and also study interstellar medium, circumstellar medium and metal abundance and isotopic ratios of extremely metal-poor stars.

Keywords: Adaptive Optics, Spectroscopy, Encircled Energy, Fiber-Feed

1. INTRODUCTION

Adaptive optics (AO) promises revolutionary advances in imaging power for ground-based optical and infrared astronomical telescopes by correcting the wave-front distortion caused by atmospheric turbulence. The AO corrected optical images are nearly diffraction-limited, about a factor of ten times smaller than that limited by the atmospheric seeing for current 4 m class telescopes. For the largest of the new generation of telescopes such LBT and VLT, the most dramatic gain is possible, permitting an imaging performance of almost two orders of magnitude.

In this new astronomical era, large telescopes will take advantage of AO to provide diffraction-limited images at IR wavelengths. Especially with laser guide star techniques, AO will be able to provide imaging correction in the infrared with full sky coverage. Small telescopes take advantage of AO to provide not only correcting power for the IR wavelengths, but also for the optical wavelengths for bright stars.

One of the most important applications of the much sharpened AO images is astronomical spectroscopy. With high order AO systems available at such as the Starfire Optical Range 1.5 m, 3.5 m telescopes and Mt. Wilson 100 inch telescope, the light from bright stars is significantly concentrated within small aperture. Therefore, spectrographs can be designed to match the much sharpened AO images to provide much higher spectral resolution. One of the most significant properties of the AO spectrograph is that the spectrograph resolving power is decoupled from the telescope aperture size, opposite to the seeing-limited spectrograph case. Therefore, a spectrograph can universally match different aperture size telescopes to provide similar spectral resolution. As demonstrated by us before (Ge et

Other author information: (Send correspondence to Jian Ge)
J. G.: Email: jge@as.arizona.edu; WWW: http://qso.as.arizona.edu/~jge; Telephone: 520-621-6535; Fax: 520-621-1532

al. 1996 a,b), spectral resolution of R $\sim$ 200,000-500,000 can be routinely reached by a spectrograph with commercial available echelle gratings.

The application of adaptive optics in astronomy is still in its early phase and the design of AO optimized instruments, especially spectrographs, is new territory now being opened for exploration. In addition to the advantage of much higher resolution AO spectrographs can provide over traditional spectrographs, there are many other advantages for AO spectrographs. Because of the much smaller AO sharpened image size, the next generation AO optimized high resolution spectrographs will have smaller overall scale, higher efficiency and slower focal ratios which result in much less cost. As the first demonstration of next generation AO spectrographs, a prototype AO cross-dispersed echelle spectrograph was built by us with a 125x250 mm^2 R2 echelle grating at Steward Observatory and tested at Starfire Optical Range 1.5 m AO telescope. The spectrograph can provide spectral resolution up to R = 700,000 (Ge et al. 1996). Because of the much smaller image size, a large amount of cross dispersed orders can be packed and recorded on the detector, and thus a factor of 100 times larger wavelength coverage over similar resolution traditional spectrographs was achieved (e.g. Diego et al. 1995; Lambert et al. 1990; Ge et al. 1996). Because of the much smaller image size, AO spectrographs can record astronomical phenomena of much smaller scale structure (Bacon et al. 1995). Further, the smaller entrance slit used in the AO spectrographs can help to block most sky background, especially in the IR where the sky background is about 100 times brighter than in the visible, so much fainter objects can be observed.

There are additional advantages in using a fiber to feed AO corrected beams from a telescope to the spectrograph. The spectrograph can be separated from the telescope, therefore a more stable optical bench set-up for the spectrograph for high precision observations can be made. If one is not interested in radial velocity measurements or other work requiring high absolute precision, the spectrograph can be designed to be a portable unit which can be easily matched to different telescopes. Further the fiber is used as a spatial filter, reducing scattered light between cross-dispersed orders, as well as defining the high spectral resolution.

In this paper, we will first review the Mt. Wilson AO system and its image performance and use it as an example for the design of a high efficiency AO spectrograph. Then we will show initial experimental results from the Mt. Wilson 100 inch telescope with our fiber-fed ultra-high resolution spectrograph. Finally we will show a new design for a low-cost, high efficiency AO optimized high resolution spectrograph.

2. IMAGE QUALITY FROM OPTICAL ADAPTIVE OPTICS TELESCOPES

As demonstrated before, adaptive optics cannot provide ideal diffraction-limited images in principle, due to the limited photon flux available from the reference source, finite response time and subaperture size of the AO systems (Sandler et al. 1994; Ge et al. 1997). The AO corrected images consist of two components: a diffraction-limited core and a broad seeing-limited halo caused by uncorrected wavefront error (Beckers 1993), which make the design of AO instruments, especially spectrograph systems, different from that of seeing limited instruments.

