Ram Pressure Stripping in NGC 4330

Anne Abramson[1] & Jeffrey D. P. Kenney[1]

[1]*Astronomy Department, Yale University, P.O. Box 208101 New Haven, CT 06520-8101*

abramson@astro.yale.edu

ABSTRACT

We present Spitzer IRAC and MIPS data which provide key insights into the ICM-ISM stripping process. The Virgo Cluster spiral NGC 4330 was observed as part of SPITSOV, the Spitzer Survey of Virgo (Kenney et al. 2008a), and is a nearby and striking case of ram pressure stripping caught in the act. Pressure from the ICM is actively removing the ISM from the galaxy's outer disk, while leaving the older stellar disk undisturbed. Spitzer enables us to observe the effects of stripping on the galaxy's ISM with high angular resolution and sensitivity at 8μm, and to measure the effects on optically obscured star formation at 24μm. We find that the ram pressure does not strongly enhance star formation in the disk near the ICM-ISM boundary, and we detect no star formation or heated PAHs associated with the stripped HI gas. The galaxy's striking "upturn" feature reveals that dense, star-forming ISM is being pushed out of the disk at the same time as the more diffuse HI gas.

Subject headings: galaxies: ISM — infrared: galaxies — infrared: ISM — ISM: dust, extinction

1. Introduction

As an edge-on Virgo Cluster spiral which is clearly experiencing an ICM-ISM interaction, NGC 4330 presents an excellent opportunity to quantify the effects of early-stage ram pressure stripping. Its high inclination allows us to distinguish between disk ISM and stripped material. Chung et al. (2007) established that ram pressure stripping is the most likely culprit for gas removal at this cluster radius for several Virgo Cluster spiral galaxies with HI tails, including NGC 4330. In this multi-wavelength study, we examine the effects of stripping on the galaxy's current and recent star formation, as well as the effects on its dust and gas morphology. In particular, the galaxy's remarkable "upturn" feature at the leading edge of the ICM-ISM interaction shows 24μm, 8μm, and Hα emission bending away from (and perhaps out of) the disk plane at an angle of about 35^{o}. The angle of the upturn places it roughly perpendicular to the direction of the HI tail on the opposite side of the galaxy, which is extended in the projected ICM wind direction. The upturn provides powerful evidence that the dense, star-forming ISM is being stripped from the disk at the same time as the more diffuse HI gas. For more information see Abramson et al. 2008 (in prep).

2. The Stripping of NGC 4330: A Chronology

Our multiwavelength observations of NGC 4330 (Figure 2) include Spitzer IRAC and MIPS imaging, as well as VLA HI from the VIVA survey (see Chung et al. 2007) and the complementary GALEX UV data, and BVR-Hα from the WIYN telescope. Together, they provide insight into the galaxy's star formation history and current ISM content.

The HI distribution in NGC 4330 (Figure 2a) provides striking evidence that the galaxy is undergoing active ram pressure stripping (Chung et al. 2008). Nearly 30% of the galaxy's HI emission is extraplanar to one side of the major axis, with 10% of the total emission from a tail which extends well outside the stellar disk. The HI tail indicates the approximate projected ICM wind direction, and the R-band stellar disk shows no asymmetries or tails that would indicate a recent gravitational disturbance. Analysis of the FIR-radio relation within NGC 4330 (Figure 1) provides further confirmation that it is actively being stripped. It is possible to predict the distribution of a galaxy's radio continuum emission based on its 70μm distribution and the FIR-radio correlation (Murphy et al. 2006). In stripped galaxies, there are significant differences between the predicted and observed radio distributions (see Murphy et al. 2008a; Murphy et al. 2008b). Several stripping candidates, including NGC 4330, show strong radio deficits near the leading edge of the ICM-ISM interactions. Some, including NGC 4330, also show radio excesses on the trailing side of the stripping interaction.

Hα traces the ongoing and recent (within $\sim 10^6$ years) star formation that is not obscured by dust (Figure 2b). The Hα distribution in NGC 4330 reveals that the star formation is confined to the galaxy's inner disk, where enough gas remains to fuel it. The lack of Hα emission from the outer disk indicates a true lack of star formation activity - since the outer disk has been stripped of its ISM, no dust remains to obscure any Hα emission which might be there.

NUV traces young ($\sim 10^8$ years) stellar populations, and extends to slightly larger radii

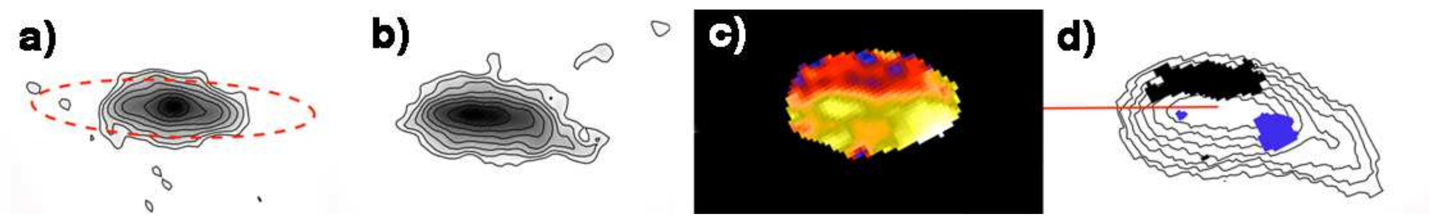

Fig. 1.— The radio-FIR correlation in NGC 4330: a) Extent of optical disk (red ellipse) on 70μm; b) 22 cm radio continuum emission; c) Log of predicted/observed radio flux; d) Radio deficit (black), excess (blue) on HI contours. A radio deficit is observed near the leading edge of the ICM-ISM interaction, while a radio excess is observed on the opposite (trailing) side of the galaxy. Figure courtesy of E. Murphy.

