The Disk Mass project; science case for a new PMAS IFU module

M.A.W. Verheijen\textsuperscript{1}, M.A. Bershady\textsuperscript{2}, D.R. Andersen\textsuperscript{3}, R.A. Swaters\textsuperscript{4}, K. Westfall\textsuperscript{2}, A. Kelz\textsuperscript{1}, and M.M. Roth\textsuperscript{1}

\textsuperscript{1} Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
\textsuperscript{2} University of Wisconsin, Dept. of Astronomy, 475N Charter Street, Madison, WI 53706, U.S.A.
\textsuperscript{3} Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
\textsuperscript{4} Johns Hopkins University, Dept. of Physics and Astronomy, 3400 North Charles Street, Baltimore, MD 21218, U.S.A.

Received date will be inserted by the editor; accepted date will be inserted by the editor

Abstract. We present our Disk Mass project as the main science case for building a new fiber IFU-module for the PMAS spectrograph, currently mounted at the Cassegrain focus of the 3.5m telescope on Calar Alto. Compared to traditional long-slit observations, the large light collecting power of 2-dimensional Integral Field Units dramatically improves the prospects for performing spectroscopy on extended low surface brightness objects with high spectral resolution. This enables us to measure stellar velocity dispersions in the outer disk of normal spiral galaxies. We describe some results from a PMAS pilot study using the existing lenslet array, and provide a basic description of the new fiber IFU-module for PMAS.

Key words: galaxies: spiral, fundamental parameters, structure, kinematics and dynamics, instrumentation: spectrographs

1. Introduction

A major roadblock in testing galaxy formation models is the disk-halo degeneracy; density profiles of dark matter haloes as inferred from rotation curve decompositions depend critically on the adopted M/L of the disk component (Figure 1). An often used refuge to circumvent this degeneracy is the adoption of the maximum-disk hypothesis (van Albada & Sancisi 1986). However, this hypothesis remains unproven. Recently, Bell & de Jong (2001) have shown that stellar population synthesis models yield plausible relative measurements of stellar M/L in old disks, but uncertainties in the IMF prevent an absolute measurement of total disk M/L from photometry. Another tool to determine the M/L, and specifically whether disks are maximal, is the Tully-Fisher relation, e.g. by looking for offsets between barred vs. un-barred galaxies, but this too is only a relative measurement. Evidently, none of these methods are suited to break the degeneracy, and without an independent measurement of the M/L of the stellar disk, it is not possible to derive the structural properties of dark matter haloes from rotation curve decompositions.

An absolute measurement of the M/L can be derived from the vertical component $\sigma_z$ of the stellar velocity dispersion. For a locally isothermal disk, $\sigma_z = \sqrt{\pi G (M/L) \mu z_0}$, with $\mu$ the surface brightness, and $z_0$ the disk scale height. The latter is statistically well-determined from studies of edge-on galaxies (de Grijs & van der Kruit 1996; Kregel et al. 2002). Thus, $\sigma_z$ provides a direct, kinematic estimate of the M/L of a galaxy disk and can break the disk-halo degeneracy.

With the advent of 2-dimensional spectroscopy using Integral Field Units (IFU), the observational prospects for measuring $\sigma_z$ have improved dramatically. This is because a wide-field ($1' \times 1'$) IFU can collect and pipe much more light to a spectrograph than a single $2''$ wide long-slit. The power of IFUs with face-on galaxies lies in the ability to azimuthally average many fibers. This yields clean $\sigma_z$ measurements well beyond 2 disk scale-lengths where contamination from bulge stars is negligible and the rotation curve of the stellar disk has reached its flat part. Here, we describe our Disk Mass project which employs two custom built IFUs to measure $\sigma_z$.

2. The Disk Mass project

Measuring the vertical stellar velocity dispersion in the outer parts of galaxy disks requires spectroscopy with a spectral
FWHM resolution of $R \approx 10^4$ on objects with a surface brightness as low as $\mu(B) = 24.5$ mag/arcsec$^2$, the typical value at three disk scale-lengths from the center of a normal spiral galaxy. With conventional long-slit spectrographs, this can only be achieved with exceedingly long integration times of several nights per object. However, it is our ambition to measure $\sigma_z$ out to three disk scale-lengths in a statistically significant sample of $\sim 40$ kinematically well-behaved spiral galaxies, selected from a larger parent sample of $\sim 100$ nearly face-on galaxies with high quality Hα velocity fields.

