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Galaxy Kinematics with Integral Field Spectroscopy and the Hobby-Eberly Telescope

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Abstract.
We describe two fiber-optical arrays under construction for the 9m Hobby-Eberly Telescope's (**HET**) Medium Resolution Spectrograph (**MRS**). These arrays optimize integral-field spectroscopy for kinematic studies of individual nearby and moderately distant galaxies. The arrays are *formatted* to deliver simultaneous rotation curve and disk velocity dispersion measurements for galaxies over a range of look-back times. From these kinematic measurements the evolution of galaxy mass-to-light ratios (**M/L**) can be explored on spatially resolved scales. One array spans ~30 arcsec using 2 arcsec (400-μm) fibers to densely sample slits at 4 position angles at spectral resolutions from 5500 to 11000. The second array spans ~15 arcsec using 1 arcsec fibers to densely sample a core area of ~60 arcsec^2 at spectral resolutions from 11000 to 22000. The first array will be installed during the commissioning phase of the MRS in early 1999. This two-beam, fiber-fed echelle spectrograph covers from 0.5-0.95 μm in a red beam, and 0.8-1.6 μm in a near-infrared beam. Below we describe the scientific motivation, design rationale, and expected performance of these two integral field units (IFUs) for the HET's MRS. The arrays are the first formatted IFUs designed for astronomical application.

1. Niche Science Mission

The primary purpose of the fiber arrays (or IFUs) under construction for the HET is to study galaxy disk kinematics in an extremely cost-effective and efficient way (Bershady 1997). Rotation curve and disk velocity dispersion measurements yield independent estimates of galaxies' total and disk masses. From these kinematic measurements, halo masses can be directly inferred without further assumptions (e.g. the assumption of maximal disks). This will provide a sensitive probe of the nature of dark matter in external galaxies, complementary to, e.g., micro-lensing experiments which probe within the Milky Way. A critical limitation in gathering the essential kinematic data has been the inefficiency of long-slit measurements made on aging spectrographs on 4m-class telescopes. In-

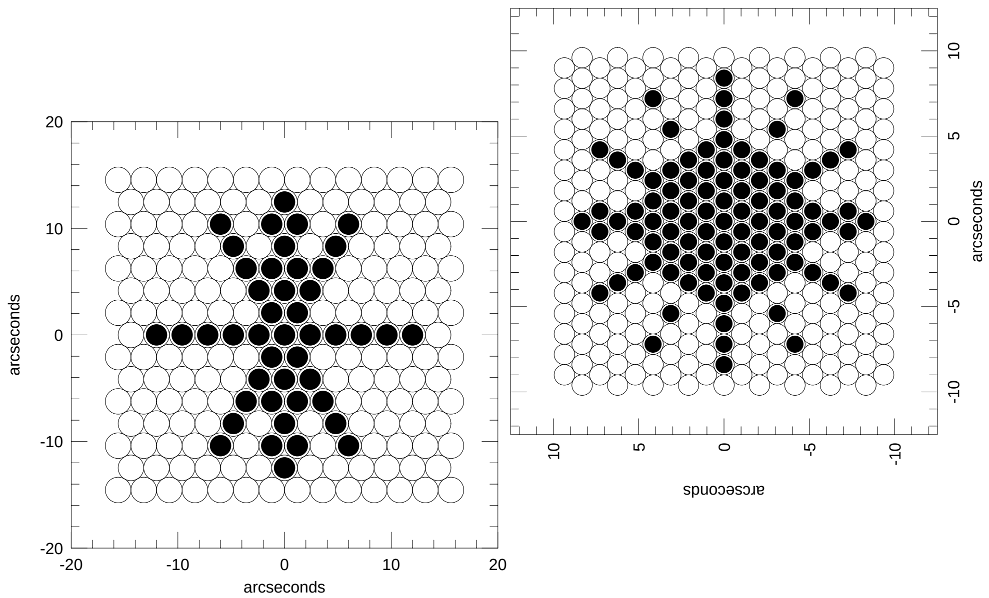

Figure 1. **[Left panel]** HET IFU #1, a 400-μm (2 arcsec) fiber array with 10:1:1 ratios of core to clad to buffer. **[Right panel]** HET IFU #2, a 200-μm (1 arcsec) fiber array with 10:1:1 ratios of core to clad to buffer. **Dark fibers** (45 and 95 in number for IFU #1 and #2, respectively) are the science fibers that go through to the spectrograph; **open fibers** are short fibers for mechanical packing. The interface yoke is not shown. Seven and nine sky fibers (IFU #1 and #2, respectively) on an independently positionable stage are also not shown.

