

Galaxy Kinematics with SALT

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Abstract.

The combination of dynamical and photometric properties of galaxies offers a largely un-tapped source of information on how galaxies assembled and where stars formed. Bi-dimensional kinematic measurements have been the stumbling block. The light-gathering power of SALT coupled with the high-throughput performance of the Prime Focus Imaging Spectrograph (PFIS) yield a superb facility for measuring velocity-ellipsoids of stars and gas in galaxies out to gigaparsec distances. From these data dynamical asymmetries arising from lopsided or elliptical halos may be probed; disk-mass and mass-decompositions may be uniquely determined; mechanisms for disk heating constrained; and a zeropoint for the mass-to-light ratios of stellar populations set. A number of groups within the SALT consortium are interested in making these measurements using a variety of different, but complementary approaches. The scientific potential from their synthesis is very promising. We describe some unusual observational modes in which PFIS may be used to probe the shape of dark-matter halos and the content of galaxy disks.

1. Introduction

Extant information about galaxies comes primarily from broad-band optical images. These deliver a wealth of information on when and where stars have formed. Missing is an accurate understanding of the distribution of mass and the details of its assembly – knowledge which requires dynamical arguments substantiated with kinematic measurements. Hence kinematic information is essential for a basic understanding of galaxy formation and evolution. The last decade has seen the growth of bi-dimensional optical spectroscopy – once the purview of radio (HI) observations. SALT can continue this development. With SALT's Prime Focus Imaging Spectrograph we will be able to measure velocity-ellipsoid maps for a variety of dynamical tracers which include (collisionless) stellar pop-

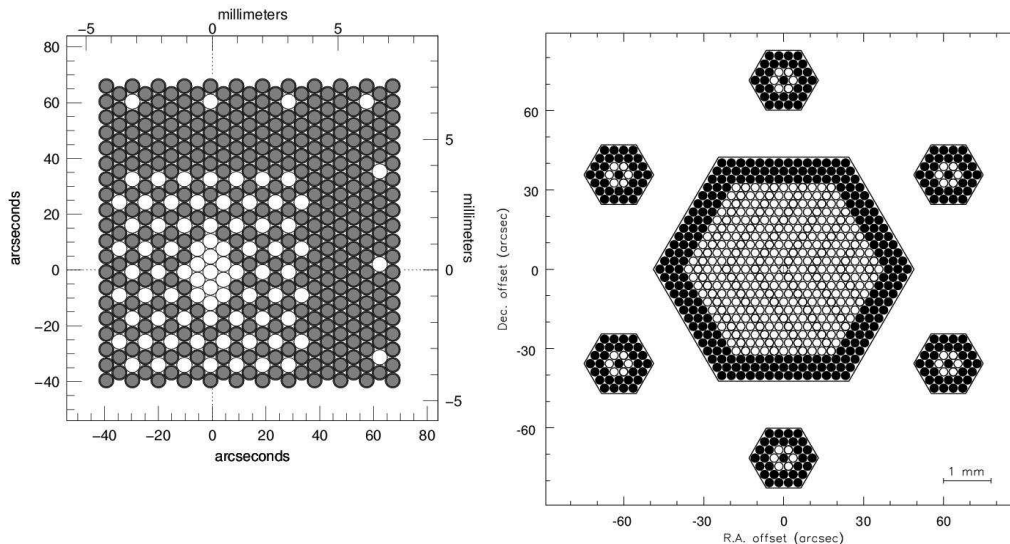


Figure 1. *SparsePak* (left, Bershady et al. 2003, 2004) and *PPAK* (right, Verheijen et al. 2004) IFUs, which respectively feed spectrographs on the WIYN and Calar Alto 3.5m telescopes, both capable of ~ 11 km/s (σ) resolution. Units are presented at the same subtended angular scale at the telescope focal-plane; physical dimensions scale with respective telescope+fore-optic f -ratios. Light fibers transmit to the spectrograph; dark fibers serve as mechanical buffers.

ulations and (‘sticky’) ionized gas. These measurements will be accessible via Fabry-Perot and dispersed spectroscopy over a very large ($8'$) field.