Secondary science goals of our survey include using the kinematic data for constraining the shape of galactic potentials. Our stellar and gaseous velocity fields will reveal kinematic perturbations due to non-circular halo shapes and disk asymmetries (lopsidedness, spiral arms and disk ellipticity). Previous studies have shown that such asymmetries may explain most of the scatter in the Tully-Fisher (TF) relation (e.g. Rix & Zaritsky 1995; Andersen et al. 2001). Due to the favorable projection of the photometric disk structure, our parent sample is uniquely suited for this study. Furthermore, with our $\sigma_z$ measurements we will also be able to calibrate the mass scale of stellar population models.

Our ambition to measure $\sigma_z$ in $\sim 40$ galaxies required the development of some special purpose instrumentation as well as a strategic long-term observing program. We have taken the three following preparatory steps:

First, of all, to obtain a clean measurement of $\sigma_z$, one needs to minimize contributions from the radial and tangential components of the velocity dispersion ellipsoid. For this reason we choose to observe nearly face-on galaxies in which $\sigma_r$ and $\sigma_\alpha$ are almost perpendicular to the line of sight and the observed velocity dispersion is largely dominated by $\sigma_z$. Since we are also interested in a galaxy’s total mass and the shape of its rotation curve, galaxies should not be too face-on in order to derive kinematic inclinations based on Hα velocity fields. Andersen and Bershady (2004) have proven to be able to derive kinematic inclinations from regular, high signal-to-noise Hα velocity fields of galaxies as little inclined as 15 degrees; they constructed a face-on TF relation based on kinematic inclinations, and found a scatter similar to TF studies based on samples of more inclined galaxies.

Second, to measure $\sigma_z$, a high spectral resolution is required, given the expected low velocity dispersions in the outer disks of spiral galaxies. Existing IFU spectrographs either lack the required light-gathering power, spectral resolution, or spectral coverage. For example, SAURON’s instrumental dispersion is 105 km/s (Bacon et al. 2001); too large for measuring $\sigma_z$. INTEGRAL’s spectral resolution of $R \approx 4200$ or $\sim 70$ km/s when using the largest fibers and the Echelle is also just inadequate. The IFU instrumentation at the VLT aims at high spatial resolutions. Consequently, individual spatial elements have become too small to collect sufficient light for $R \approx 10^4$ spectroscopy of low surface brightness objects, despite the 8.4m diameter mirrors.

To obtain measurements of $\sigma_z$ with sufficient spectral resolution, Bershady et al. (2004a, 2004b) built the SparsePak IFU for the WIYN facility at Kitt Peak. It consists of 75 bare object fibers in a sparsely filled but regular hexagonal grid with a $72^"\times 71^"$ field of view. This grid can be filled with three offset pointings. Each fiber has an extremely large diameter of $4.69^\prime\prime$ and collects light from a circular area of $17.3$ arcsec$^2$ on the sky. Using the Echelle grating on the WIYN Bench Spectrograph, a spectral resolution of $R=1.1 \times 10^4$ can be achieved ($\sim 40$ km/s in the CaII region around $\sim 860$nm).

Although the SparsePak IFU has great light collecting power, the Bench Spectrograph to which the fibers pipe their collected light has a very low throughput of $\sim 4\%$. Consequently, we can use SparsePak only for efficiently observing Hα velocity fields, while stellar velocity dispersion measurements are limited to the bright inner regions of spiral galaxies.

Third, the high throughput of the modularly built PMAS spectrograph (Roth et al. 2000) makes it particularly attractive to equip it with a SparsePak-like IFU module. A successful pilot study with PMAS in March 2003 demonstrates that PMAS provides the required throughput, spectral reso-
lution and stability. Equipped with the new fiber IFU module described in Section 4, it will be possible with PMAS to measure $\sigma_z$ in the dim outer regions of disk galaxies.

Having built the new SparsePak and PMAS IFUs, we are now ready to measure $\sigma_z$ with an optimized experimental design, taking a two-phased observational approach toward measuring galaxy disk masses over a 3-4 year period.

(i) We selected our parent sample from the UGC, choosing disk galaxies at $|b| \geq 25^\circ$, with diameters of $1'-1.5'$ to match them to the field-of-views of SparsePak and PMAS, and with approximate inclinations in the range $15^\circ < i < 35^\circ$, based on their optical axis ratios. This yielded a total sample of 470 galaxies from which we remove the strongly barred and interacting galaxies and randomly pick $\sim 100$ galaxies to observe.