AO spectroscopy is much more complicated than seeing limited spectroscopy. The AO corrected image quality depends not only on instantaneous seeing conditions, described by the atmospheric turbulence coherence length r_0, but also atmospheric wind velocity, described by t_0. If the scientific object is not in the same direction as the guide star (natural or laser), the image quality will also depend on the angle between the guide star and the object, caused by atmospheric anisoplanatism. Moreover, image quality from the correction by the laser guide star, which provides much larger sky coverage over bright natural guide stars, will also suffer degradation caused by the effect of finite laser guide star height, called focal anisoplanatism. Therefore, it is necessary to study the image properties such as Strehl ratio and encircled energy from a particular AO telescope before the design of the spectrograph.

The Mt. Wilson 100 inch telescope is the first astronomical telescope to be equipped with an AO system to providing usable image correction in the visible wavelengths. In the following, we will use the image performance from this telescope to show how to match AO images to a high resolution spectrograph. The Mt Wilson AO system uses bright natural guide stars for wavefront sensing and correcting (Shelton et al. 1995; 1997). The system has a 241-actuator deformable mirror. Subaperture size is 0.156 m. The wavefront sensor uses a front-side illuminated 32x32x2 frame-transfer silicon array. It is used for sensing both tilt and high order wavefront errors. The delay time of the system, from mid-CCD exposure to updating the deformable mirror, is 4.5 ms for objects in the R=2.5 to 9.5 magnitude range, 3.0 ms for objects brighter than R=2.5, 4.5-7.5ms for objects in the R=9.5 to 13.7 range, depending on seeing.

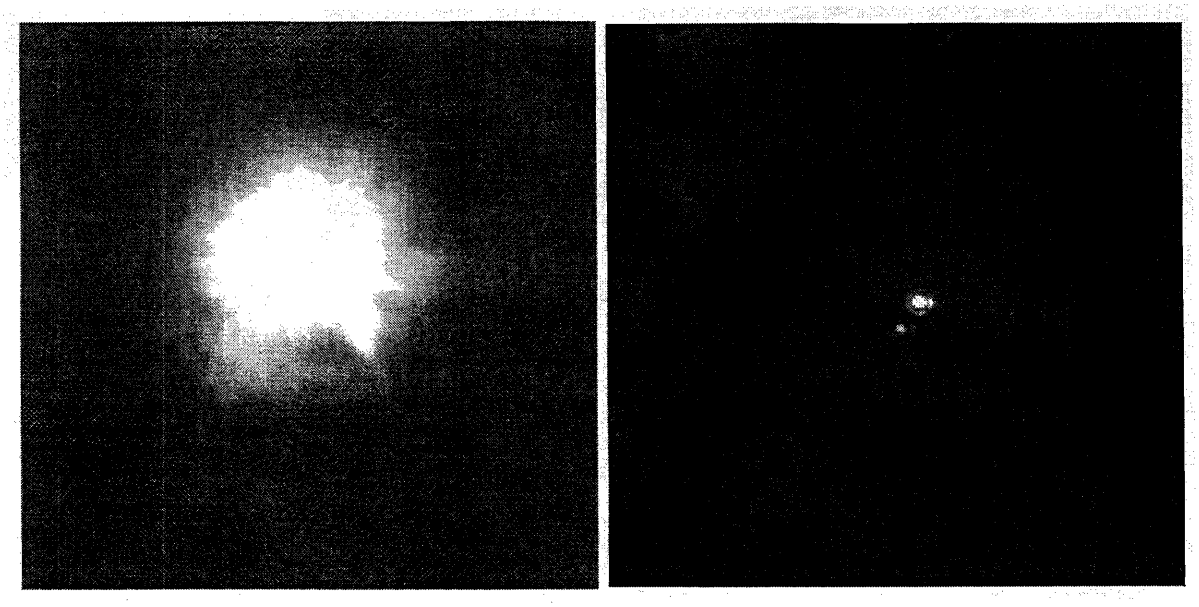

Figure 1. a. I-band image without AO correction; b. I-band image with AO correction, bright star HR 5747 (V= 3.7 mag.)

Figure 1 shows the comparison of I band images of bright star HR 5747 with and without AO correction, obtained in July, 1996. The FWHM (full width half maximum) of the image without AO is 1″, corresponding to $r_0 = 11$ cm at 0.55 μm. The FWHM of the image with AO correction is 0.1″, which clearly shows the Airy disk. The image also shows a fainter companion with separation of 0.3″ from the primary.

From the appearance of the AO corrected image, it appears that spectrograph should be designed to match the diffraction limited core size. However, in order to obtain high throughput, further study beyond first appearances is very important because even though the intensity near the core is much higher than the halo, the halo occupies much large area, and may include a significant amount of energy.

As an example, Table 1 shows the measurements of Strehl ratio, encircled energy percentage for the typical summer observation at the Mt. Wilson 100 inch. Table 2 shows the measurements for the typical winter observation. The results demonstrate that a significant number of photons are spread out over a large area. In order to obtain high throughput spectroscopy, a slit or fiber with width or core diameter of 3-4 times diffraction-limited core size is required for Strehl ratio less than 0.4.

