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Growth and Destruction of Disks: Combined H I and H II View

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Abstract.
How large disk galaxies have evolved in, and out of, the blue cloud of actively star-forming galaxies as a function of environment and time is an outstanding question. Some of the largest disks become systems like M31, M33 and the Milky Way today. In denser environments, it appears they transform onto the red sequence. Tracking disk systems since $z<0.5$ as a function H I mass, dynamical mass, and environment should be possible in the coming decade. H I and optical data combined can sample outer and inner disk dynamics to connect halo properties with regions of most intense star-formation, and the gas reservoir to the consumption rate. We describe existing and future IFUs on 4-10m telescopes that complement upcoming H I surveys for studying disks at $z<0.5$. Multiple units, deployable over large fields-of-view, and with logarithmic sampling will yield kinematic and star-formation maps and properties of the stellar populations, resolving the core but retaining sensitivity to disk outskirts.

THE BLUE CLOUD AND RED SEQUENCE

A general but powerful statement about galaxy evolution stems from the results of merger simulations (e.g., Mihos & Hernquist 1994): Disks are fragile, destroyed in major mergers, and heated in minor mergers. It has been suggested that wet (gas-rich) mergers may complicate this picture, in that wet mergers can make new disks (Hammer et al. 2005, Springel & Hernquist 2005). To yield old stellar populations in dynamically-cold, star-forming disks today such wet-merging must happen early. We can therefore conclude that over the last Hubble time large disks we see today have been stirred, not shaken; they have tidal streams but are not train-wrecks.

However, some disk galaxies do evolve from the blue cloud to form the red sequence. Indeed, most of the stars made in the blue-cloud population end up in the red sequence (e.g., Bell et al. 2007). Much of this transformation appears to hinge on local environment. A tractable problem is to identify which galaxies have been stirred and which shaken (or stripped) at each cosmic epoch, and tag their environment. Some of this tagging can be done purely from optical photometrics, as we illustrate in Figure 1. For those only stirred, we can then monitor statistically their smooth and continuous accretion (growth and gas supply) and star-formation (gas consumption). To make this last critical step requires connecting optical and H I views, and ultimately also tying in a picture of the molecular gas distribution.

Considerable attention in the SKA science-literature is paid to connecting the H I mass-function evolution and the comoving star-formation rate (e.g., van der Hulst et al.

