

Spitzer Observations of Environmental Effects on Virgo Cluster Galaxies

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ABSTRACT

We present initial results from SPITSOV, the Spitzer Survey of Virgo, which includes MIPS and IRAC observations for a carefully selected sample of 44 Virgo cluster spiral and peculiar galaxies. SPITSOV is part of a multiwavelength campaign to understand the effects of the cluster environment on galaxy evolution. These Virgo galaxies are different from galaxies outside of clusters, since most of them have been significantly modified by their environment. The SPITSOV data can serve the community as the Spitzer sample of nearby cluster spiral galaxies, a complement to the SINGS data for nearby non-cluster galaxies.

In this paper we describe the sample, the goals of the study, and present preliminary results in 3 areas: 1. Evidence for ram pressure-induced disturbances in radio morphologies based on changes in the FIR-radio ($70\mu\text{m}$ - 20cm) correlation. 2. Evidence for ram-pressure stripped extraplanar gas tails from comparisons of dust/PAH ($8\mu\text{m}$) emission and optical dust extinction. 3. Evidence for unobscured star-forming regions with large ratios of $\text{H}\alpha$ to $24\mu\text{m}$ emission in some galaxies due to ram pressure stripping of dust.

Subject headings: clusters: general — galaxy clusters: individual (Virgo)

1. Introduction

Studies of galaxies near and far show broad evidence for the basic picture of hierarchical galaxy formation, in which large galaxies assemble from smaller pieces, and interactions

play a large role in evolution. Yet the dominant interaction processes, and what actually happens in them, are still not sufficiently well-known. Many of the processes driving galaxy evolution can be clearly observed in and around clusters. Since hierarchical galaxy formation is scale-free, cluster formation is much like galaxy formation and the processes of gravitational interactions, gas accretion, and gas stripping occur both as galaxies fall into clusters and as small galaxies fall into larger galaxies. Thus by studying cluster galaxies we learn not only about their own evolution but also about the processes which occur during galaxy formation.

The morphology-density relation (Dressler 1980) and the observed differences between clusters at different redshifts (Dressler et al. 1997) show that the environment significantly drives the evolution of galaxies. It is still not clear which are the dominant environmental processes in clusters, although both gravitational and gas dynamical processes seem to be important. Gravitational effects include slow galaxy-galaxy interactions and mergers (Mihos 2004), harassment (Moore et al. 1996; Moore, Lake & Katz 1998), the effects of the global tidal field (Byrd & Valtonen 1990; Henriksen & Byrd 1996) and the effects of sub-cluster merging (Bekki 1999; Stevens et al. 1999). Gas dynamical effects include ram pressure and turbulent viscous stripping of the cold ISM (Gunn and Gott 1972; Abadi et al. 1999; Schulz & Struck 2001; Vollmer et al. 2001) and starvation (Larson, Tinsley & Caldwell 1980). While there is much new evidence for both gravitational interactions and ram pressure gas stripping in cluster galaxies (Mihos et al. 2005; Moran et al. 2007; Chung et al. 2007; Tonnenson et al. 2007), it remains a challenge to clearly identify which process is occurring and to quantify the impacts for each type of interaction.

As the nearest rich cluster, Virgo is one of the best places to study evolutionary processes in action. It is close enough to show observational details that, when combined with simulations, can constrain key interaction parameters. The majority of its galaxies have clearly been modified by the environment. Virgo has a dense ICM, and has already provided some of the best evidence for ongoing ram pressure stripping. The cluster also exhibits a lot of sub-structure, with infalling groups containing tidally interacting galaxies and mergers. There is evidence for ongoing sub-cluster cluster mergers (Schindler, Binggeli & Bohringer 1999), allowing us to study the possible impacts of a dynamic ICM and a varying global potential. There are also HI-deficient galaxies far away from the dense core. These are ideal candidates to study the mysterious mechanisms that seem to affect galaxies far beyond the virial radius (Solanes et al. 2001; Balogh et al. 1998).

Here we present the Spitzer Survey of Virgo (SPITSOV), an infrared imaging study of Virgo Cluster galaxies using the IRAC and MIPS instruments aboard the Spitzer Space Telescope. SPITSOV forms part of our large multi-wavelength study of Virgo cluster galaxies, which includes optical BVRH α , HI, 20cm radio continuum, GALEX UV, and optical spec-

troscopy. A major goal of our studies is to identify clear diagnostics for each process from detailed studies of individual galaxies, and to quantify the impacts for each type of interaction. Our goal for the Spitzer study is to compare IR distributions with other wavelengths and with numerical models, to improve our understanding of the ISM, star formation, and stellar populations in environmentally-modified cluster galaxies.