As promising for SALT is the critical mass of consortium scientists with overlapping interests in galaxy dynamics (see, for example, contributions by Balona, Cecil, Cote, Crawford, Ferrarese, Sellwood, Sparke, Wilcots, Williams, and Ziegler in this volume). A few specific scientific prospects of interest to members of the consortium include (but are not limited to!) the frequency and amplitude of lopsided disks and triaxial halos as probed by dynamical and photometric asymmetries; mergers and perturbations inferred studies of kinematic irregularities; disk heating mechanisms judged from velocity dispersion ellipsoids (σ_z/σ_R , Gerssen et al. 2000); feed-back processes in disks and the ISM; bar dynamics and their pattern-speeds; the Tully-Fisher relation and its evolution; and direct dynamical mass decompositions determined by combining rotation curves with stellar velocity dispersions.

Here we focus on how well we can directly separate disk from halo mass in spirals to yield dark-halo profiles, the zeropoint for stellar M/L ratio, and plausible constraints on the faint-end of the stellar IMF. These are of fundamental interest, respectively for testing both hierarchical cold-dark-matter structure-formation scenarios and star-formation models. This particular science case allows us to illustrate a novel application of PFIS to bi-dimensional spectroscopy with wide application. The concept combines narrow-band filters with dispersed spectroscopy to form what we call *massively multi-plexed spectroscopy*, or MMS. The approach complements other methods using fluid-dynamical modeling and kinematic measurements of barred potentials (Weiner et al. 2001; Gerssen et al. 2003; Debattista & Williams 2004).

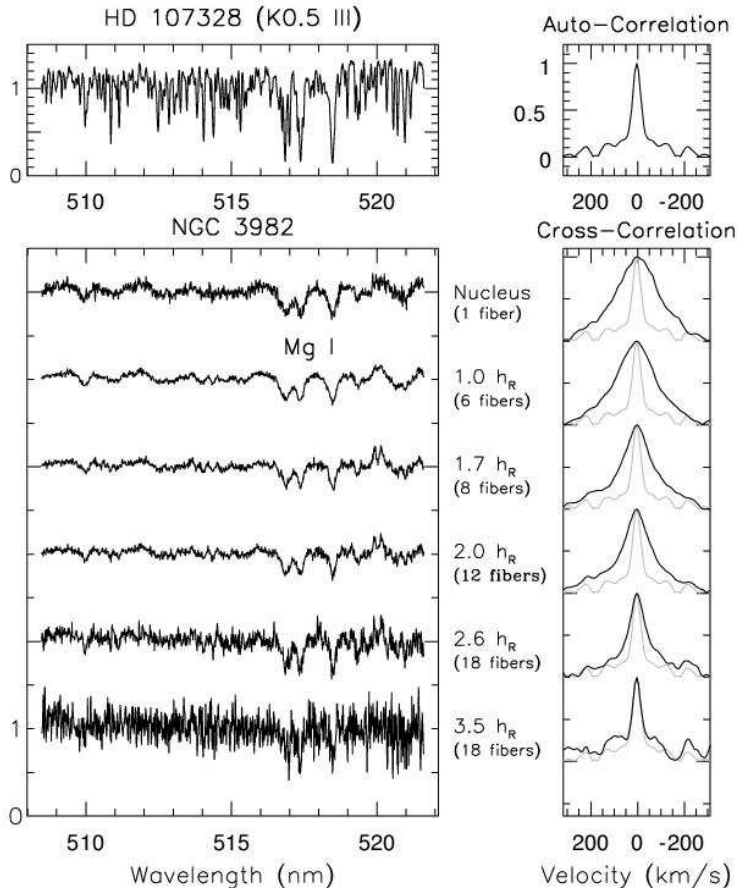


Figure 2. SparsePak spectra of a K0.5 III template-star and *azimuthally-averaged* fiber rings for NGC 3982 at 6 different radii, labeled in units of disk radial scale-length h_R . Auto- and cross-correlations are shown (right) for ~ 10 nm of spectra in the MgI region.