Table 1 and 2 also indicate a significant difference between the results from the summer observations and winter observations, which is mainly caused by the different wind velocities for the different seasons. The typical wind velocity is about 10 m s^{-1} for summer time and about 20 m s^{-1} for winter time. For typical atmospheric turbulence coherence length, $r_0 = 14$ cm (or 0.8 arcsec FWHM seeing disk size), at 0.55 μm, the atmospheric turbulence coherence time scale t_0 is about 4.3 ms and 2.2 ms for summer and winter, respectively. The temporal error caused by the delayed correction (Sandler et al. 1994),

$$\sigma^2_{time} = (\frac{\Delta t}{t_0})^{5/3}, \tag{1}$$

where Δt is the wavefront delay time. The temporal error becomes very significant at the short wavelength especially in the winter time because of much longer wavefront correcting delay time than the coherent time scale.

Table 1. Strehl and Encircled Energy(EE) for Summer Observations

Band	Strehl	0.1″(EE)	0.2″(EE)
I	0.36	22%	42%
R	0.17	17%	35%
V	0.09	17%	31%
B	0.03	8%	22%

Table 2. Strehl and Encircled Energy for Winter Observations

Band	Strehl	0.1″(EE)	0.2″(EE)
I	0.27	18%	36%
R	0.05	8%	20%
V	0.03	5%	16%
B	0.02	5%	14%

Tables 3 and 4 pull together the various image motion and high-order wavefront error sources, derived from the typical measured parameters at Mt. Wilson in summer and winter, into an overall error budget for the 100 inch telescope.

The calculations of Strehl ratio, high order residual errors and tilt errors are based on the formula described in previous papers (Sandler et al. 1994; Ridgway 1994; Ge et al. 1997).

The calculation results match the observation results from typical summer and winter observations well. The temporal error is the dominant one for this AO system. Higher frequency correction is required to significantly improve the flux concentration ability, especially in short wavelengths.

Table 3. Error Budget for Summer Observation at the Mt. Wilson 100 inch

	λ=0.9 μm	λ=0.7 μm	λ=0.55 μm	λ=0.44 μm
σ^2_{fit}	0.13	0.21	0.34	0.53
σ^2_{time}	0.78	1.28	2.08	3.25
σ^2_{rec}	0.01	0.02	0.03	0.05
σ^2_{HO}	0.92	1.51	2.45	3.83
σ^2_{tilt}	0.02	0.02	0.02	0.02
Strehl Ratio	0.37	0.21	0.08	0.02

Table 4. Error Budget for Winter Observation at the Mt. Wilson 100 inch

	λ=0.9 μm	λ=0.7 μm	λ=0.55 μm	λ=0.44 μm
σ^2_{fit}	0.13	0.21	0.34	0.53
σ^2_{time}	1.47	2.01	3.63	5.08
σ^2_{rec}	0.01	0.02	0.03	0.05
σ^2_{HO}	1.61	2.24	4.00	5.66
σ^2_{tilt}	0.04	0.04	0.04	0.04
Strehl Ratio	0.23	0.10	0.03	0.01

3. NEAR SINGLE-MODE FIBER-FED EXPERIMENT RESULTS AT THE MT. WILSON 100 INCH TELESCOPE

The image quality from the Mt. Wilson 100 inch AO system is suitable for high resolution spectroscopy. A 0.2″ entrance aperture size instead of 1″ for the seeing-limited spectroscopy can be applied to maintain similar throughput. At the same time, spectral resolution is expected to be a factor of 5 times higher than that for the seeing-limited spectroscopy with a same size echelle grating.

We conducted a first high resolution spectroscopy experiments at the Mt. Wilson 100 inch telescope in November 1997 to take advantage of AO sharpened images in the optical wavelengths. An innovation in our implementation at the Mt. Wilson compared to our previous AO spectroscopy experiments at SOR (Ge et al. 1996a,b; 1998) is the use of a fiber to feed the spectrograph, which was set up on an optical bench (Figure 2). In order to feed the AO corrected beam to a fiber efficiently, the fiber entendue, or $A\Omega$ value, should be well matched to the AO beam quality. The AO beam entendue of the Mt. Wilson 100 inch is about 0.16 $m^2 arcsec^2$, a factor of 25 times smaller than the seeing-limited beam entendue. In order to match the AO beam quality, a fiber with core size of 10 μm is required for f/4 fiber feed. Therefore, typical astronomical fibers with core size larger than 50 μm cannot be served for AO spectroscopy.