In this paper we briefly describe the galaxy sample, the data processing, and three examples of how the SPITSOV data is used to learn about ram pressure stripping in clusters. Many basic things are still not known about stripping, such as: How does the real, complex, multi-phase ISM react to ram pressure? How do distinct parts of the ISM react? Are shocks driven into the unstripped ISM by the strong external pressure? Under what circumstances is star formation enhanced or disrupted? What is the fate of star-forming molecular clouds? What are the rates of triggered star formation vs. gas removal? Does stripping happen only in the core, or does it also occur in the outskirts, perhaps due a dynamic rather than a static ICM? Spitzer data allows us to address many of these questions.

2. The sample

We have chosen a representative sample of 44 S0/a-Sm Virgo spirals, with a range of 20 in mass, a range of H α and HI properties, and spread throughout the cluster. With this sample we can explore the range of galaxy interactions and evolutionary stages which exist in Virgo spirals, and conduct statistical analyses. The SPITSOV sample is the MIR-FIR counterpart to the H α (Koopmann & Kenney 2004a) and HI VIVA (VLA Imaging of Virgo in Atomic gas) Virgo cluster samples (Chung et al. 2007; Chung et al. 2008).

The spatial distribution of the survey galaxies has good sampling from the core to the cluster outskirts, including galaxies both within and beyond the X-Ray emitting region. Since there is much recent evidence showing significant evolution in the outskirts of clusters (Solanes et al. 2001; Balogh et al. 1998), we have included galaxies located out as far as 10° ($=2.5$ Mpc= $3R_{\text{vir}}$). The galaxies have a wide range of Hubble types and H α distributions including Normal, Anemic, Starburst, and Truncated (Koopmann & Kenney 2004b). We believe that these categories represent different types of interactions, different evolutionary phases, and the effects of different parameters for a given type of interaction. Figure 1 shows three-color composite IRAC images of twelve galaxies from the sample. These include galaxies with normal stellar disks and evidence for ongoing or past ICM-ISM stripping, some with disturbed stellar disks indicating gravitational encounters, and some with peculiarities that are not yet understood.