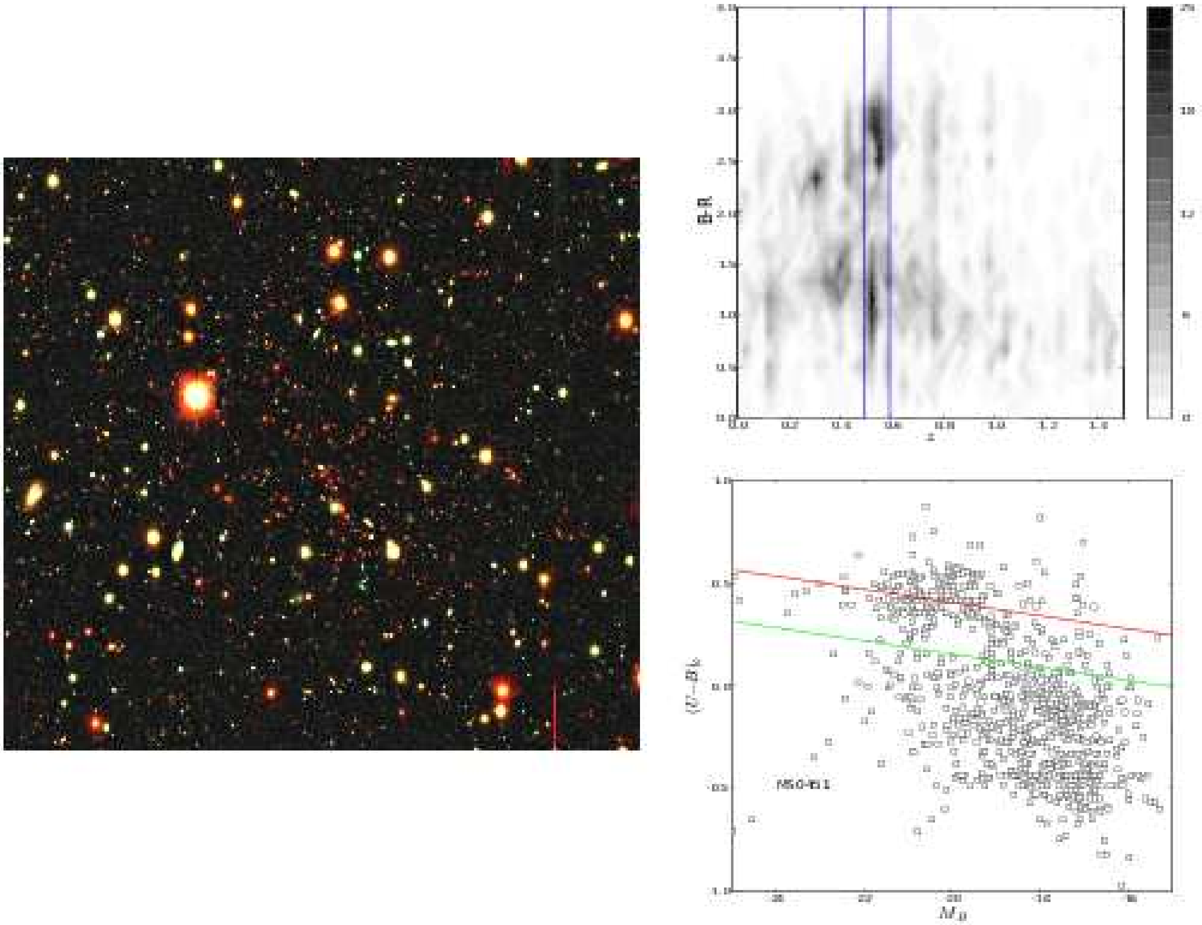

FIGURE 1. The blue cloud and red sequence in a deep field around MS0451, a rich cluster (σ = 1354 km s^{-1} and L_x = 40e44 ergs s^{-1}) at z=0.54 from the the WIYN Long-Term Variability Survey (*UBRIz* bands, Crawford et al. 2006, 2008) The *UBI* 3-color image at left is a 10x10 arcmin field. The corresponding $B-R$ color–photometric-redshift diagram illustrates isolation of the cluster volume and the surrounding environment. The rest-frame $U-B$ color-magnitude diagram shows the blue cloud and red sequence in this redshift slice. Data like these are at the upper-redshift limit of what could be well-probed with deep SKA-precursor H I surveys.

2004). At this conference, Zwaan has reported a clear picture on the H I mass function and its evolution, or lack thereof. However, do we know if these trends of mass (fuel) and star-formation (consumption) are self-consistent? To get a handle on this, we need to unpack the comoving quantities (e.g., Heavens et al. 2004), and look specifically at the multivariate distributions over epoch, such as the star-formation rates (SFR) as function of both dynamical and H I mass. Likewise we need to identify the individual galaxies, e.g., at the knee of the H I mass-function, which we can presume are likely to include many of the large-disk systems.

These broad brush-strokes motivate a program to trace a set of key observables in the blue cloud across comic time. The observables include dynamical mass, baryonic mass (H I molecular, and stellar), SFR, and abundances. These allow us to frame a model of baryon processing in gravitational wells, and constrain the efficiency of this processing. At our disposal are the now well-known correlations between dynamical mass, baryonic mass (light), and metallicity. Let us assume that molecular gas is estimated from the atomic, or measured with ALMA, and that stellar mass is dynamically calibrated via low-redshift studies such as the DiskMass survey (Verheijen et al. 2007a). Here we

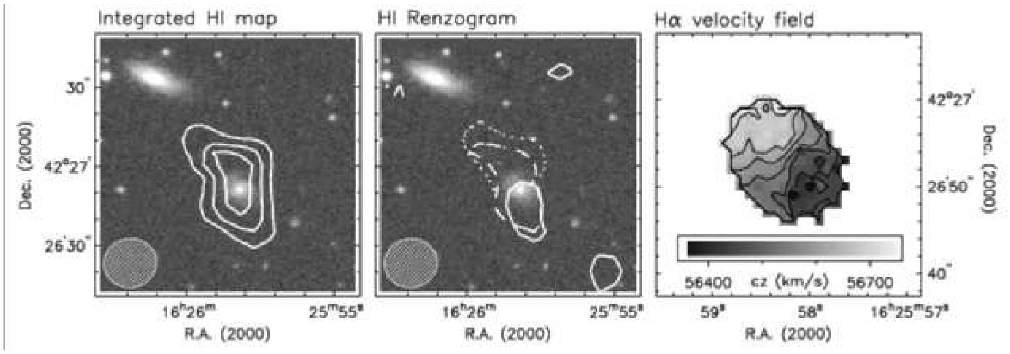

FIGURE 2. H I and Hα internal-velocity structure in a cluster galaxy at z=0.2 in A2192 (Verheijen 2004). H I data is typical of what can be achieved with today's deepest surveys in advance of SKA-pathfinder facilities such as eVLA, ASAKP and MeerKAT. The Hα velocity-field was taken in 80 minutes on the Calar Alto 3.5m telescope using a 16x16 1" element integral field-unit of PMAS.

focus on the optical instrumentation needed to connect future H I surveys with spatially resolved star-formation rates and gas-phase abundances.