The properties of this kind of extremely thin fibers, especially the focal ratio degradation, have not been well studied before. These properties are crucial for the design of fiber coupler. We set up a lab at Steward Observatory and tested a commercial OH dry 8 μm core size fiber made of fused silica in 1997. This fiber is mainly used for single mode communication at near-IR 1.5 μm. It transmits a few modes (Keiser 1991) in the optical wavelengths and has excellent transmission to about 0.4 μm. Figure 3(a) shows the typical mode structure once a He-Ne laser beam passes through the fiber. Figure 3(b) shows the focal ratio degradation of this extremely thin fiber. The measurements show that the focal ratio degradation of this extremely thin fiber is very similar to that of a single mode fiber, i.e. the output focal ratio is almost independent of the input focal ratios (Foresto et al. 1993). For f/4 input, 80% photons emerge within f/4.

A very similar single-mode fiber with 10 μm core size and 20 m length has been used to transmit AO corrected beams from the 100 inch Cassegrain focus to the spectrograph optical bench during the 1997 November observation run at the Mt. Wilson. An input coupler with control in x,y and z and tip-tilt was used to feed the fiber at f/4, corresponding to 0.2″ on the sky. At the fiber output, another coupler was used to convert the f/4 beam to f/50, with a corresponding magnification to an apparent slit size of 130 μm. The expected spectral resolution is about 200,000. The spectrograph was used in the Littrow configuration. It used the same echelle grating as was used at SOR, a 250x125 mm^2 Milton Roy R2 echelle grating with 23.2 grooves/mm and a blaze angle of 63.5° (Ge et al. 1996; 1998). This provides the main dispersion in a large number of relatively short orders. The same 8° wedge BK7 prism was used for the cross dispersion.

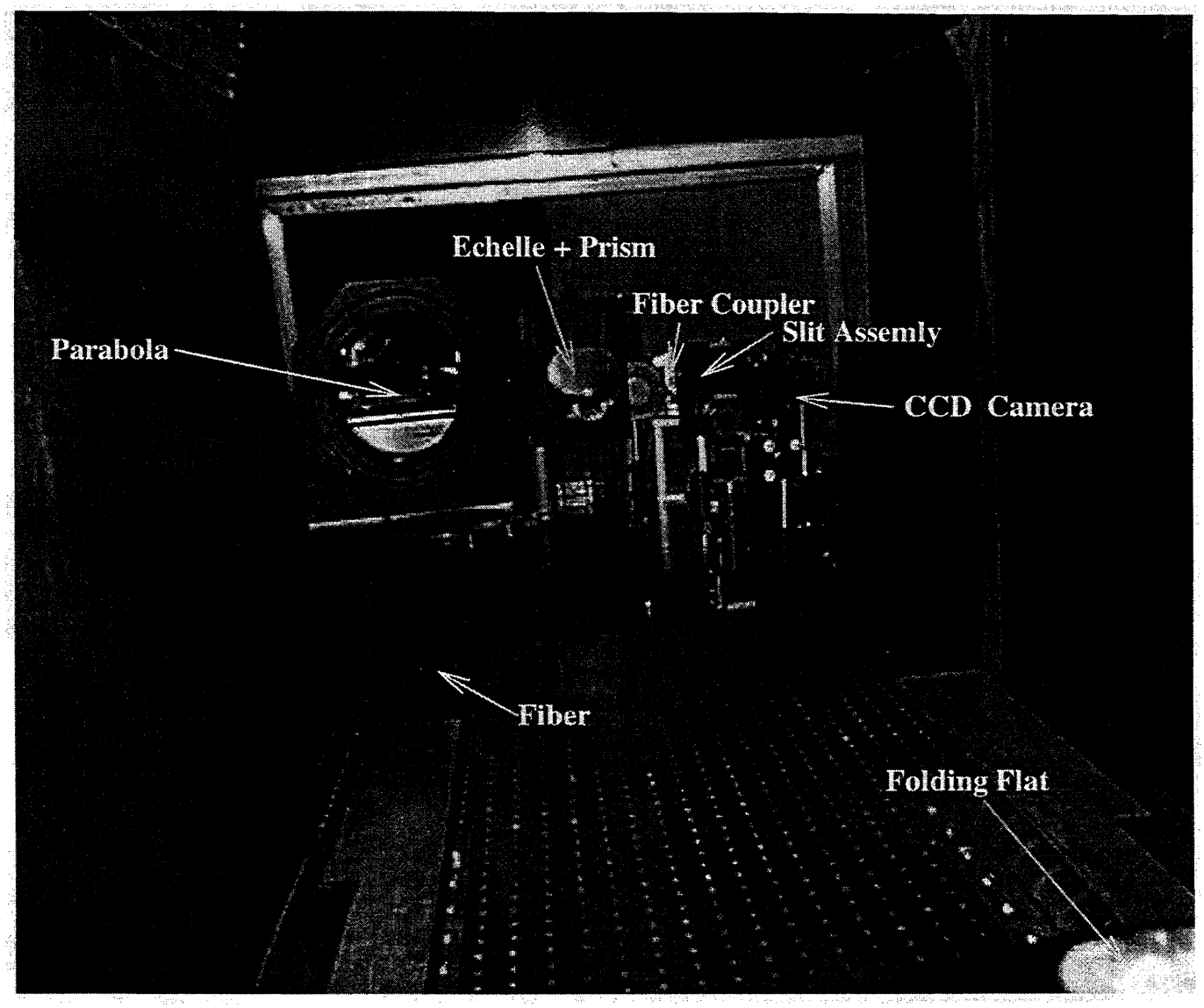

Figure 2. The setup of the spectrograph at the Mt. Wilson 100 inch telescope Optical bench, Nov. 2nd-6th, 1997

