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Cold Gas in Blue-Sequence E/S0s: Galaxies in Transition

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Abstract. We examine the HI+H_2 content of blue-sequence E/S0s — a recently identified population of galaxies that are morphologically early type, but reside alongside spiral galaxies in color vs. stellar mass space. We test the idea that the majority of low-to-intermediate mass blue-sequence E/S0s may be settled products of past mergers evolving toward later-type morphology via disk regrowth. We find that blue-sequence E/S0s with stellar masses $\leq 4 \times 10^{10}\,M_{\odot}$ have atomic gas-to-stellar mass ratios of 0.1 to >1.0, comparable to those of spiral galaxies. Preliminary CO(1-0) maps reveal disk-like rotation of molecular gas in the inner regions of several of our blue-sequence E/S0s, which suggests that they may have gas disks suitable for stellar disk regrowth. At the current rate of star formation, many of our blue-sequence E/S0s will exhaust their atomic gas reservoirs in $\lesssim 3$ Gyr. Over the same time period, most of these galaxies are capable of substantial growth in the stellar component. Star formation in blue-sequence E/S0s appears to be bursty, and likely involves inflow triggered by minor mergers and/or interactions.

1 Introduction & Sample

Blue-sequence E/S0s represent a unique population of galaxies — morphologically classified as early types, but occupying the same blue locus as spirals in color vs. stellar mass space. While high-mass blue-sequence E/S0s often appear to be young merger/interaction remnants likely to fade to the red sequence, blue-sequence E/S0s with lower stellar masses appear to be much less disturbed. These galaxies typically occupy low-density field environments where fresh gas infall is possible, and may provide an evolutionary link between traditional early-type galaxies and spirals through disk regrowth (Kannappan, Guie, & Baker 2009).

We examine the disk growth potential of blue-sequence E/S0s by measuring cold gas reservoirs — the raw material for star formation. Our sample includes all 14 blue-sequence E/S0s with stellar masses $M_* \leq 4 \times 10^{10}\,M_{\odot}$ (chosen with respect to where blue-sequence E/S0s tail off, Figure 1a) from the Nearby Field Galaxy Survey (NFGS, Jansen et al. 2000). We also include 11 red-sequence and two mid-sequence NFGS E/S0s with comparable stellar masses for comparison. Because the NFGS was designed to be a statistically representative

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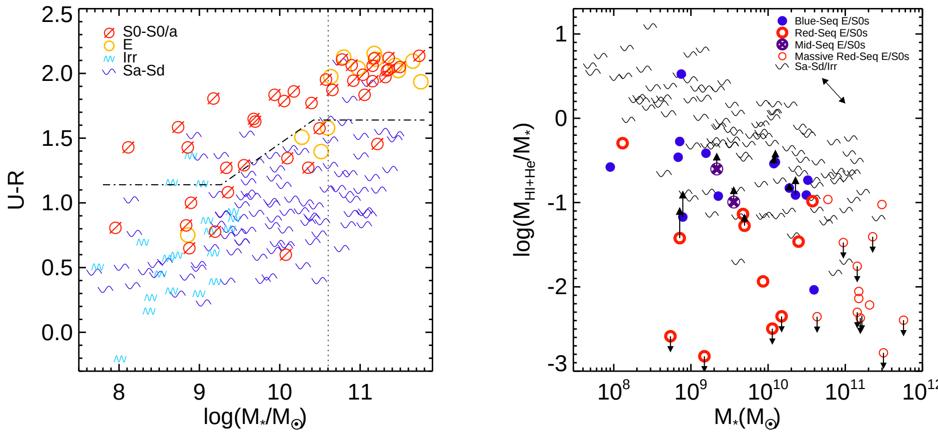

Figure 1. Left: $U-R$ color vs. stellar mass of galaxies in the NFGS, with the dashed line marking the division between the blue and red sequences. Blue-sequence E/S0s fall below the division alongside spiral galaxies, but are morphologically classified as early type (Kannappan, Guie, & Baker 2009). The vertical dotted line marks $M_* = 4 \times 10^{10}\, M_\odot$. Right: Atomic gas-to-stellar mass ratio as a function of stellar mass for galaxies in the NFGS. Blue-sequence E/S0s have gas reservoirs comparable to many late-type galaxies. Symbols indicate $M_{\rm HI+He}/M_*$ ratios. For galaxies with CO observations, the tip of the upward arrow marks the ratio including molecular gas. Downward arrows indicate the ratio is an upper limit. The arrow in the upper right corner indicates a factor of two error in stellar mass in either direction.

sample of the local universe, spanning the natural variety of galaxy morphologies, masses, and environments, these 27 galaxies should correspond to a broad range of evolutionary stages.

