OBSERVATIONS OF STRIPPED EDGE-ON VIRGO CLUSTER GALAXIES

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Abstract

We present observations of highly inclined, HI deficient, Virgo cluster spiral galaxies. Our high-resolution VLA HI observations of edge-on galaxies allow us to distinguish extraplanar gas from disk gas. All of our galaxies have truncated H\textalpha disks, with little or no disk gas beyond a truncation radius. While all the gas disks are truncated, the observations show evidence for a continuum of stripping states: symmetric, undisturbed truncated gas disks indicate galaxies that were stripped long ago, while more asymmetric disks suggest ongoing or more recent stripping. We compare these timescale estimates with results obtained from two-dimensional stellar spectroscopy of the outer disks of galaxies in our sample. One of the galaxies in our sample, NGC 4522 is a clear example of active ram-pressure stripping, with 40\% of its detected HI being extraplanar. As expected, the outer disk stellar populations of this galaxy show clear signs of recent (and, in fact, ongoing) stripping. Somewhat less expected, however, is the fact that the spectrum of the outer disk of this galaxy, with very strong Balmer absorption and no observable emission, would be classified as “k+a” if observed at higher redshift. Our observations of NGC 4522 and other galaxies at a range of cluster radii allow us to better understand the role that clusters play in the structure and evolution of disk galaxies.

1. Introduction

The morphology-density relationship (Oemler 1974; Melnick & Sargent 1977; Treu et al 2003) is one of the clearest examples of the effect that clusters have on their member galaxies. There are several cluster processes that may contribute to this observed effect (Treu et al 2003). ISM-ICM stripping (which includes both ram-pressure stripping and turbulent viscous stripping)
may be among the most important processes in the transformation of late-type cluster spirals into Sa’s and S0’s. This process, which removes gas from the galaxy but leaves the stars unperturbed, results in galaxies with truncated gas and star-forming disks (Koopmann & Kenney 2004a;b). Simulations of ICM-ISM interactions (e.g. Schulz & Struck 2001; Vollmer et al 2001) have shown that a smooth, uniform ISM can be stripped from the outer regions of galaxies in clusters via ram pressure. Some of this gas and dust will escape from the galaxy and become part of the ICM, while some will fall back onto the galaxy (Vollmer et al 2001). In either scenario, simulations show large amounts of extraplanar material near the disk of the galaxy during ISM-ICM stripping. Therefore, by studying the details of ISM-ICM stripping events, we can gain a better understanding of the structure and dynamics of galaxy clusters.

2. HI Imaging and Optical Spectroscopy

As part of a larger VLA survey of Virgo Cluster spiral galaxies (Chung et al. 2006, in preparation), we have observed several edge-on spiral galaxies to allow us to distinguish potential extraplanar gas from disk gas. In at least one case (NGC 4522; described in detail in the next section), there has been the unambiguous detection of extraplanar gas. Figure 1 shows HI maps of the outer disks of four of the sample edge-on galaxies. The HI morphologies range from very symmetric, truncated disks (IC 3392 and NGC 4419) to NGC 4522, with extraplanar gas making up 40% of the measured HI.

In order to better characterize the stellar population of the outer disks of these galaxies, we observed them with the SparsePak Integral Field Unit (Bershady et al. 2004) on the WIYN 3.5m telescope. SparsePak allows us to take simultaneous spectra of many positions in the disk. Through averaging of several positions, we have obtained high signal-to-noise spectra of the outer stellar
disks just beyond the gas truncation radius (Figure 1). The outer disk integrated spectra of these galaxies also show a notable trend: an increase in strength of the Hβ line from IC 3392 (EW(Hβ)=3.8 Å) and NGC 4419 (EW(Hβ)=2.7 Å) to NGC 4388 (EW(Hβ)=6.5 Å) and NGC 4522 (EW(Hβ)=8.2 Å). Taken together, these data seem to suggest an evolutionary sequence. Galaxies with very symmetric disks (i.e. NGC 4419 and IC 3392) have outer disks with older stellar populations and, as the gas disks become more asymmetric and irregular (i.e. NGC 4388 and NGC 4522), the age of the stellar population is younger.

3. NGC 4522: A Local Analog to k+a Galaxies

NGC 4522 is a highly inclined, 0.5L∗, spiral galaxy in the southern part of the Virgo Cluster, 0.6 r100 from M87 at the center of the cluster, and only 0.3 r100 from M49, which is at center of subcluster B. There is strong evidence, both from HI (Kenney et al. 2004) and radio continuum (Vollmer et al. 2004) observations that it is currently being stripped of its gas by interaction with an ICM. In a galaxy stripped of its gas such as this, we expect rapid cessation of star formation as the raw materials for forming stars are removed from the disk. Indeed, Koopman & Kenney (2004a;b) find many such galaxies in the Virgo cluster: galaxies with normal stellar disks, but truncated Hα disks.

The spectrum of NGC 4522 (Figure 2) shows no signs of active star formation and, indeed, the Hα line shows moderately strong absorption. The higher order indices show extraordinarily strong absorption: EW(Hδ)=5.3 Å, EW(Hγ)=5.5 Å, and EW(Hβ)=8.2 Å. Models have suggested (Couch & Sharples 1987; Shioya et al. 2002) that rapid truncation of star formation will leave distinct spectral signatures, most notably a sharp rise in strength of the higher order Balmer line indices. In their models of a simple stellar population, Sh-
ioya et al. 2002 show that H\(\delta\) equivalent width rises by \(\sim 5\) \(\text{\AA}\) on very short timescales as the O and B stars die and the A stars, with very strong Balmer lines, begin to dominate the integrated light. Such galaxies, with no active star formation but strong Balmer absorption lines have been observed in clusters and are commonly called “k+a” galaxies, in reference to their mix of stellar populations. Galaxies with a k+a spectral signature were first discovered in high-z clusters (Dressler & Gunn 1982, 1983) but have been since discovered as nearby as the Coma cluster (Poggianti et al. 2004). Our observations of NGC 4522 imply the outer disk is similar in stellar population to the k+a galaxies at higher redshift (as described by Dressler et al. 1999). While we are studying only one region of a galaxy, it appears possible to create a k+a spectrum with ram pressure stripping.

4. Summary

There is little doubt that cluster processes play an important role in the evolution of their member galaxies. The relative importance of specific processes, however, has yet to be fully understood. Recent work (Shioya et al. 2004) has suggested a convergent evolutionary scheme; that different processes that lead to the same morphological endpoint. By studying galaxies in the nearby Virgo cluster, we can hope to better understand the details of cluster galaxy evolution processes. It appears that ram pressure stripping must play an important role in the transformation of galaxies in clusters and that k+a spectra of galaxies observed at higher redshift can plausibly be caused by ram pressure stripping of gas-rich spirals.

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