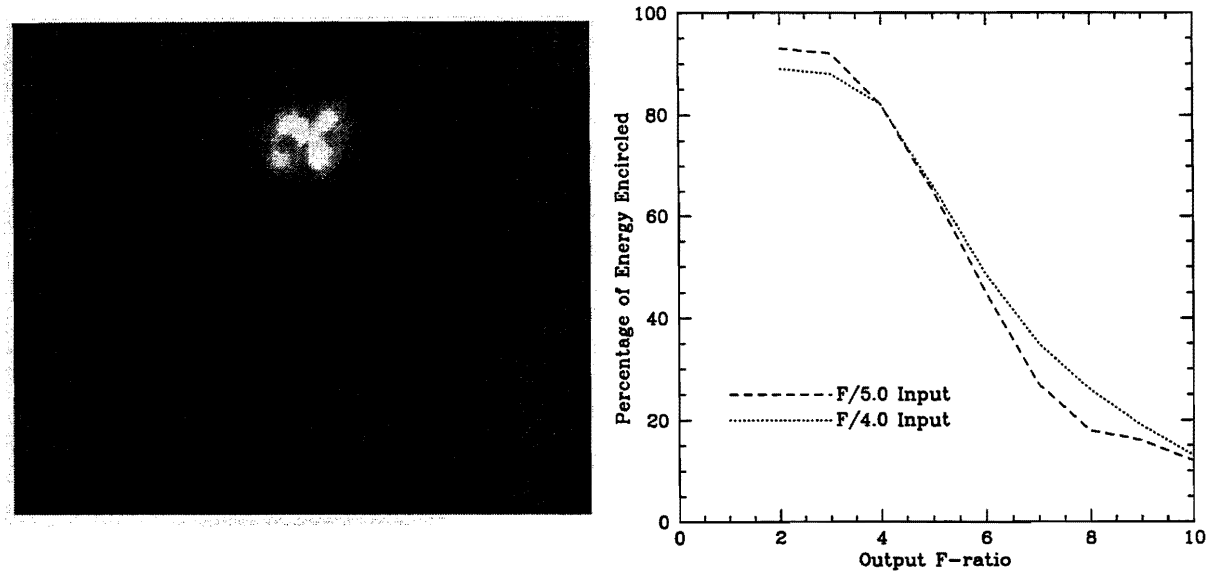

Figure 3. (a). Image of mode structure of a HeNe laser (at 6328 Å) beam through an 8 micron fiber. The magnification is 60 times. The physical dimension of the whole frame is 4.3x3.7 mm^2. (b). Focal ratio degradation for an OH dry fused-silica fiber with 8 μm core size

Figure 4 shows the spectrum obtained through the near single-mode fiber-fed echelle spectrograph and reduced spectrum from the cross dispersed order 112 at wavelength around 6868 Å. The 1kx1k thermally cooled CCD with 24 μm pixel size covers about 80 cross-dispersed orders, from order 75 to order 156. Totally about 650 Å is covered with one exposure. The main results from the observation run are summarized in Table 5. Throughput of the fiber-feeds has been measured up to 70%. However, we found that it is quite difficult to maintain the alignment of the input fiber-feed optics with the telescope AO system for a period of time. Tiny misalignment between the AO optics and fiber feed optics reduced the throughput tremendously. A much more robust mechanical mount is required to stabilize the efficient transmission of AO beams to the fiber.

Table 5. Main results from 1997 November run at the Mt. Wilson 100 inch

Spectral resolution	$\sim$ 200,000
Wavelength coverage per exposure	650 Å
Fiber-feed transmission	65% for laser, 20% for star
Spectrograph + Fiber + CCD transmission	2.5%
Overall telescope + AO transmission	2%
Encircled Energy within 0.2″	$\sim$ 20%
1Kx1K CCD size	25x25 mm^2