2 Cold Gas Reservoirs

We have complete HI data for our sample of E/S0s with $M_* \leq 4 \times 10^{10}\, M_\odot$. All of our blue-sequence E/S0s and both mid-sequence E/S0s are detected in HI and have atomic gas masses ranging from 10^7 to almost $10^{10} M_\odot$. In contrast, four of our 11 red-sequence E/S0s are not detected. Normalized to stellar mass, the atomic gas masses for 12 of the 14 blue-sequence E/S0s range from 0.1 to >1.0 (Figure 1b), demonstrating that morphological transformation is likely if the detected gas can be converted into stars. These gas-to-stellar mass ratios are comparable to those of spiral and irregular galaxies and have a similar dependence on stellar mass.

High-resolution mapping of the molecular gas distribution in blue-sequence E/S0s is underway with the Combined Array for Research in Millimeter-wave Astronomy (CARMA). The molecular gas mass derived from the CO(1-0) maps boosts some of the galaxies further into the region occupied by spirals. These maps also reveal disk-like rotation of molecular gas in the inner regions of some of our blue-sequence E/S0s (Figure 2), which suggests that they may have gas disks suitable for stellar disk growth. HI profiles and resolved ionized-gas rotation

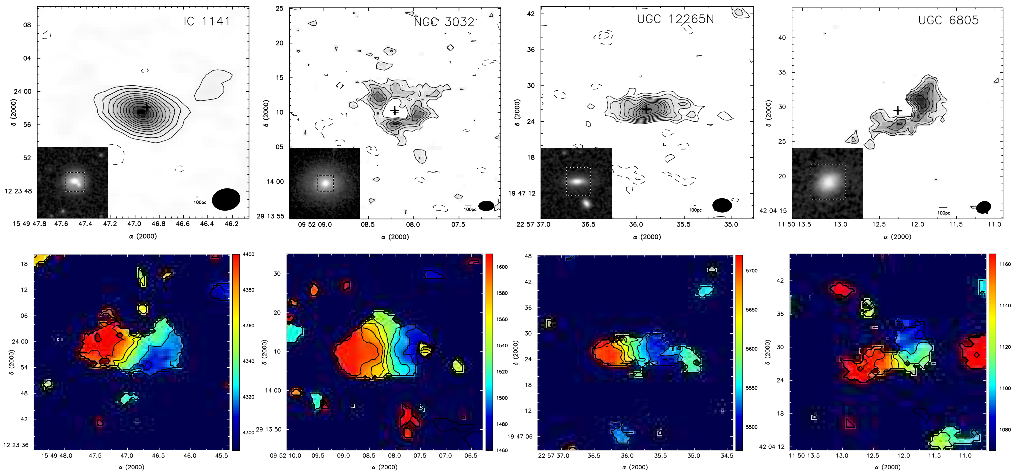

Figure 2. Top: CARMA maps of velocity-integrated CO(1-0) emission for four of our blue-sequence E/S0s. Combining high-resolution C-array observations with D-array data resolves interesting central gaseous structures. The size of the CO map corresponds to the dashed box marked on the DSS optical image inset in each panel. Beam and scale sizes are noted in the lower right corner, and the nucleus of the galaxy is marked with a cross. Bottom: Velocity fields for each galaxy, showing fairly regular rotation.

curves also confirm the presence of disks in many of our blue-sequence E/S0s (Wei et al. 2009).

3 Star Formation Potential

The timescale that can be directly estimated from the atomic gas mass and star formation rate of a galaxy is the gas exhaustion time — the amount of time it would take to convert all the gas into stars, assuming the current star formation rate remains constant. We find that blue-sequence E/S0s will typically exhaust their gas reservoirs in $\lesssim 3$ Gyr without fresh gas infall (Wei et al. 2009). Figure 3a shows that over half (9 of 14) of our blue-sequence E/S0s can increase their stellar masses by 10–60% over 3 Gyr in either of two limiting scenarios — constant star formation rate with ongoing infall, or exponentially declining star formation without infall. This growth is comparable to the amount of fractional stellar mass growth by spiral and irregular galaxies in the same time (grey vertical lines) and suggests that most of our blue-sequence E/S0s are capable of significant morphological transformation.