in NGC 4330 than Hα emission does (Figure 2c). Due to the relative stellar population ages traced by Hα and UV, we can measure the distance between the boundaries of the two at the leading edge of the ICM-ISM interaction to estimate the recent progress of the stripping boundary. We find that the boundary has progressed $\sim$1 kpc in the past $\sim 10^8$ years, which is roughly consistent with what simulations (e.g. Vollmer et al. 2001) predict. However, this preliminary estimate needs to be further refined before direct comparisons can be made with models.

IR wavelengths enable higher resolution imaging of the ISM than is possible with HI. In the composite IRAC image shown in Figure 2d, note the undisturbed stellar disk, traced by 3.6 and 4.5μm, and the PAH emission, traced by 5.8 and 8μm, which is truncated well within the stellar disk. The leading-edge upturn at the ISM's radial truncation boundary on the galaxy's eastern side is clearly visible at 5.8 and 8μm.

3. ICM Effects on Star Formation

We use 24μm and Hα data to map the "total" star formation in the galaxy, using the formula of Calzetti et al. (2007). It has been suggested (e.g. Koopmann & Kenney 2004b) that pressure from the ICM in galaxies undergoing stripping may initiate a burst of star formation along the interaction boundary as molecular clouds are compressed. However, in NGC 4330 we do not observe a large enhancement in star formation at the leading edge of the ICM-ISM interaction (Figure 3c). By far, the strongest star formation activity is taking place near the center, as would be expected for an undisturbed spiral. The leading edge upturn does not show strongly enhanced star formation relative to the trailing edge at similar radii - rates do not differ by more than about a factor of 2 at equal distances from the galactic center. Small amounts of extraplanar star formation are detected in the galaxy, but