(ii) Using SparsePak, we are collecting high signal-to-noise H$\alpha$ velocity fields for $\sim 100$ galaxies (Figure 2). We need such a large sample not only for a thorough statistical analysis of disk asymmetries and their relation to the scatter in the TF relation, but also because we found during our SparsePak pilot study that only 2 in 5 galaxies have sufficiently regular H$\alpha$ velocity fields to determine both the rotation curve and kinematic inclination. Because of intrinsic ellipticities of stellar disks (Andersen et al. 2001), optical axis ratios do not provide good estimates of the inclination, and a kinematic inclination is needed. Collecting these H$\alpha$ data requires significant amounts of bright time granted by the University of Wisconsin and matched by NOAO via an approved long-term program. At the moment of this writing, some 70 H$\alpha$ velocity fields have already been acquired. They are inspected for their regularity, and kinematic inclinations are being measured.

(iii) From this large parent sample we will select $\sim 40$ kinematically regular galaxies suitable for follow-up measurements of $\sigma_z$ with PMAS. This number is needed for a statistically meaningful sampling of a range in galaxy luminosity, colour, and disk surface brightness. With PMAS we will focus on the MgI$b$ region of the spectrum ($\sim 515$ nm) where only few sky lines are present. Comparing the H$\alpha$ and stellar kinematics yields a measurement of the asymmetric drift which provides another means to constrain $\sigma_z$. Notably, the [OIII] emission line is also measured with PMAS, yielding gas and stellar kinematics from the same observations.

(iv) Galaxies with observed H$\alpha$ velocity fields are being imaged in the U, B, V, R and I passbands on the 2.1m telescope on Kitt Peak. At the moment, 38 galaxies have been imaged through all five filters and 17 additional galaxies have been observed in V and R. These photometric images will be used to verify the pointings of our IFU observations, to study optical asymmetries, to construct TF relations in different bands, and to calibrate stellar population models.

SparsePak provides a high spectral resolution in the CaII region, and for selected targets we may explore systematic differences between values of $\sigma_z$ measured with PMAS in the MgI$b$ region and with SparsePak in the CaII region of the spectrum. This allows us to test the effects of radial stellar population gradients, and population differences among galaxies. Detecting the presence of a kinematically distinct thick disk requires an additional increase in the signal-to-noise to be able to characterize the detailed shape of the line-of-sight velocity distribution function, beyond measuring its dispersion $\sigma_z$. Currently, this goal seems unattainable.

3. PMAS test observations

The PMAS spectrograph, with its high throughput optimized for blue and visual wavelengths, provides us with the primary survey engine to measure $\sigma_z$ in the MgI$b$ region of the spectrum. It is mounted on the 3.5m telescope at Calar Alto which has the same mirror diameter as the WIYN telescope. Furthermore, PMAS has a modular design, and without too much effort, the existing lenslet array can be exchanged with a new wide-field SparsePak-like IFU module. To verify the usability of PMAS for measuring $\sigma_z$, we performed pilot observations on 2003 March 4-6 using the existing lenslet array, configured for a $16 \times 16$ arcsec field-of-view or a light collecting area of 1 arcsec$^2$ per lenslet. We were interested in the achievable spectral resolution, throughput and stability of PMAS.

To verify the throughput, we observed the same galaxy with PMAS for which data were collected earlier with SparsePak. One SparsePak fiber has the same collecting area as a single SparsePak fiber. The detected signal of both the SparsePak and the co-added PMAS spectra were scaled to the same exposure time, dispersion and collecting area. As illustrated in Figure 3, the SparsePak spectrum...
suffers from significant spectral vignetting while the PMAS spectrum covers a larger wavelength range, including more stellar absorption features. The throughput of PMAS is a factor 2-8 higher than that of the WIYN Bench Spectrograph, demonstrating that PMAS is roughly a factor 5 more efficient.

To achieve the required spectral resolution at 515nm, we used the 11200 grating, blazed for λ=1μm, in second order. By mounting the grating backwards in its cartridge, we could rotate it to such a large angle that an anamorphic demagnification of a factor 0.49 was obtained. For the existing 100μm fibers, we measured a FWHM spectral resolution of ~0.45Å near the center of the CCD (Figure 4). This corresponds to R≈11400 at λ=5150Å which implies that we can use 150μm fibers for the new IFU module and still achieve an acceptable FWHM spectral resolution of R≈7600 or 39 km/s.