tegral field spectroscopy on 10m-class telescopes using high-throughput, echelle spectrographs promises to open a new window on the mass and mass distributions of galaxies over a range of look-back times.

For example, a key survey with the larger HET IFU (#1, Figure 1) will be to measure disk M/L for samples of nearby spirals. Rotation curves and non-axisymmetric motions can be probed via line emission to intermediate redshifts using the smaller IFU (#2, Figure 1). Such surveys will map the evolution of M/L to epochs at half the current age of the universe. On 4m-class telescopes such instrumentation is impractical for low-surface-brightness spectroscopy at medium spectral resolution; fiber arrays planned for other 10m-class telescopes generally are optimized for smaller areas and higher angular resolution (see these proceedings). However, spiral galaxy disks are predominantly at low surface brightness; at high redshift their surface brightness fades further still. The MRS fiber arrays fill a powerful niche for low surface-brightness spectroscopy at medium spectral resolution over relatively large areas.

2. Design and Fabrication

Sampling geometry: To maximize science returns given a finite number of fibers, two patterns are adopted (**Figure 1**), sampling 4 position angles over large areas ($\sim$700 arcsec^2 and 300 arcsec^2 respectively for IFUs #1 and #2). For both IFUs, there is a densely sampled inner region. The remaining fibers are for mechanical packing, are short, and of little cost. **Figure 2** shows the larger IFU (#1) artificially mapped onto a nearby galaxy. Many trade-offs were considered when allocating 'science' fibers; chosen patterns reflect compromises between linear size and dense sampling while avoiding preferred angular scales.