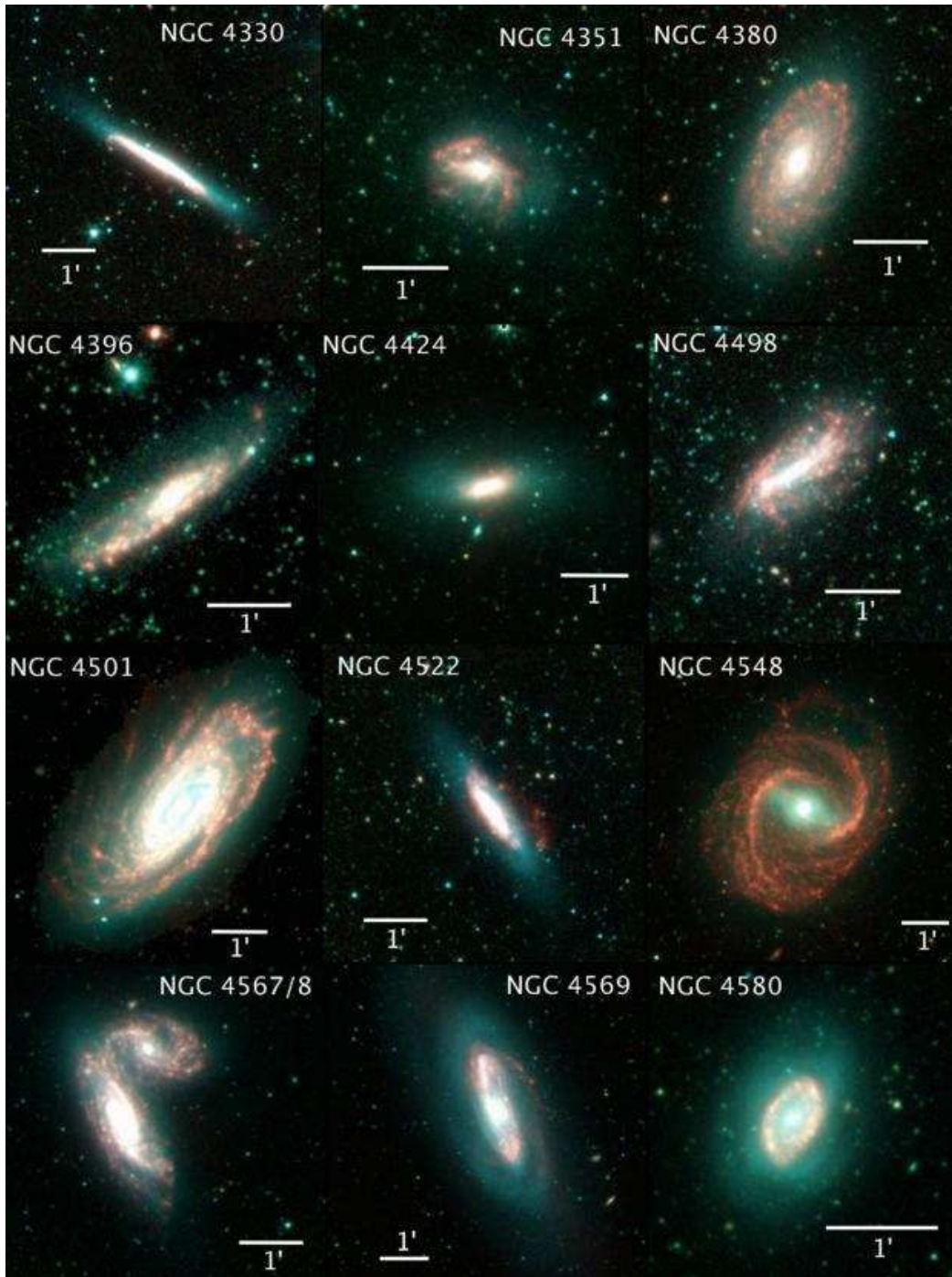


Fig. 1.— Three-color IRAC composite images of twelve Virgo cluster galaxies from the SPITSOV sample. Blue and green represent the $3.6 \mu\text{m}$ and $4.5 \mu\text{m}$ emission, respectively, and the $5.8 \mu\text{m}$ and $8.0 \mu\text{m}$ emission are shown in red. Many Virgo spirals lack gas and PAH emission in their outer disks due to ram pressure stripping. Some of these are in an active stripping phase and have extraplanar gas, PAH emission and star formation (NGC 4522, NGC 4569, and NGC 4330).

3. Observations

Each of our Virgo Cluster galaxies are fully-mapped using the IRAC and MIPS imagers. The IRAC 3.6 μm and 4.5 μm images trace the stellar populations, while the IRAC 8 μm images map the PAH emission. The MIPS 24 μm is a good indicator of unobscured star formation and the MIPS far-infrared bands (70 μm & 160 μm) probe the cooler dust population which accounts for the majority of the total dust mass.

Our observing strategy is guided by that of the SINGS Legacy team (Kennicutt et al. 2003). However, our observing integration times are twice that of SINGS because we are interested in detecting extraplanar and outer galaxy infrared emission. Our integration times correspond to $3\text{-}\sigma$ sensitivity levels of 0.014, 0.020, 0.077, 0.089, 0.14, 0.55 and 2.39 MJy/sr at 3.6, 4.5, 5.8, 8.0, 24, 70 and 160 μm , respectively.

The basic calibrated datasets (BCDs) delivered by the Spitzer Science Center (SSC) are further processed using the standard Post-BCD tools developed by the SSC. The SSC data reduction pipeline is also tuned to achieve further improvement in the data (especially in the 70 & 160 μm images).

4. Results

4.1. Evidence for Ram Pressure from Changes in the FIR-Radio Correlation

Although HI observations can show whether a galaxy was stripped, radio continuum emission can be used to differentiate between active and past stripping. A clear tracer of ram pressure can help show whether the galaxies are stripped in the cluster cores or in the outskirts (which seems to occur for some galaxies). Is ram pressure sometimes stronger than that expected for a smooth static ICM? If the ICM is dynamic and lumpy, as might be expected during subcluster mergers, this can make it easier to strip galaxies. Thus clear tracers of ram pressure are relevant for learning the relative importance of stripping to other processes which drive galaxy evolution.

