Beyond the Break: Observational Evidence of Stellar Migration

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We use the VIRUS-P IFU spectrograph to observe 6 nearby disk galaxies. In three cases (NGC 2684, NGC 6155, and NGC 7437), we find that a downward break in the disk surface brightness profile corresponds with a change in the dominant stellar population with the interior being dominated by active star formation and the exterior having older stellar populations. This is similar to theoretical models that predict surface brightness breaks are caused by stellar migration, with the outer disk being populated from scattered old interior stars.

In three more cases (IC 1132, NGC 4904, and NGC 6691), we find no significant change in the stellar population as one crosses the break radius. In these galaxies, both the inner and outer disks are dominated by active star formation and younger stellar populations. While radial migration can contribute to radial profile breaks, it appears multiple mechanisms are required to explain all of our observed stellar profile breaks.

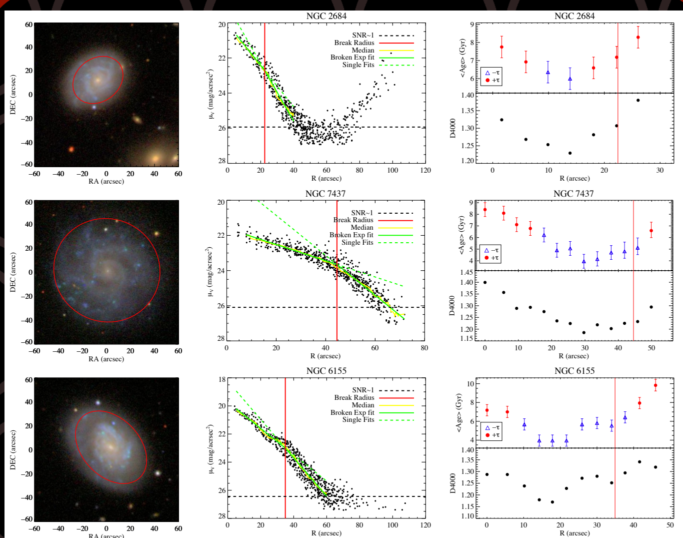

Figure 1:
Left column: SDSS images of galaxies targeted with VIRUS-P. Middle Column: Surface brightness profiles along with the best-fit broken exponentials. Right Column: Best fit mean stellar ages and 4000 Angstrom break strengths as a function of galactic radius. Red points show decreasing star formation histories, while blue points show increasing star formation rates. A red line marks the surface brightness break radius in each figure. All of these galaxies show surface brightness profile breaks. Our best fit models show increasing ages beyond the breaks, and a change from increasing to decreasing star formation histories. This matches the prediction of radial migration theories that find profile breaks are caused by a combination of a star formation threshold and old stars from the interior migrating to the outskirts of the galaxy.

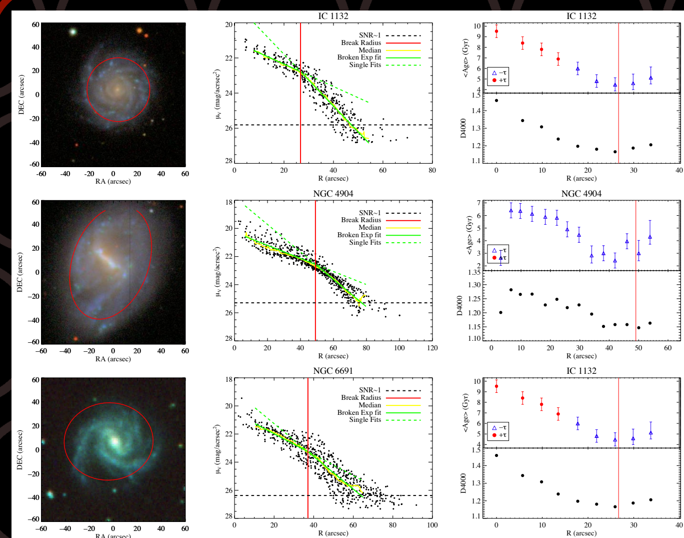

Figure 2:
As in Figure 1, we show three galaxies with surface brightness breaks. Unlike the galaxies in Figure 1, the best fit star formation histories show young stars and active star formation beyond the breaks. This suggests that we need a mechanism besides radial migration to explain the profile breaks in these systems. For NGC 4904 (middle panel), the break radius seems to correspond with the break expected from secular evolution at two times the bar radius. While these systems do not show much evidence for radial migration, it is still possible they have experienced significant migration, but the signal has been swamped by recent star formation in the galactic outskirts.