H I VIEW: STATE OF THE ART

Deep aperture-synthesis surveys with Westerbork and the VLA have now mapped H I to z=0.2 at masses well below M* (Verheijen et al. 2007b). The extensive scientific dividends from such studies are discussed in these proceedings by van Gorkom. These impressive surveys have solid detections for 42 sources in 2 x 0.4 deg^2 fields, and expect 200 sources in 1000 hours of integration.

With dedicated, deep surveys using SKA path-finders (e.g., eVLA, MeerKAT, ASKAP) we can expect to extend to $z \leq 0.5$. The meat of these surveys (where the H I detections go well below M*) will be in something like the Sloan Volume, i.e., with a characteristic redshift of 0.1-0.2. Optical follow-up, especially for emission-line science (kinematics, abundances, SFR) are well in the domain of 4m-class telescopes.

As an example of the power in optical follow-up, Figure 2 contrasts state-of-the-art H I and Hα kinematic data for a cluster galaxy at z=0.2. The optical data offers a spatially detailed supplement which connects the H I map of the fuel reservoir and mass enclosed on large scales to the dynamical heart of the galaxy where the fuel is being processed. This is achieved in the optical in a very modest amount of time per target.

MATCHING THE STATE OF THE ART IN THE OPTICAL

The challenge for matching H I surveys with optical spectroscopy is field-of-view. While the sensitivity per target (or spaxel) is substantially higher in the optical, radio aperture-synthesis telescopes have significantly larger primary beams than most optical spectrographs. Since the science signal is only coming from a small portion of the solid angle, what is needed most importantly are optical spectrographs with large patrol fields. This has been achieved, traditionally, with fibers. A number of telescopes have such capability. Here we focus on the WIYN 3.5m telescope, the multi-fiber positioner Hydra