We find clear indications of ram pressure from a comparison of radio and far-infrared distributions, in a preliminary sample of 10 Virgo galaxies (Murphy et al. 2008b). Figure 2 shows maps for the Virgo spiral NGC 4522. Both the radio and FIR distributions (along with all ISM tracers) are truncated at $0.4R_{25}$, as the outer ISM has been stripped from the galaxy, leaving an ISM-free outer stellar disk (Kenney, van Gorkom & Vollmer 2004). However the radio and FIR have different distributions. Whereas the FIR map is relatively symmetric, the radio map shows clear asymmetries, with compressed contours to the southeast, and an

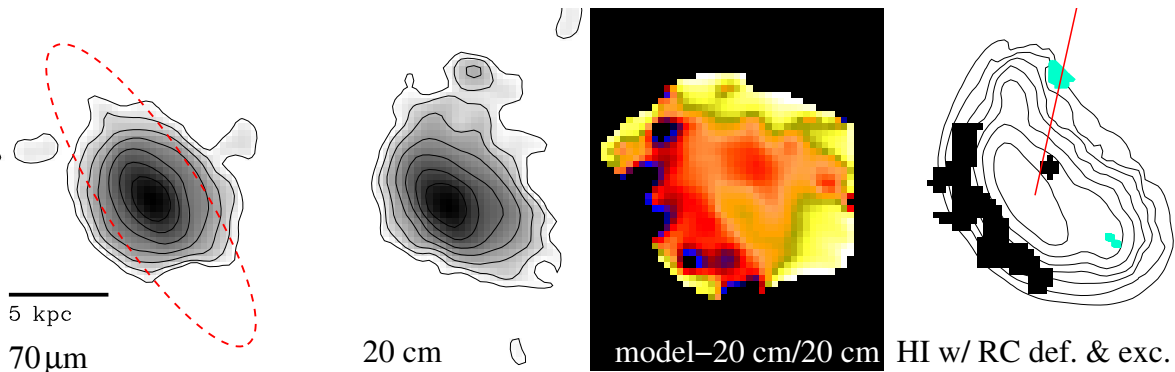


Fig. 2.— Radio and far-infrared maps of Virgo spiral NGC 4522, known to be experiencing ram pressure stripping. a.) MIPS $70\mu\text{m}$ map. b.) VLA 20cm radio map. c.) Ratio of smoothed $70\mu\text{m}$ (=“expected radio”) to observed 20cm radio emission. d.) HI contours with radio deficit regions marked in black and radio excess regions marked in cyan. The radio deficit region is where the observed radio brightness is less than 50% of the expected value, based on the $70\mu\text{m}$ map (from Murphy et al. 2008b).

extended tail to the northwest. The radio-emitting cosmic rays and magnetic fields are more strongly affected by ram pressure than the denser components of the ISM, as traced by the $70\mu\text{m}$ emission.

Spitzer $70\mu\text{m}$ maps help show evidence for ram pressure by providing a way of calibrating “normalcy” for the easily disturbed radio continuum distribution. We use the Spitzer $70\mu\text{m}$ maps and the FIR-radio correlation to predict what the radio continuum distribution would be in the absence of ICM pressure. Differences between the observed and predicted radio maps show “radio deficit” regions near the leading edges of several galaxies, and “radio excesses” on the trailing side, clearly indicating ongoing ICM-ISM interactions. Galaxies with local radio deficits seem to have global radio enhancements (relative to the FIR emission), suggesting that ICM-ISM interactions accelerate cosmic ray electrons (see Murphy et al. 2008a; Murphy et al. 2008b).

4.2. Evidence for Extraplanar Gas Tails from Comparisons of $8\mu\text{m}$ and B-I Images

One-sided extraplanar gas distributions in galaxies with undisturbed stellar disks are clear signatures of ram pressure stripping. They can be easily identified in nearly edge-on galaxies, but are harder to identify in less inclined galaxies like NGC 4569. In such galaxies, comparisons of $8\mu\text{m}$ PAH images with B-I “dust extinction” maps can demonstrate that gas is extraplanar, and thereby constrain interaction models by clarifying the ISM geometry.