Introduction
It is generally believed that galaxy disks should not extend to infinite radius. Describing the exact nature of where and how galaxy disks end has proven elusive. While spiral galaxies are usually modeled as exponential disks, only ~10% of disks exhibit a single exponential profile down to the observational noise limit[2]. It is much more common for disk galaxies to have broken exponential profiles, with a single exponential fitting for 2-3 scale lengths followed by the profile switching to a (usually steeper) different exponential.

There have been two primary models proposed for creating the observed breaks. In the first, a star formation threshold creates a sharp truncation radius and the outer regions of the disk are populated by stars that have gravitationally scattered from the interior[3]. In the second, star formation in the outer regions of galaxies simply becomes very inefficient and must rely on non-gravitational cloud collapse mechanisms[4].

Thilker et al. 2008 find that a significant fraction of galaxies have extended UV disks revealing star formation well beyond the optical extent of the disks. If this is the dominant mode of populating outer disks with stars, we should expect stars beyond the break to be primarily young. Alternatively, Roškar et al. 2008 present simulations that show gravitational scattering populate the outer parts of galaxies and that the break radius should host a local minimum in mean stellar age.

Stacked broad-band images of galaxies have hinted that the regions outside profile breaks are slightly redder[1], but it has been difficult to make firm conclusions about the stellar populations outside the break compared to inside. VIRUS-P spectra can be binned to reach high signal-to-noise ratio and compared to stellar population synthesis models to quantify the ages and metallicities of stars.

Observations
We used the Visible Integral-field Replicable Unit Spectrograph Prototype (VIRUS-P) mounted on the Harlen J Smith 2.7m at McDonald Observatory to observe of a sample of nearby face-on galaxies. The large field-of-view (1.8 arcminutes on a side) and large fibers

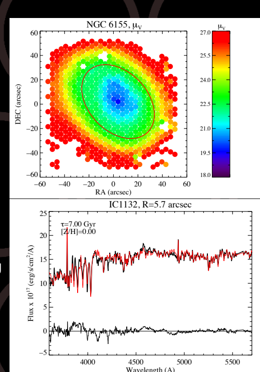

Figure 3: (top) Example VIRUS-P image (each point represents a single fiber). (bottom) An example of our SFH fitting.

References
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[3] Roškar, R., Debattista, V. P., Stinson, G. S., Quinn, T. R., Kaufmann, T., & Wadsley, J. 2008, ApJ, 675, L65
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(4.1 arcsecond diameter) make VIRUS-P an ideal instrument for observing the low surface brightness regions of galaxies. VIRUS-P returns 246 spectra with a wavelength range of 3550-5850 and a spectral resolution of R~1000.

For each galaxy, we observed for ~1 hour at each of three dither positions to achieve full spatial coverage. We use the emission line kinematics to correct each fiber to a common velocity and bin fibers in concentric elliptical annuli to reach signal-to-noise ratios of ~80 in the outer regions. An example VIRUS-P image and spectrum are shown in Figure 3 along with a best-fitting model spectrum.

Results
We show results for 6 galaxies in Figures 1 and 2. In Figure 1, we show three galaxies where the star formation histories show marked change beyond the break radius. In these cases, the stars are systematically older, consistent with the theory that the outer disk was built through stellar migration of older stars from the inner disk

In Figure 2, we show three galaxies that have break radii, but no significant change in the stellar populations in the outer disks. In these cases, the best fit star formation histories inside and outside the break radius have active on-going star formation.

One interesting result is that the strength of the profile break does not seem to correlate with change in the stellar populations. NGC 6155 and NGC 6691 both have weak profile breaks, but only NGC 6155 shows a strong change in the age across the break. Meanwhile, NGC 7437 and IC 1132 both have strong breaks, but again have different behavior.

These results are consistent with broad-band studies that found galactic outskirts had redder colors than regions inside the break radius. However, we note those studies stacked multiple galaxies, and thus their results could have been diluted by galaxies such as IC 1132 where there is a profile break but no change in the stellar populations. The variety of behaviors suggest there are multiple mechanisms for forming profile breaks.

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