Since PMAS is not mounted on an optical bench but located at the Cassegrain focus, possible flexure is a main concern. To characterize the flexure we took several exposures with the Thorium-Argon lamp, pointing the telescope at various declinations and hour angles. For each pointing direction, we measured the position of a bright emission line on the chip. The shift in its centroid with respect to a pointing lamp, keeping track of flexure and allowing for a synchronous spectral calibration. Compared to a SparsePak fiber, each PPak fiber collects only a third of the light, but there are 4.4 times more fibers feeding a highly efficient spectrograph.

Construction of PPak at the AIP is at an advanced stage and the IFU will be commissioned at Calar Alto by the end of December 2003. For the spring semester of 2004, the PPak mode of PMAS has been made available on a shared-risk basis, requiring members of the AIP instrumentation team to be present during the observations. For the fall semester of 2004, PPak will be offered as a public observing mode of PMAS.

**4. PPak: a new fiber IFU-module for PMAS**

PPak consists of 331 bare fibers in a hexagonal grid behind a f/3.5 focal reducer with a plate scale of 17.89 ″/mm. The hexagonal field-of-view has a diameter of 75″ while each fiber is 2.68″ in diameter. An additional 36 fibers are placed 62″ from the center (Figure 5). Fifteen extra fibers are diverted from the focal plane to be illuminated by calibration lamps, keeping track of flexure and allowing for a synchronous spectral calibration. Compared to a SparsePak fiber, each PPak fiber collects only a third of the light, but there are 4.4 times more fibers feeding a highly efficient spectrograph.

Table 1. Results of the flexure tests; relative shifts in pixels of a bright emission line in the spectral and spatial directions on the chip.

| Dec. (deg) | -6 | -4 | -2 | 0 | +2 | +4 | +6 |
|-----------|----|----|----|---|----|----|----|
| Spectral shifts: |
| +80 | -2.42 | -1.86 | -1.97 | 1.23 | 2.95\* | 1.75 | 2.48 |
| +60 | -2.57 | 0.82 | 0.77 | 1.87\* | 0.71 | |
| +40 | -2.27 | -2.25 | 0.34 | 0.21 | |
| +20 | -2.72 | 0.34 | 0.21 | |
| 0 | -2.63 | -2.46 | 0.00 | -0.12 | 0.21 |
| -20 | -2.41 | -3.54 | -0.12 | |
| Spatial shifts: |
| +80 | 4.79 | 4.59 | 4.39 | 1.91 | -0.64\* | -1.17 | -3.49 |
| +60 | 4.64 | 0.95 | -0.70 | -3.34\* | -4.01 | |
| +40 | 4.62 | 4.20 | -0.77 | -3.71 | |
| +20 | 4.66 | -0.77 | -3.71 | |
| 0 | 4.65 | 4.16 | 0.00 | -2.41 | -3.54 |
| -20 | 4.21 | |

\* out of focus, ‡ after refocus

Fig. 5. Layout of the 331 science and 36 sky fibers of the new fiber IFU for PMAS. The solid black fibers are inactive packing fibers.

**References**

Andersen, D.R. et al.: 2001, Astrophys. J. Lett. 551, 131
Andersen, D.R., Bershady, M.A.: 2004, Astrophys. J. Lett., in press
van Albada, T.S., Sancisi, R.: 1986, Philosophical Transactions of the Royal Society of London 320, 447
Bacon, R., Copin, Y., Monnet, G., et al.: 2001, Mon. Not. R. Astron. Soc. 326, 23
Bell, E.F., de Jong, R.S.: 2001, Astrophys. J. 550, 212
Bershady, M.A., Andersen, D.R., Harker, J., Ramsey, L.W., Verheijen, M.A.W.: 2004, Publ. Astron. Soc. Pac., in press
Bershady, M.A., Andersen, D.R., Verheijen, M.A.W., et al.: 2004, Astrophys. J. Suppl., in press
Bottema, R.: 1997, a328, 517
de Grijs, R., van der Kruit, P.C.: 1996, A&A Suppl. 117, 19
Kregel, M., van der Kruit, P.C., de Grijs, R.: 2002, Mon. Not. R. Astron. Soc. 334, 646
Rix, H.-W., Zaritsky, D.: 1995, Astrophys. J. 447, 82
Roth, M.M. et al.: 2000, SPIE, 4008, 277