2. Mass Decomposition

The traditional technique of decomposing galaxy rotation curves into disk and halo mass contributions is inherently degenerate (see discussion by Sellwood, this volume). One way to break the disk-halo degeneracy is to measure directly the disk potential via the vertical motions and scale-height of the stars. To within factors of order unity: $\sigma_z = \sqrt{\pi G z_0 \mu M/L}$, where σ_z is the vertical component of the disk velocity dispersion, z_0 is the disk scale height, μ the surface light-intensity, and M/L the mass-to-light ratio (hence $\mu M/L$ is the disk surface mas-density, Σ). Recent studies of edge-on galaxies (Kregel et al. 2002) permit vertical scale-heights to be inferred with reasonable accuracy for face-on systems given the observed correlations between the radial scale-length, h_R , rotation speed, type, and z_0 . Face-on disks are ideal for measuring σ_z , typically the smallest component of the velocity ellipsoid, but low inclination makes measurement of inclination and rotation speed difficult. Inclined disks require careful correction and decomposition of the observed, line-of-sight velocity-dispersion to extract σ_z . Past attempts to realize this kinematic approach (e.g., Bottema

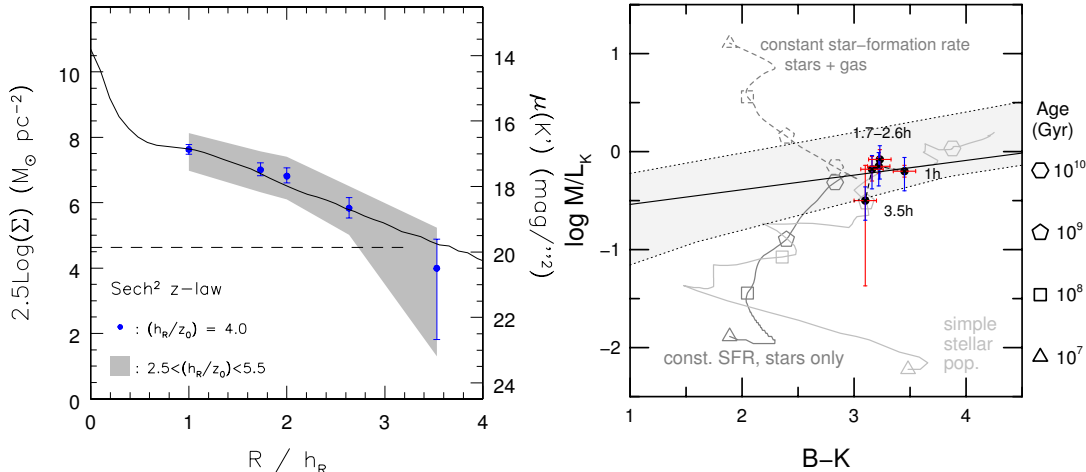


Figure 3. Direct kinematic surface-mass density and M/L measurements from integral-field spectroscopy at 515nm and optical-NIR photometry of NGC 3982: Surface mass-density (Σ) and surface-brightness (μ) vs radius (**left**); K -band M/L vs rest-frame $B - K$ color (**right**). Dashed line (left) represents a reference Σ for the MW in the solar neighborhood (Kuijken & Gilmore 1991). Model curves (right) are adopted from Bruzual & Charlot (1993) and Bell & De Jong (2000). Error limits show systematic and random components.

1997) have not overcome these problems, and have been limited by long-slit spectroscopy that does not reach well beyond a single disk scale length.

The observational approach can be rectified by application of integral-field observations of nearly face-on disks at medium spectral resolutions ($7000 < \lambda/\Delta\lambda < 15000$) and multi-band optical and NIR imaging. Two suitable integral-field units (IFUs) are shown in Figure 1. Galaxy sizes can be carefully matched to the IFUs. Observations with these units yield kinematic maps from which accurate inclinations can be derived to $i \sim 15^\circ$ (Andersen & Bershady 2003). Most importantly, the area sampled with IFUs increases with radius. For nearly face-on disks, one may average the signal in rings, which greatly enhances the limiting depth and radius of the observations.