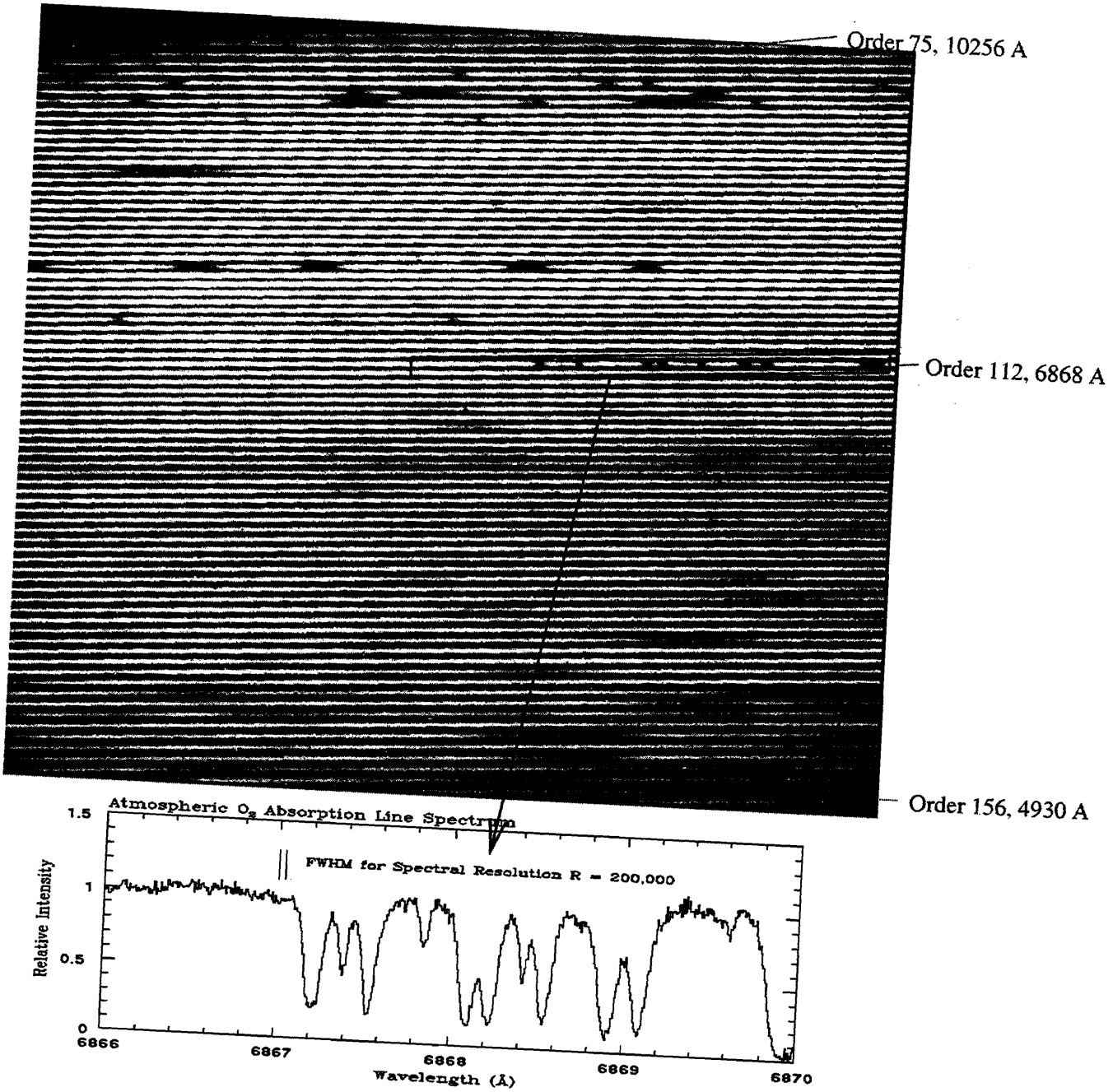

Figure 4. Spectrum of α Ori from the AO echelle spectrograph at the Mt. Wilson 100 inch telescope