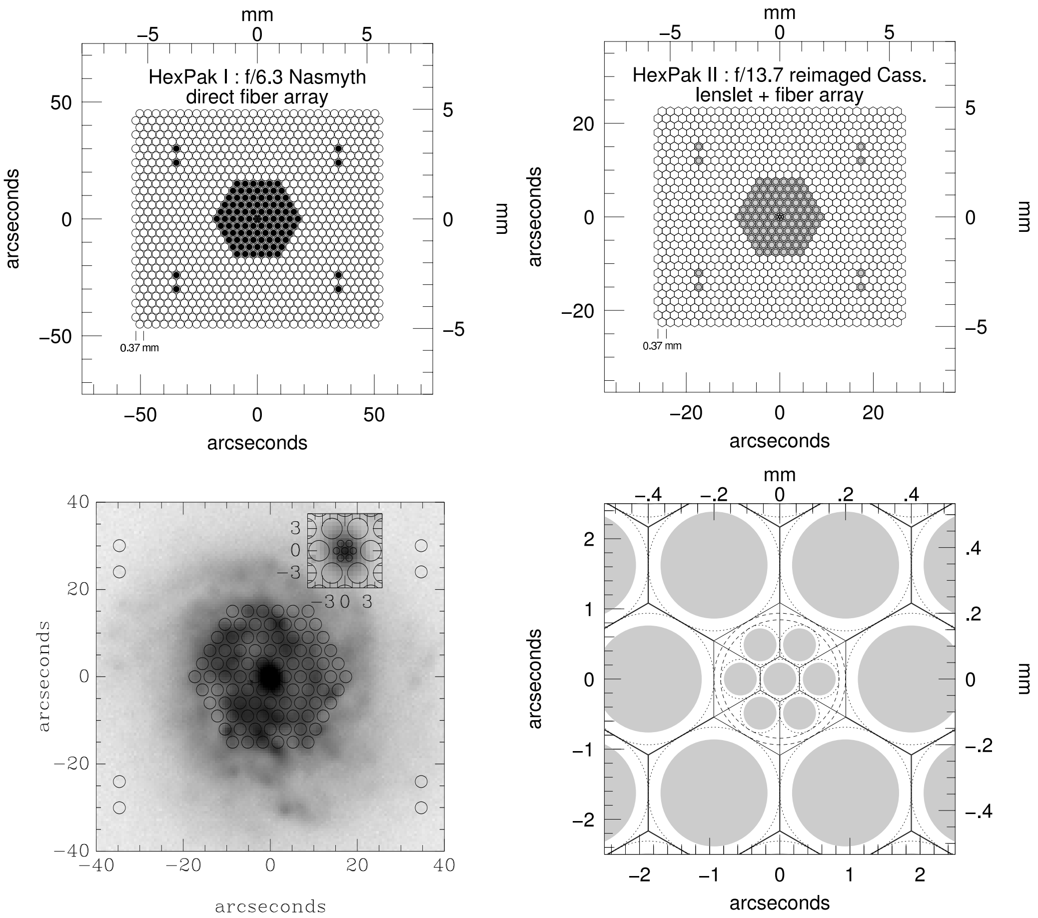

FIGURE 3. HexPak I & II, logarithmic-sampled IFUs proposed for WIYN, well-suited for ALFALFA survey follow-up. *Top Left.* HexPak I bare-fiber IFU for the f/6.3 Nasmyth port, sampling at 2.”81 over 30” is a replacement of, and improvement on the former DensePak IFU. Open fibers are for mechanical packing and buffering. *Bottom Left.* HexPak I overlay on Seyfert galaxy NGC 3982 in Ursa Major, with an inset shows sampling of AGN core. *Top Right.* HexPak II fiber+lenslet IFU for the f/13.7 reimaged-Cassegrain port, sampling at 1.”29 over 15”. *Bottom Right.* Blow-up of inner 2-arcsec region showing variable-pitch region of array for HexPak II. Shaded regions are active fiber areas which are fed by an integrally-covering array of hexagonal and trapezoidal lenslets. Fibers are a new broad-spectrum product with transmission performance surpassing older fibers in both blue and red.

(Barden et al. 1993), and the spectrograph which this feeds: the Bench.

Hydra has a superb advantage for H I survey follow-up due to its 1 degree patrol field. The problem with WIYN multi-fiber spectroscopy has been that the Bench Spectrograph, while used for roughly 65% of the observing time only has 3-4% throughput. The solution has been to undertake a major, multi-year effort to rebuild the spectrograph.

Bench Spectrograph improvements include two new high-throughput volume-phase holographic (VPH) gratings; a new, high-QE, low-noise CCD; and a new, high-throughput and faster refractive collimator. With the exception of the new collimator (due to be commissioned in late-summer to early Fall 2008), all components are now in place. The total gains over the original system are up to a factor 3.5 improved efficiency with little-to-no loss in spectral resolution (due to better sampling and improved optical image quality). This yields a competitive total system efficiency of 10% at $\lambda/\Delta\lambda = 20,000$ (echelle), and 15% at $\lambda/\Delta\lambda = 10,000$ (VPH).

In addition to the Hydra multi-fiber feed, the Bench Spectrograph can also be fed