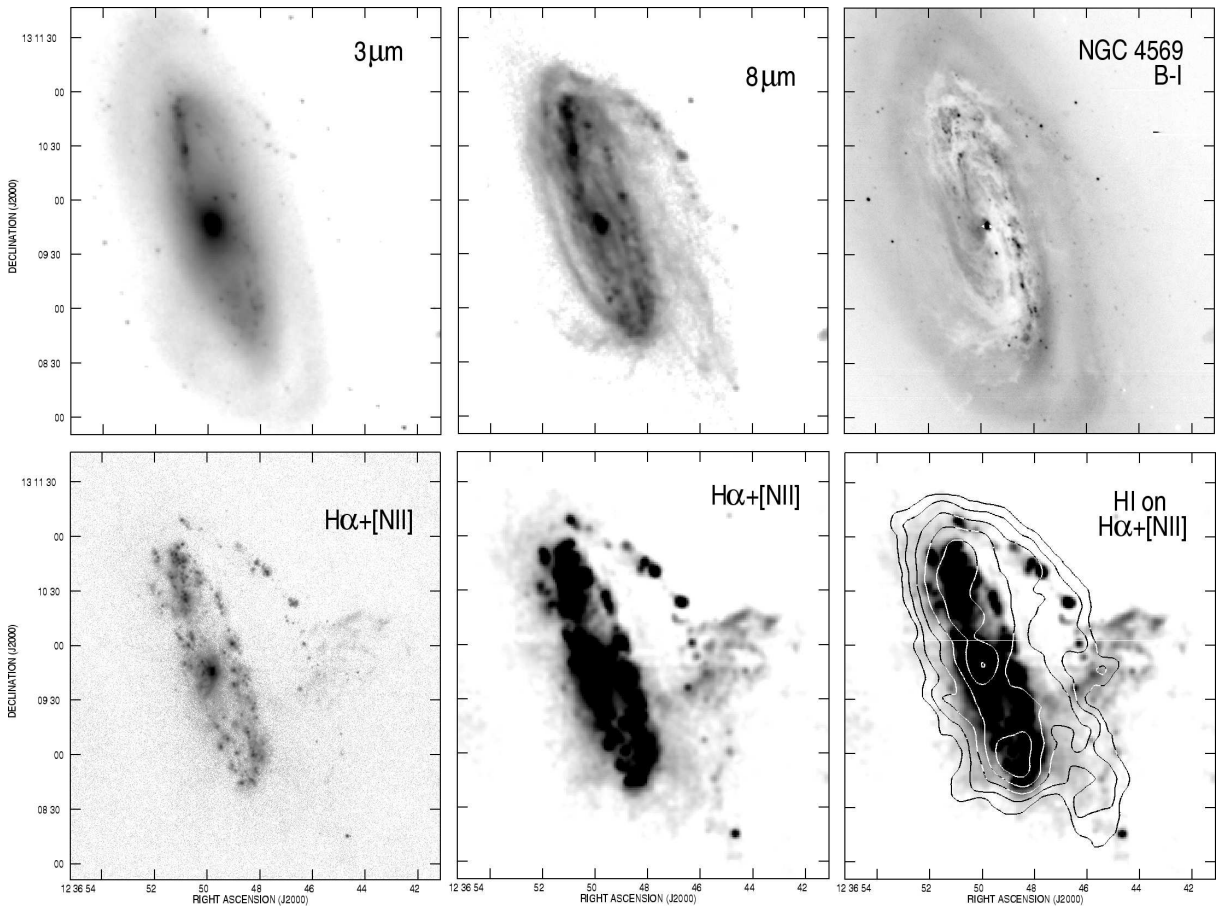


Fig. 3.— Six-panel montage of central $4' = 16$ kpc in NGC 4569, a large Virgo spiral experiencing ram pressure stripping. a.) Spitzer IRAC $3.6\mu\text{m}$ showing stellar distribution. b.) Spitzer IRAC $8\mu\text{m}$ showing PAH/dust emission. c.) WIYN B-I image showing dust extinction as white (“red”) young star clusters as black (“blue”). d.) $\text{H}\alpha + [\text{NII}]$ image, showing star formation truncated in disk at $1.4' = 6.5$ kpc, and arm of extraplanar HII regions in West. e.) Deeper, smoothed $\text{H}\alpha + [\text{NII}]$ image, showing diffuse extraplanar nebulosity from nuclear outflow, as well as arm of extraplanar HII regions. f.) HI contours on $\text{H}\alpha + [\text{NII}]$ greyscale image, showing extraplanar HI arms extending to the West. Note that the extraplanar emission is detected with very good sensitivity and resolution at $8\mu\text{m}$.