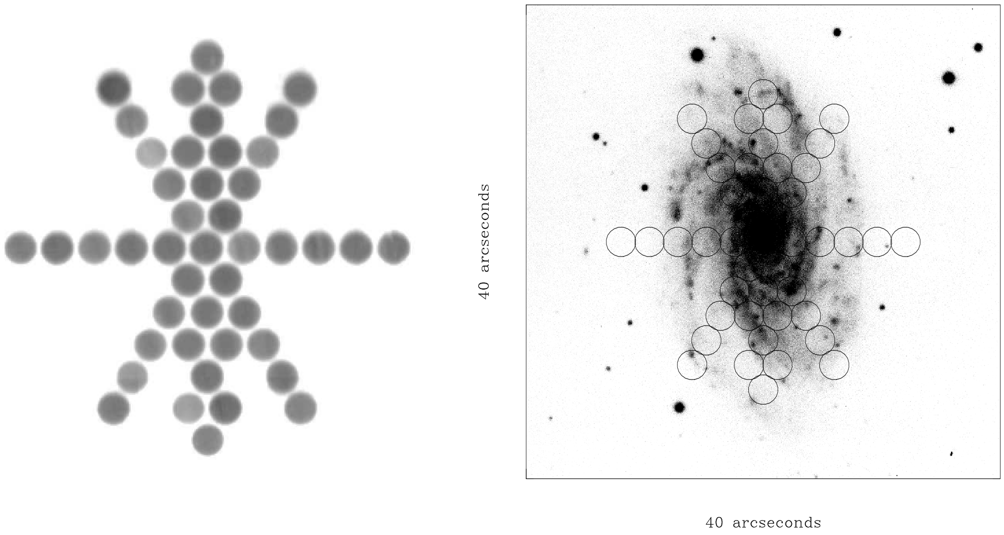

Figure 2. **[Left panel]** CCD image of a test version of HET IFU #1, a 400-μm (2 arcsec) fiber array with 10:1:1 ratios of core to clad to buffer. **Dark fibers** (45 in number) are the science fibers that go through to the spectrograph. Packing fibers are not visible because only the long (science) fibers are illuminated. This type of image is used to check the fiber array's astrometric alignment and polishing. The uneven illumination of some fibers is due to the fact that their back ends are not polished. **[Right panel]** HET IFU #1 superimposed on a typical nearby galaxy. Shown are only the science fibers. From this spatial sampling it will be possible to determine kinematics position angles, non-axisymmetric motions, and six independent measures of the disk velocity dispersion at each radius for three unique projections of the velocity ellipsoid – all in *one* exposure. Note that the sampling in galaxy azimuth is, to first order, independent of galaxy scale.

<u>Packing fraction:</u> To minimize cost and maximize construction efficiency, the fiber arrays do not employ lenslets, but simply rely on dense packing (e.g. Barden & Wade 1988). The coverage on sky, including 5:1 ratio of fiber core to fiber clad+buffer, is 62%. This can be increased by 10% if it is possible to remove the fiber buffer. For the initial arrays, the buffer will remain to avoid making the fibers too brittle. The covering factor has little consequence on the science performance of the IFUs given the formatted nature of their design.

<u>Spectral resolution:</u> For the 2 arcsec fiber array (#1), the ambient resolution is 5500. A slit mechanism at MRS focus will be used to achieve resolutions up to 11,000 by stopping the slit down to a 1 arcsec width and passing 61% of the light. Because of the greater fiber diameter and favorable geometry (unblocked in the spatial dimension) this configuration provides **2.4 times higher throughput** for an extended source than an array of one arcsec fibers. The one arcsec fiber array is designed for regimes where spatial sampling is critical, e.g. for distant galaxies where image sizes are small. Likewise, the one arcsec array can be stopped down to achieve resolutions approaching 22000 with comparable gains over yet smaller fibers.

<u>Fabrication:</u> Fiber arrays are epoxyed together using Epotek 354 in a pressing jig consisting of a U-shaped clamp adjusted by a micrometer stage(. To date, five test arrays have been made from 200-μm and 400-μm fibers in a variety of configurations. To meet mechanical constraints in the HET Fiber Instrument

Feed (**FIF**), the final 14×15 400-μm fiber array uses 2.5 cm short, packing fibers. The FIF interface consists of an aluminum yoke connected to a one-dimensional translation stage for removal from, and insertion into the field of view. Fiber arrays are glued to one side of the yoke, and held rigid with a soft rubber gasket on the opposing side. Sky fibers are mounted together in a mini-bundle on a separately positional probe on x,y-translation stages. Both sky fibers and IFU will be telecentrically corrected to within 0.2 degrees.

3. Performance Summary

The expected IFU performance should be comparable to that of individual fiber feeds for the MRS (Ramsey 1995, and this proceedings). In particular, the IFUs are not expected to have substantial additional focal ratio degradation (**FRD**); a pupil simulator has been constructed to confirm this for a 1-meter test array of 400 μm fibers. Taking the design goal of 15% total throughput for the MRS (atmosphere through to the detector), the following Table gives the expected performance for IFUs in terms of **limiting surface-brightness** in the V band for a one hour exposure yielding a signal-to-noise of 10 per resolution element. The astrometric performance should also be excellent; fiber rows and columns are placed within 7 μm (rms) of their optimal positions. In summary, the integral field units for the Hobby-Eberly Telescope's Medium Resolution Spectrograph will deliver high throughput spectroscopy for medium resolution studies of extended sources at low surface-brightness.

HET IFU Characteristics

	Array # 1	Array #2
Fiber size	2 arcsec (400 μm fibers)	1 arcsec (200 μm fibers)
Science fibers	52 (7 sky)	104 (9 sky)
Linear active area	27×26.4 arcsec	18×17.6 arcsec
Filling factor	34%	39%
Resolution ($\lambda/\Delta\lambda$)	5500-11000	11000-22000
$\lambda/\Delta\lambda$	Limiting V band Surface Brightness	
5500	23.5 mag arcsec^{-2}	22.6 mag arcsec^{-2}
11000	22.8	22.0
22000	21.7	21.1

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