Using the two IFUs shown in Figure 1 we have undertaken a survey of nearly face-on, nearby disk galaxies to determine their disk masses. The survey has yielded $H\alpha$ kinematic maps for ~ 100 normal, late-type galaxies. We are now gathering absorption-line spectroscopic observations (for stellar kinematics) for 40 of these galaxies, selected to have regular velocity fields (see Verheijen et al. 2004, Figure 2).

Results from a pilot target, NGC 3982, yield σ_z out to 3.5 disk scale-lengths in this albeit high-surface-brightness disk in both the MgI (515nm; Figure 2) and CaII triplet (860nm) regions. Cross-correlations yield similar results and show that the trend of disk surface-density well traces near-infrared surface-brightness – *mass traces light!* – as shown in Figure 3. Contrary to our earlier, preliminary reports, a renewed analysis of the data indicates a K -band M/L of the disk which is consistent with a maximum-disk situation in the sense of van Albada & Sancisi (1986). The colors and dynamical M/L *measurements* in Figure 3 agree

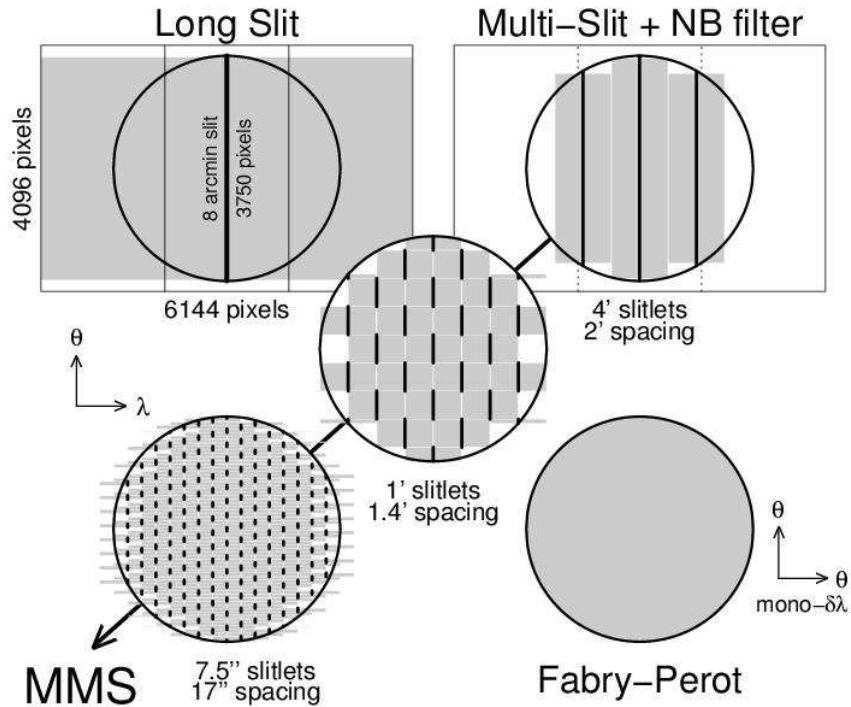


Figure 4. Examples of Massively Multiplexed Spectroscopy (MMS) compared to Long-slit and Fabry-Perot spectroscopy with PFIS. Each present a different slice of the spatial (θ) \times spatial (θ) \times wavelength (λ) data-cube. “NB” is a narrow-band filter, which in the case of PFIS has a bandwidth of $\lambda/\Delta\lambda = 50$. Grey regions denote used portions of the CCD. Long-slit spectroscopy makes best use of the CCD array, while MMS and Fabry-Perot modes use only $\sim 50\%$ compared to the Long-slit case.

well with stellar population synthesis models of, e.g., Bell & De Jong (2001), yet this source lies over 2 mag *below* TF. Here is a small, blue high-surface-brightness, actively star-forming disk, which is rapidly rotating and dominated by normal, baryonic matter out to 3-4 scale-lengths of the light distribution. At face value, this calibration of Bell & De Jong’s (2001) models implies, as they note, a Salpeter-like IMF truncated below $0.35 M_{\odot}$. It is critical to test the generality of this result in a variety of “normal” systems over a range in type, color and surface-brightness. Our on-going survey will begin to address this issue, but the low-surface-brightness regime will be difficult to probe at the required spectral resolution using 4m-class telescopes.