4 The Merger Connection

While high-mass blue-sequence E/S0s often show signs of major mergers or interactions, blue-sequence E/S0s with M_* below $\sim 3 \times 10^{10}\, M_\odot$ appear more settled, with a minority experiencing major disturbances. Nonetheless, the similarity of their compact morphologies and relatively hot stellar dynamics to red-sequence

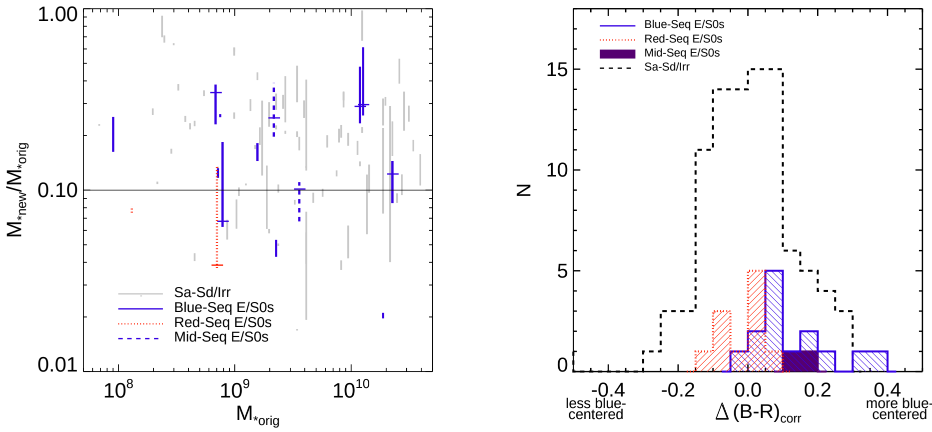

Figure 3. Left: Fractional stellar mass predicted to form within the next 3 Gyr. For each galaxy, exponentially declining/constant SFR scenarios are represented by the lower/upper end of a vertical line. The horizontal dash marks the fractional new stellar mass formed with the original gas reservoir. Right: Distribution of "blue-centeredness" $\Delta(B-R)_{\rm corr}$, the outer disk color minus the central color, corrected for the typical color gradient of a galaxy at that blue luminosity. Blue- & mid-sequence E/S0s are much more often blue-centered than typical spiral/irregular galaxies (Kannappan et al. 2004).

E/S0s suggests that many of these galaxies are products of major mergers in the past (Kannappan, Guie, & Baker 2009).

The long gas exhaustion timescales for blue-sequence E/S0s allow time for minor mergers/interactions with small companions to trigger episodic inflows of gas, resulting in bursts of star formation. In addition to having bluer inner and outer disk colors than red-sequence E/S0s, half of the blue-sequence E/S0s have centers that are bluer than their outer disks. Figure 3b shows that all but one of our blue-sequence E/S0s and both mid-sequence E/S0s are on the more blue-centered end of the distribution for spiral/irregular galaxies. For galaxies of all morphologies, blue-centeredness reflects central star formation enhancements and correlates strongly with morphological peculiarities and the presence of nearby companions (Kannappan et al. 2004). Most of the more blue-centered blue-sequence E/S0s also have enhanced total specific star formation rates (Wei et al. 2009). These results are broadly consistent with a picture of episodic outer-disk and inner-disk (pseudobulge) growth, allowing E/S0s to evolve toward typical spiral galaxy morphology (Kannappan, Guie, & Baker 2009).

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References

Jansen, R. A., Franx, M., Fabricant, D., & Caldwell, N. 2000, ApJS, 126, 271
Kannappan, S. J., Jansen, R. A., & Barton, E. J. 2004, AJ, 127, 1371
Kannappan, S. J., Guie, J. M., & Baker, A. J. 2009, AJ, 138, 579
Wei, L. H., Kannappan, S. J., Vogel, S. N., & Baker, A. J. 2009, submitted