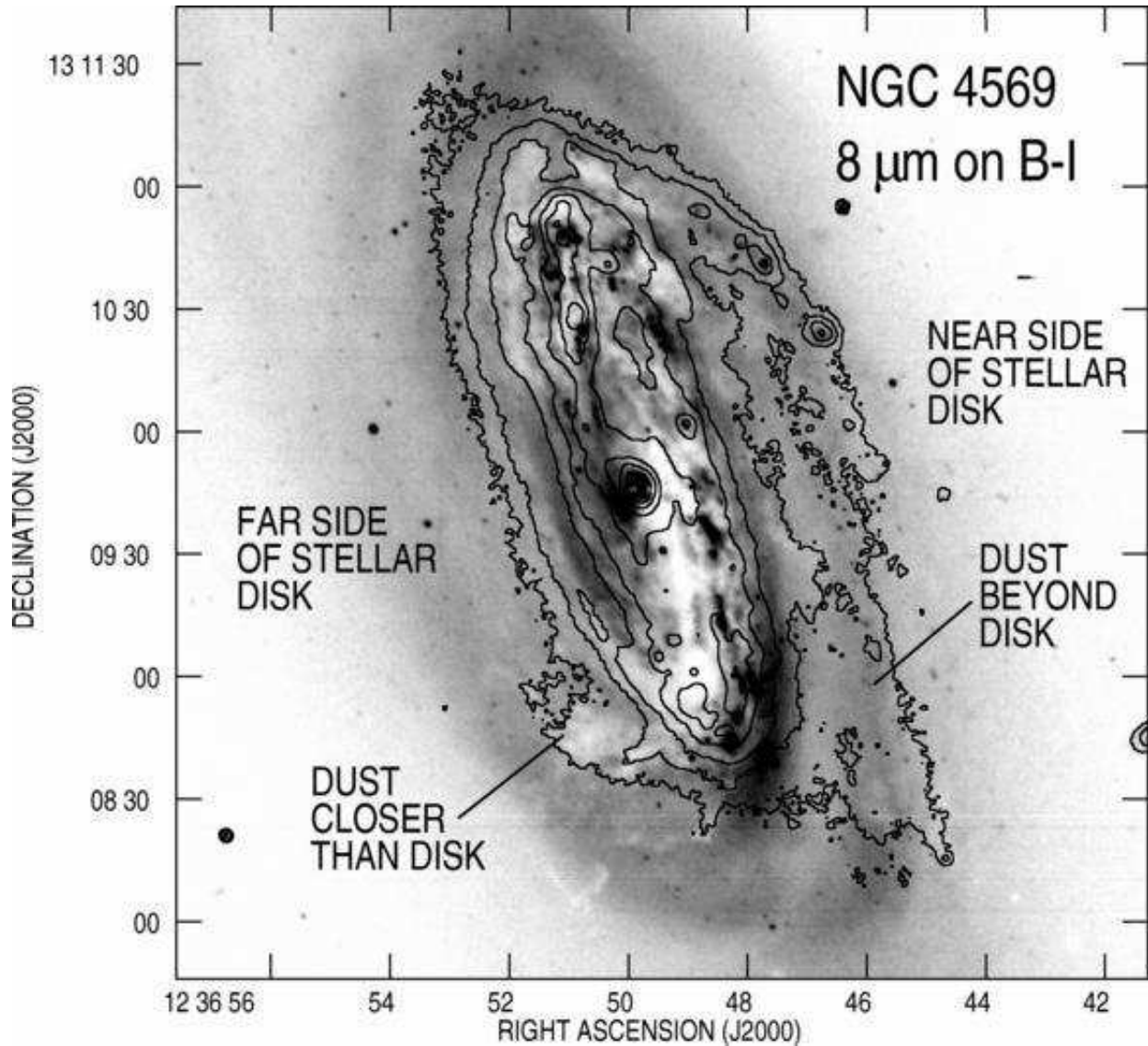


Fig. 4.— IRAC $8\mu\text{m}$ contours on WIYN B-I greyscale image in the Virgo spiral NGC 4569. Dust within the disk plane produces strong optical extinction on the near side of the stellar disk, which is to the west. The anomalous western complex show strong $8\mu\text{m}$ /PAH/dust emission but weak optical dust extinction (“red” B-I colors, shown as white), indicating that this gas and dust lies behind the stellar disk and is therefore extraplanar. The southeastern extraplanar feature shows weak $8\mu\text{m}$ /PAH/dust emission but strong extinction, indicating that this gas and dust lies in front of the stellar disk.

One of the largest Virgo spirals with evidence for ongoing ICM-ISM stripping is NGC 4569, in which all disk ISM tracers (HI, $8\mu\text{m}$, $\text{H}\alpha$) are sharply truncated at 30% of the optical radius R_{25} , as shown in Figure 3. Anomalous arm-like features of $8\mu\text{m}$, HI and $\text{H}\alpha$ to the west of the truncated disk may be gas stripped from the disk by ram pressure. This has been suggested for the HI by (Vollmer et al. 2004), however the gas morphology and kinematics alone do not demonstrate that the gas is extraplanar.