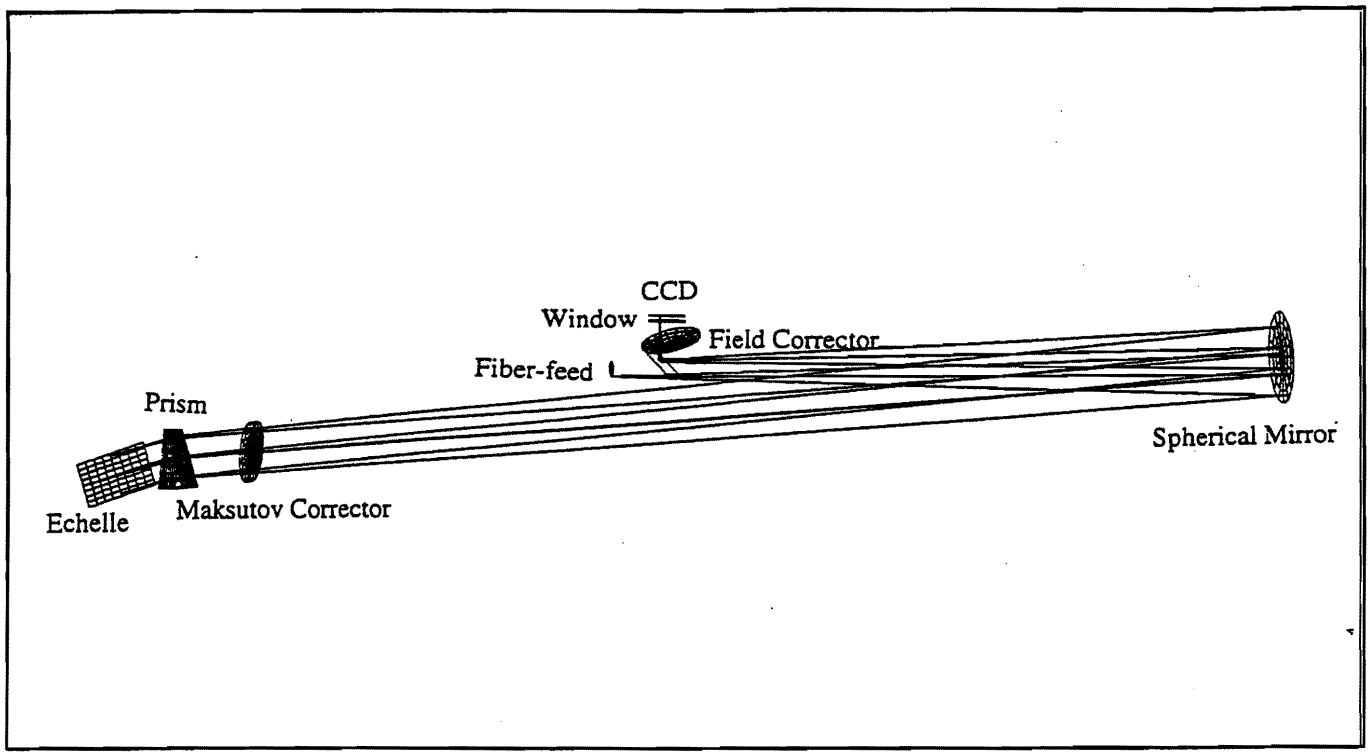

Figure 5. Optical layout of the AO echelle spectrograph with R = 200,000. All surfaces are spheres.

4. DESIGN OF A NOVEL AND LOW-COST FIBER-FED CROSS-DISPERSED OPTICAL ECHELLE SPECTROGRAPH WITH SPECTRAL RESOLUTION OF 200,000

As shown in Table 1 and 2, it is important to design a high resolution spectrograph to match with 0.2″ entrance slit size, or the first Airy disk size at the I band, at the Mt. Wilson 100 inch telescope to maintain high throughput of the whole system. The theoretical spectral resolution with the 125x250 mm^2 R2 echelle is expected to be about 200,000. The fiber core size of 10 μm should be chosen for f/4 fiber coupling. In order to well sample the spectral resolution elements on a CCD detector, a f/16 beam is sufficient for the spectrograph optics. Therefore, the projected resolution element on the detector is 40 μm, which is well beyond Nyquist sampling for 15 μm pixel size. This focal ratio is about 3 times faster than that for the old echelle spectrograph, f/50 (Ge et al. 1996; 1998). If a design similar to the old one is pursued for the new spectrograph, a quite expensive off-axis paraboloid, which is used as the spectrograph collimator and camera, has to be made.

In order to build the spectrograph within short period of time and low budget, a novel design with an off-axis Maksutov collimator/camera is applied. Therefore, no conic surfaces are included in this new design. The optical layout is shown in Figure 5. The collimator/camera is a sphere and its radius is concentric with the Maksutov plate radii. A field corrector is used near the CCD detector to correct residual Coma and Astigmatism over about 2x2 deg^2 field-of-view. The resulting RMS spot size over the whole field-of-view is much smaller than the first Airy disk size. Therefore, the whole spectrograph system optics is diffraction-limited. The residual aberrations from the spectrograph optics will not degrade the spectral resolution. For this new design, the echelle will be the same one used at SOR and Mt. Wilson. A 21 deg BK7 prism will be used to provide enough cross-dispersion over wavelengths from 0.4 to 1.0 μm. The order separations between orders are quite homogeneous, with the minimum separation is 240 μm or 15 Loral CCD pixels. The spectral format with this new design is shown in Figure 6. A physical size for a 2Kx4K loral CCD size (30x60 mm^2) has also been shown in this Figure. About 4000 Å can be covered by this CCD in one exposure.