3. Prospects with the Prime Focus Imaging Spectrograph

The power of PFIS lies in its unique combination of 3 Fabry-Perot etalons spanning a factor of 50 in resolution, 6 gratings covering from the UV-atmospheric cutoff to 850 nm at resolutions up to $\lambda/\Delta\lambda \sim 13000$, and a suite of narrow-band filters filling an octave at optical wavelengths. All of these options are

configurable with imaging, longslit, or multi-slit mode. Most of the gratings are high-transmissivity volume-phase holographic (VPH) elements, tunable with an articulating camera.

For most galaxy kinematic studies, long-slit measurements are inefficient: Two-dimensional sampling is needed to gain velocity field information and to gather more light at large radii. Fabry-Perot imaging, in contrast, is excellent for gas and stellar velocity fields based on single, strong lines. However, for velocity dispersion work in narrow-lined (low-mass) systems, ideally many (weak) lines are probed, which requires scanning a significant band-pass ($\lambda/\Delta\lambda < 100$). Hence an intermediate trade between the spectral and spatial sampling of longslit and Fabry-Perot spectroscopy is needed. Integral- or formatted-field spectroscopy, with limited spatial coverage is one alternative, but at first-blush PFIS appears to have no such capability.

Other possibilities include using different tracers, such as planetary nebulae (e.g., Ciardullo et al. 2003; Merrett et al. 2003). Traditionally this requires narrow-band imaging and multi-object spectroscopic follow-up. PFIS is well suited for both. While this is efficient, newer techniques, such as counter-dispersed imaging (e.g., Douglas et al. 2002) also can be accomplished with PFIS. Another approach for multi-object emission-line kinematics would be to use slitless, dispersed imaging, i.e., slitless grism spectroscopy, at high spectral resolution over a limited “on” and “off” band-pass using a combination of gratings and narrow-band filters. The on and off bands replace the function of counter-dispersion. The technique should be considered by prospective PFIS users. We describe, instead, an alternative method using gratings and narrow-band filters with slits for IFU-like spectroscopy – suitable for emission and absorption line studies of extended sources.

3.1. MMS: Massively Multiplexed Spectroscopy

The wavelength-spatial multiplex trade for galaxy kinematic studies can be accomplished with PFIS by combining the suite of $\lambda/\Delta\lambda \sim 50$ narrow-band filters with the tunable VPH gratings. The filters serve to limit the range of the dispersed spectra on the detector, thereby allowing for an increase in the spatial multiplex: Multiple, parallel slits or slit-lets can be placed on a mask and produce non-overlapping spectra covering roughly, e.g., 10nm centered at 515nm – just what is shown in Figure 2 from SparsePak. The concept for mapping extended sources is illustrated in Figure 4; multi-object applications are possible (Crawford, this volume).¹

The minimum spatial separation in the dispersion direction is ~ 1 arcmin at the highest spectral resolutions (grating angle $\alpha = 50^\circ$), and decreases linearly with resolution ($\propto \tan \alpha$, i.e., the Littrow condition for the VPH gratings). At the highest spectral resolutions MMS yields a spatial multiplex increase of roughly a factor of 4. **For lower-dispersion setting, the spatial multiplex can be significantly increased.** At any resolution, the slits can be staggered to yield a variety of two-dimension sampling patterns (Figure 4) that resemble

¹The Fabry-Perot image is not truly monochromatic (there is a radial field-dependence to the band-pass), and the MMS slits are not uniformly spaced due to field-dependence of the grating incidence angle.