A comparison of the relatively strong $8\mu\text{m}$ dust/PAH emission with the relatively weak associated dust extinction in the B-I image, shown in Figure 4, indicates that the anomalous western dust and gas must lie *behind* the stellar disk. The extinction associated with this much dust would be much larger if this dust were within or in front of the disk, as seen by a comparison with the extinction in the inner galaxy. This clearly shows that the anomalous western gas and dust are extraplanar and therefore have been stripped from the disk. Moreover, it shows that this extraplanar gas is on the far side of the disk, as expected for stripping from a galaxy which is moving through the intracluster medium towards us. NGC 4569 is one of the few blueshifted galaxies, with a line-of-sight velocity of -235 km s^{-1} , and its orbit through the cluster must have a large component toward us.

While the western extraplanar gas feature confirms the basic stripping scenario, there is another ISM feature which doesn't fit in with the simplest picture. A small feature in the southeast beyond the gas disk truncation radius is clearly observed in the $8\mu\text{m}$, HI, and $\text{H}\alpha$ emission even though it is weaker and has less mass than the western extraplanar feature (see Figure 3 and Figure 4). However the dust extinction traced by the B-I image from this feature is strong, as seen by a comparison with the extinction in the inner galaxy on the same side of the major axis. This indicates that the southeast feature is also extraplanar, but unlike the much larger western extraplanar gas feature, it lies on the near side of the stellar disk. How is this to be understood, in the context of a scenario in which stripping acts to push gas to the far side of the galaxy?

The explanation may be gas fallback after peak pressure. Comparisons between simulations and observations (Vollmer et al. 2004) as well as stellar population studies (showing that star formation has stopped 300 Myr ago; Crowl & Kenney 2008) indicate that NGC 4569 is currently observed 300 Myr after peak pressure. Simulations show that after peak pressure, some gas which had been pushed upwards by ram pressure falls back to the galaxy. Perhaps the SE extraplanar feature is such a fallback feature. Regardless of the explanation, it is clear that comparisons of $8\mu\text{m}$ PAH emission with B-I “dust extinction” images provide valuable constraints on interaction models by clarifying the ISM geometry (more details can be found in Kenney et al. 2008).

4.3. Star Formation: Triggered, Obscured, or Revealed

Among the biggest impacts of interactions on galaxy evolution are changes in the rates and locations of star formation. In clusters, there are many things that can alter galaxies’ star formation histories that we would like to understand. Is star formation triggered by gravitational interactions or ram pressure? For galaxies experiencing ram pressure, what are the relative rates of gas loss due to stripping and triggered star formation? How much star formation occurs in galaxy disks versus galaxy halos and intra-cluster space? Studies to date have attempted to address these questions with $H\alpha$ imaging (Koopmann & Kenney 2004a; Koopmann & Kenney 2004b), but the results are somewhat compromised by extinction effects. We wish to explore these questions by using the MIPS $24\mu\text{m}$ dust emission in combination with the $H\alpha$ emission (Calzetti et al. 2007), to derive more accurate star formation rates and distributions in cluster galaxies.