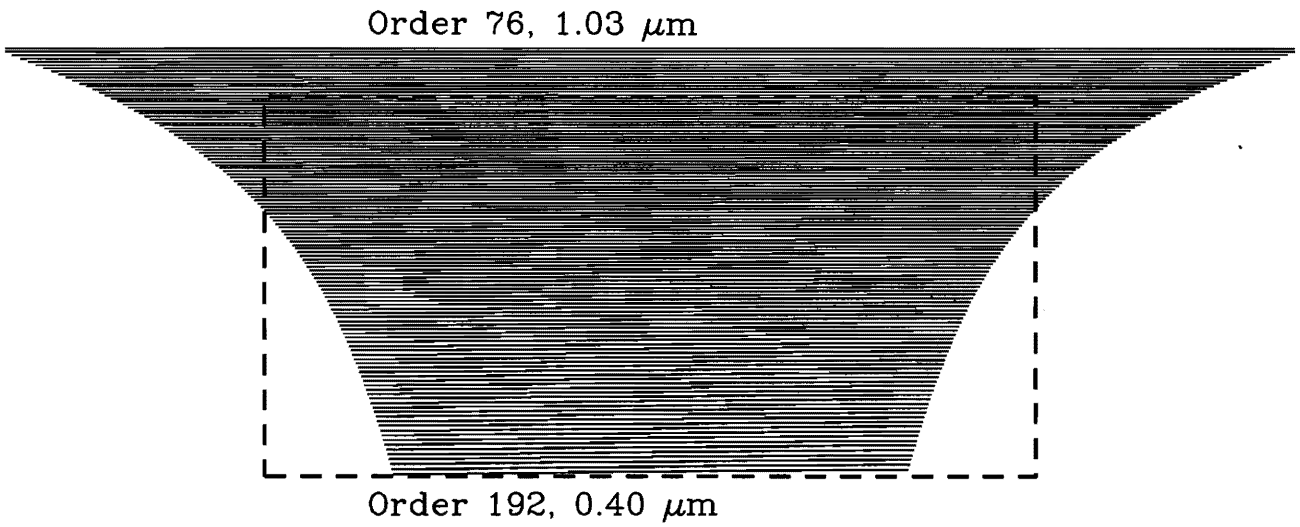

Figure 6. Spectral format for the new AO optimized echelle spectrograph with R = 200,000. The dotted line box is the physical size of a Loral 2Kx4K CCD with 15 μ pixel size. About 4000 Å spectrum can be covered in one wavelength set-up with the Loral CCD

5. SUMMARY

The observation run at the Mt. Wilson 100 inch AO telescope with the fiber-fed high resolution echelle spectrograph demonstrates the possibility of matching the AO corrected beams with high resolution spectrograph through an extremely thin fiber. The coupling efficiency of the single-mode IR fused silica fiber has been measured up to 70%, which is very close to the theoretical limit of about 80% for single mode fibers (Foresto et al. 1993). In order to obtain high throughput spectroscopy, a projected entrance slit size of 0.2″ or first Airy disk size is required. Therefore, for a commercial available 125x250 mm^2 R2 echelle grating, spectral resolution of R = 200,000 can be routinely reached with help from high order adaptive optics. Residual error caused by the delay of wavefront correction has been found to be the dominant one in the Mt. Wilson 100 inch telescope AO system. Image performance, especially at the short wavelength regions, is expected to be significantly improved through faster wavefront sensing and correction. Wavelength coverage with the AO high resolution spectrograph has been significantly increased compared to that with the seeing limited high resolution spectrograph. Spectroscopy with R $\sim$ 200,000, a factor of 4 times higher than most of present high resolution spectroscopy, will be routinely obtained with telescope equipped with high order AO systems.

ACKNOWLEDGEMENTS

We thank staffs at Mt. Wilson Institue for supporting the observation run. The observation is supported by NSF grant to Mt. Wilson Institute. We wish to thank Matt Rademacher for helping design the mount for the fiber-feeds and set up the spectrograph at the Mt. Wilson 100 inch. This work has been supported by the AirForce office of Scientific Research under grant number F 49620-96-1-0366 and NSF AST-9421311.

REFERENCES

Beckers, J.M. 1993, ARA&A, 31, 13
Bacon, R. et al. 1995, A&AS, 113, 347
Diego, F. et al. 1995, MNRAS, 282, 323
Foresto, V. et al. 1993, in Fiber Optics in Astronomy II, ASP Conf. Series, Vol. 37, 285
Ge, J. et al. 1996, in Adaptive Optics, Vol. 13, OSA Technical Digest Series (OSA, Washington DC), 122
Ge, J. et al. 1996, BAAS, 28, 905
Ge, J. et al. 1997, Proc. SPIE conf. on Adaptive Optics and Applications, Eds. R.K. Tyson & R.Q. Fugate, in press
Ge et al. 1998, in preparation
Keiser, G. 1991, Optical Fiber Communications, (McGraw-Hill, Inc.)
Lambert, D.L. et al. 1990, ApJL, 359, L19
Ridgway, S.T., 1994, in Adaptive Optics for Astronomy (Kluwer Academic Publishers), eds: Alloin, D.M., & Mariotti J.-M. 269
Sandler, D.G. et al. 1994, JOSA, 11, 925
Shelton, C. et al. 1995, Proc. SPIE 2534 on Adaptive Optics Systems and Applications, 72
Shelton, C. et al. 1997, Proc. SPIE conf. on Adaptive Optics and Applications, in press