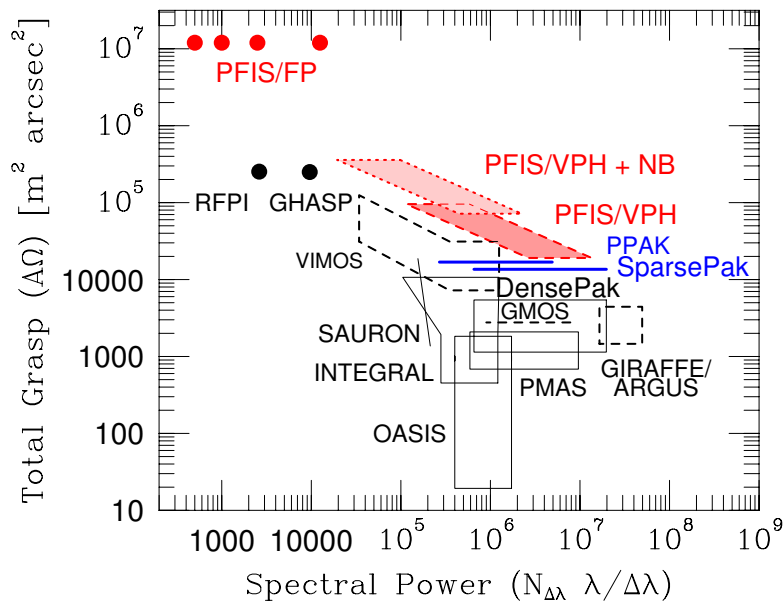


Figure 5. Grasp versus spectral power for two-dimensional spectroscopic systems on 4m and 8m-class telescopes (solid and dashed lines, respectively, with Fabry-Perot instruments shown as filled circles). Total grasp is the product of area \times solid-angle ($A\Omega$). Spectral power is the product of the spectral resolution, $\lambda/\Delta\lambda$, times the number of spectral resolution elements, $N_{\Delta\lambda}$. Variations in the shapes of covered parameter space depends on how a given instrument achieves a range of spectral resolution and spatial sampling, i.e., through changes in gratings, slit-widths, or both. Note the unique location of PFIS in these diagrams is significantly extended with the use of MMS.

e.g., SparsePak. Such data are suitable for constructing velocity fields and dispersion maps. Hence MMS should provide a competitive approach to the stellar dynamical studies illustrated in the previous section.

It is useful to examine where PFIS lies in comparison to other bi-dimensional spectrographs in terms of “information gathering power,” which we loosely parametrize with the two quantities “total grasp” and “spectral power”. These parameters are defined in Figure 5, where it is seen that PFIS has very large grasp while spanning a wide range in spectral power. The addition of MMS extends the range in grasp and spectral power, bridging between Fabry-Perot and traditional slit-spectroscopy modes. The light-gathering power of PFIS and SALT is over an order of magnitude larger than the 4m-class IFU instruments we have discussed. As such, PFIS can extend the study of galaxy kinematics significantly into the low surface-brightness regime.

4. Summary and Discussion

Galaxy kinematic measurements with SALT’s PFIS can be used to answer many outstanding, and fundamental questions about the structure and formation of galaxies. Highlighted here is one example of unique, dynamical mass decompo-

sitions of spiral galaxies. A number of observational modes are available with PFIS. We have described one powerful, new mode, referred to as “massively multiplexed spectroscopy,” (MMS), which is enabled by the unique combination of VPH gratings and narrow-band filters in PFIS. With MMS and Fabry-Perot imaging, PFIS is a highly competitive survey instrument for two-dimensional studies of gas *and* stars in nearby galaxies. There are several groups within the SALT consortium interested in applying these to a similar range of dynamical problems. This holds the promise of fruitful collaboration, cross-checks, and innovation.

What about higher redshift studies (see Ziegler and Crawford, this volume)? PFIS can sample a 0.6 arcsec slitwidth, but the sub-arcsec image quality enjoyed regularly by VLT and Gemini is needed unless we remain content with spatially-unresolved line-widths. Should it prove feasible to phase the SALT primary segments, we may consider pushing aggressively for significantly improved image quality. This will have a major impact on both resolved, extragalactic as well as high-resolution stellar spectroscopic observations. But SALT is merely a 9m telescope; for extended sources observed at significant spectral resolution, the area–solid-angle product ($A\Omega$) is what counts. As other facilities rush for the highest possible angular resolution that, with today’s detectors, may be better suited for tomorrow’s 30m-class telescopes, we should keep good aim on the type of ground-breaking science enabled by our large field of view and the exquisite, multi-faceted spectroscopic capabilities of PFIS.

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