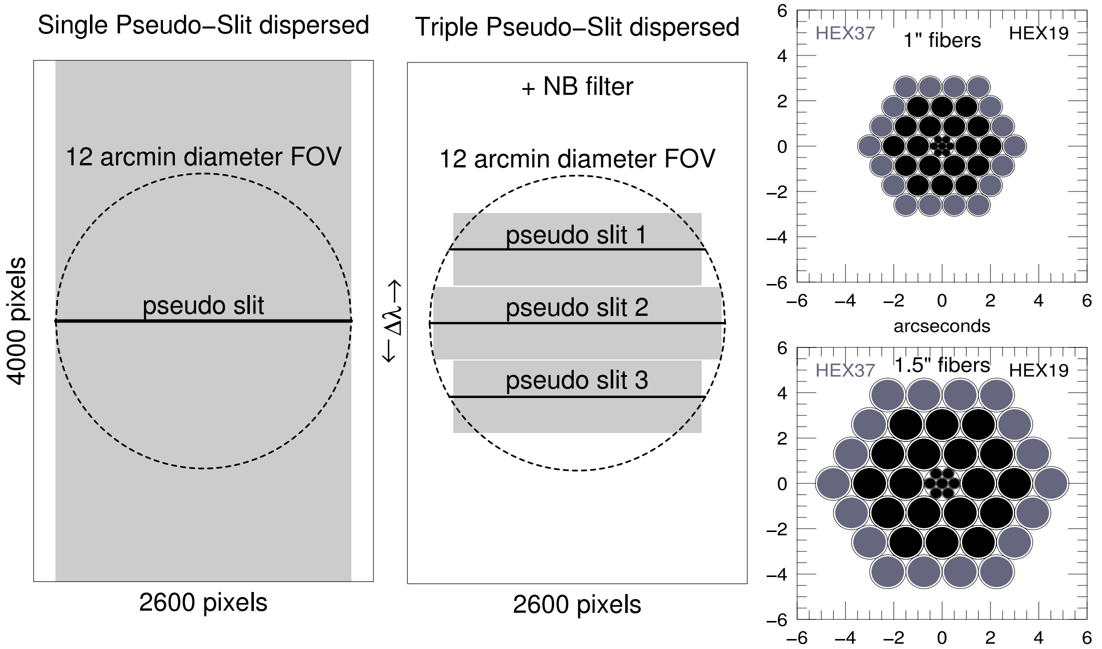

FIGURE 4. The MDX concept for the WIYN Bench Spectrograph and Hydra. At left is shown the traditional fiber pseudo-slit with the collimator spatial field-of-view (dashed circle), and the camera field-of-view (dispersed light; grey) on the 2600x4000 pixel CCD. With the new refractive collimator we can use multiple pseudo-slits, each with reduced band-pass via a narrow-band pre-filter (middle panel). Mini-IFUs of 19-37 fibers (black and grey circles, respectively, in right panels) can be positioned in Hydra, patrolling 1 deg^2. Examples given are for 1” and 1.5” fibers. The total number of mini-IFUs (up to 33) depends primarily on the size of the IFUs (# of fibers) and pseudo-slits.

with single-object fiber integral field-units, including DensePak (Barden et al. 1998) and SparsePak (Bershady et al. 2004, 2005). These arrays span 30-70 arcsec, sampled at 3-5 arcsec. While unfortunately the DensePak bundle has recently failed, we plan to replace it with two new IFUs: HexPak-I & II, illustrated in Figure 3. They are well suited, for example, to ALFALFA survey follow-up (Giovanelli, these proceedings). They also offer a logarithmically-sampled inner core to improve spatial and kinematic resolution in the centers of galaxies where beam-smearing is traditionally a problem, dynamical structures are small, AGN can contribute, and yet there is sufficient flux to enable the finer spatial sampling.

The IFU concept, however, really achieves its forte for H I survey follow-up when coupled to the multi-object capacity of traditional single-fiber positioners. In short, multi-object IFUs covering large patrol fields can enable high-efficiency follow-up and extension of the H I aperture-synthesis array surveys noted above. This instrument idea is not new, e.g., GIRAFFE on VLT (Flores et al. 2004), but the application needs re-tuning.

Given the depth and area needed to match H I surveys, this instrument application is best suited to 4m-class telescopes. As an example, Hydra could be retrofitted (with available extra slots) to hold 5-12 mini-IFUs spanning 6-9 arcsec in field, sampled at 1-1.5 arcsec per fiber, and patrolling 1 deg^2. The range in number depends on whether 2 or 3 rings of fibers (19 or 37 total) are desired (i.e., field of view) about the logarithmically-sampled core. Two examples are illustrated in Figure 4 (right-most panels). Such a configuration would use a single pseudo-slit of fibers, as done with current fiber feeds.

This delivers a large free spectral range, suitable for cluster foreground and background studies (field surveys), as well as abundance work.

Because of the WIYN Bench Spectrograph's new, all-refractive collimator, however, another exciting possibility emerges. By using narrow-band filters, the effective band-pass (spectral range) can be reduced, and multiple pseudo-slits can be introduced. This permits a trade-off of spectral for spatial multiplex. Consequently this would allow us to increase the same mini-IFUs up to 14-33 in number, also patrolling 1 deg^2. This so-called MDX concept is outlined in Figure 4. Each fiber would deliver, e.g., $\lambda/\Delta\lambda = 5000$ ($\sigma = 25.6$ km s^{-1}) with a velocity range of 5600 km s^{-1}, or other commensurate combinations of coverage and resolution (depending on grating design and angle). This is well-matched to galaxy cluster studies.

Optical instruments on 4m-class telescopes, such as those described above, if built, will play a dramatic role in defining the environmental impact on galaxy evolution at late-times in the universe. This is a time when clusters are still actively building and processing galaxies from the blue cloud to the red sequence. The combined H I and optical views of this transformation – taken at redshifts low enough to discern detailed galaxy properties – offers an unprecedented opportunity to advance our knowledge of how galaxies form and evolve.

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