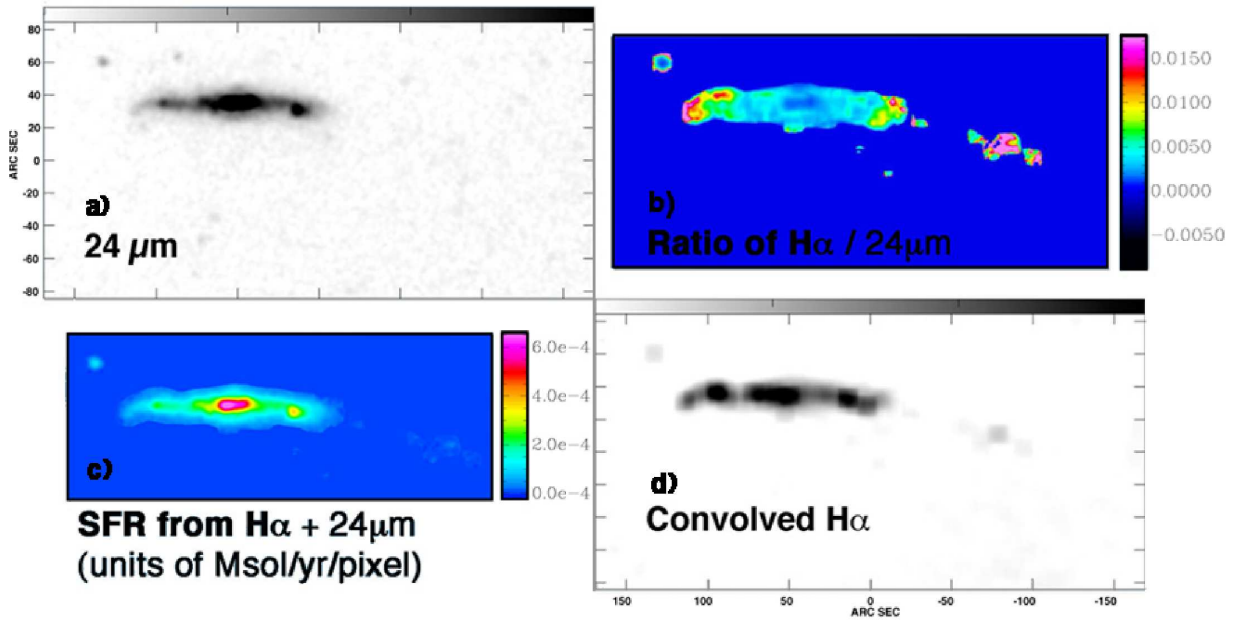


Fig. 5.— Star formation images of NGC 4330, experiencing ram pressure. a.) MIPS $24\mu\text{m}$ image. b.) $H\alpha/24\mu\text{m}$ ratio map, showing the star forming regions which are most and least obscured by dust. Regions near the leading edge and the extraplanar tail are least obscured. c.) Combined star formation map, a linear combination of $24\mu\text{m}$ and $H\alpha$ images. d.) WIYN $H\alpha$ image, convolved to same $6''$ resolution as $24\mu\text{m}$ map.

There is suggestive evidence based on $H\alpha$ imaging for triggered star formation due to ram pressure in some Virgo spirals (Koopmann & Kenney 2004b), but this was not conclusive due to dust extinction effects. For example the highly-inclined Virgo spiral NGC 4402, which is clearly experiencing ICM ram pressure, has optically luminous star-forming regions

at its “leading edge” (Crowl et al. 2005). Yet it is unclear whether the ICM wind has triggered star formation, or merely removed some of the dust thereby exposing “normal” star formation. Preliminary results from combining the $24\mu\text{m}$ with $\text{H}\alpha$ emission suggest only modest enhancements in star formation triggered by ram-pressure (Wong & Kenney 2008; Abramson & Kenney 2008), although the full SPITSOV sample needs to be studied, and star formation traced by UV emission may also need to be incorporated.

Do interactions cause star formation in cluster galaxies to be obscured more or less than non-cluster galaxies? Preliminary results in a few galaxies indicate that ram pressure stripping may remove dust from some star forming regions, allowing more of the optical and UV photons to escape. Figure 5 show star-forming regions with high $\text{H}\alpha/24\mu\text{m}$ ratios at the leading edge and the extraplanar tail of the galaxy NGC 4330. This could prove to be an indicator of active pressure on the galaxy, and may provide interesting targets for detailed optical/UV studies of unobscured young star clusters.

5. Summary

The Spitzer Survey of Virgo (SPITSOV) is an imaging study of 44 Virgo Cluster spiral galaxies using the Spitzer Space Telescope, whose goal is to advance our understanding of the environmental effects on cluster galaxy evolution. We describe preliminary results in 3 areas.

Spitzer $70\mu\text{m}$ maps and the FIR-radio correlation are used to predict what the radio continuum distribution would be in the absence of ICM ram pressure. Differences between the observed and predicted radio maps show “radio deficit” regions near the leading edges of several galaxies, and “radio excesses” on the trailing side, clearly indicating ongoing ICM-ISM interactions. Radio deficit regions may be an excellent diagnostic of active ram pressure. The galaxies with local radio deficits seem to have global radio enhancements, perhaps due to the acceleration of cosmic rays by shocks driven by ram pressure.

We combine the $\text{H}\alpha$ and $24\mu\text{m}$ images to produce star formation maps and explore the effects of interactions on star formation. Preliminary results in a few galaxies suggest that star formation is only moderately enhanced by ram pressure. Star-forming regions with large ratios of $\text{H}\alpha$ to $24\mu\text{m}$ emission are observed at the edges of some galaxies, probably due to ram pressure sweeping of the dust away from star forming regions. Large $\text{H}\alpha/24\mu\text{m}$ ratios at galaxy edges may be a good diagnostic of ongoing ram pressure.

For galaxies experiencing stripping, comparisons of dust emission and extinction can constrain interaction models by clarifying the 3D ISM distribution. IRAC $8\mu\text{m}$ and optical

B-I (“dust extinction”) images are used to show whether the dust is in front of or behind the stellar disk. In the case of the Virgo spiral NGC 4569, this comparison shows that the “anomalous” western dust and gas features lie behind the stellar disk and are clearly extraplanar, and therefore have been stripped from the disk.

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