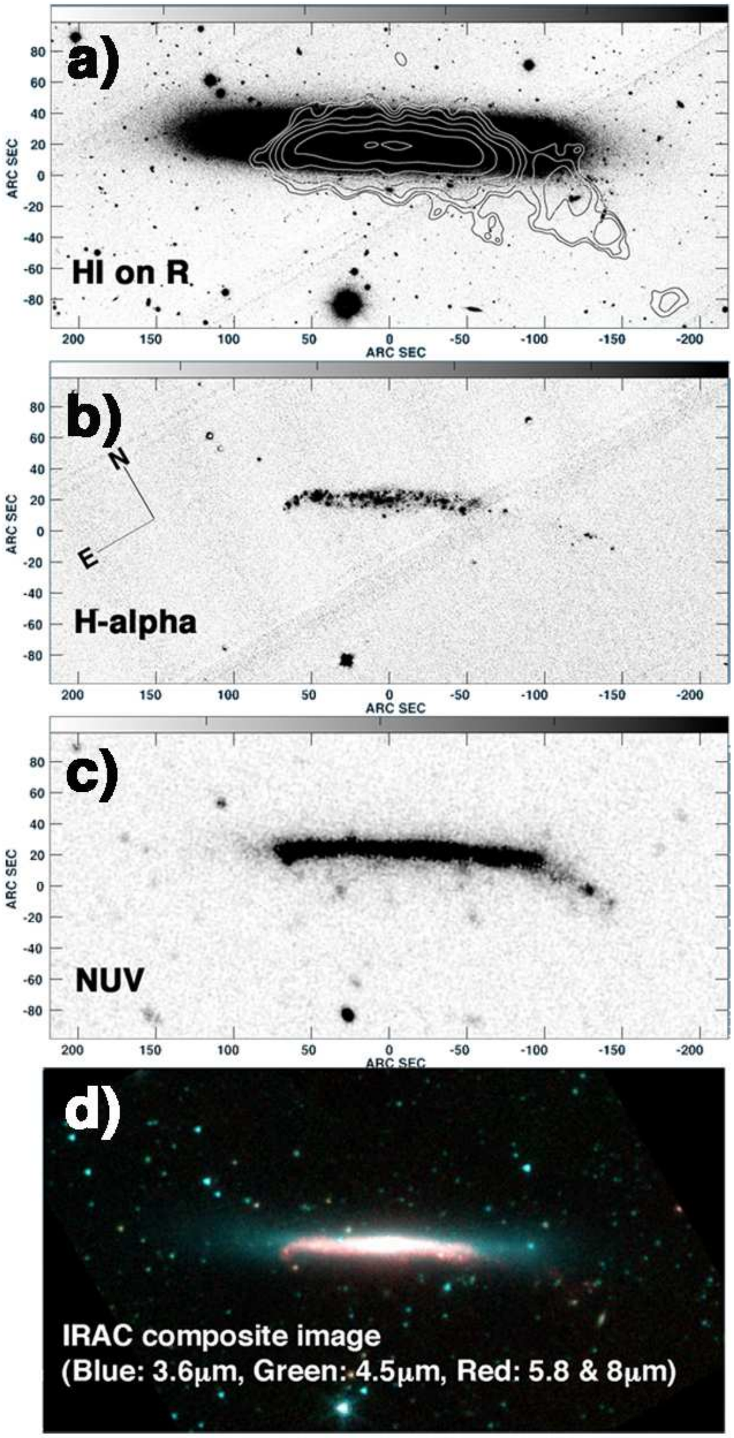

Fig. 2.— a) HI on R - the older stellar disk is undisturbed, but fragile HI has been removed from the galaxy's outer disk (contours 2, 4, 8, 16..., $\times 10^{19}\text{cm}^{-2}$); b) H$\alpha$ - ongoing star formation is largely confined to the inner disk, with a small amount in the tail; c) NUV - recent star formation is slightly more radially extended than Hα; d) IRAC composite image - the stellar disk (3.6, 4.5μ) is undisturbed, but the ISM (5.8, 8μm) is radially truncated.

not enough to suggest that star formation is widespread in the stripped ISM. For analyses of radial star formation rates in other galaxies undergoing stripping, see Wong & Kenney 2008.

If we assume that 24μm emission comes from star-forming regions enshrouded in dust, while Hα emission comes from relatively unobscured star-forming regions, then taking the ratio of Hα to 24μm emission strength should reveal the locations where star formation is relatively obscured and where it is relatively unobscured. In the case of NGC 4330, Hα is strongest relative to 24μm at the two sides of the star-forming disk (Figure 3b). In particular, at galaxy's leading edge, the ratio of Hα to 24μm peaks are over 10 times greater than in the center of the galaxy. This may indicate that at least some dust that would normally obscure Hα in the outer regions has been stripped away. Typical ratios for the leading and trailing edge are ∼8 times greater than at the galaxy's center. The upturn at the leading edge is visible curving away from the major axis in both Hα and 24μm, indicating that the dense, star-forming ISM is being pushed out of the disk along with the lower-density HI.

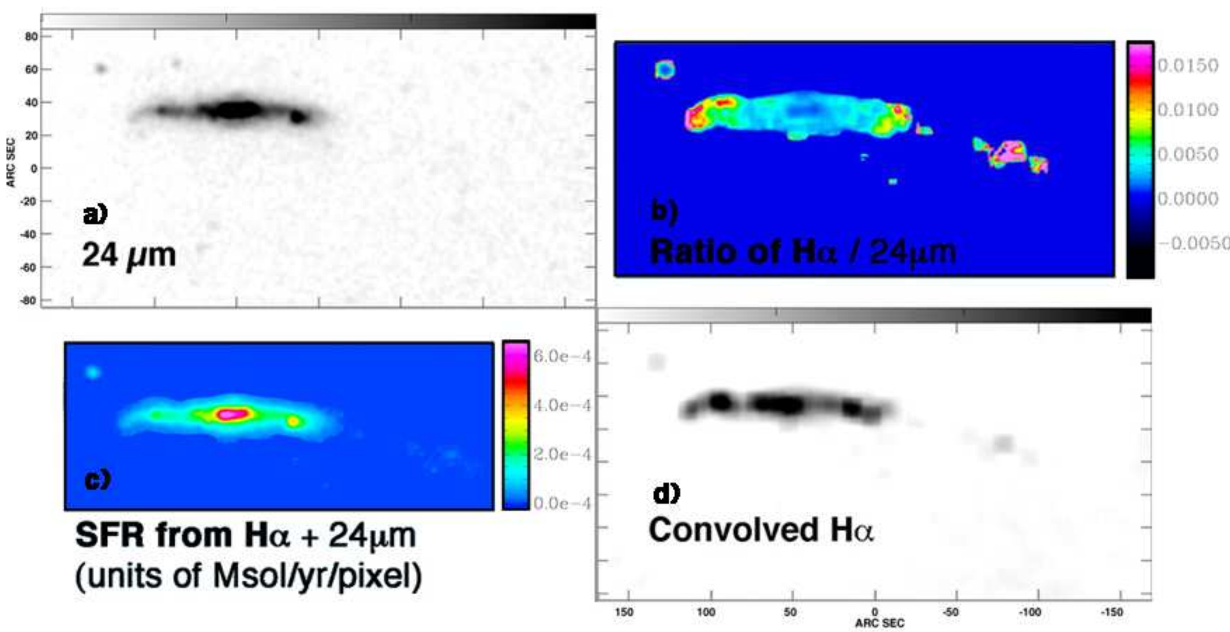

Fig. 3.— a) Spitzer 24μm emission; b) Hα/24μm reveals the least obscured star-forming regions by showing where Hα is strongest relative to 24μm emission; c) Hα+24μm maps show relative star formation rates throughout the galaxy; d) Hα convolved to 6" seeing in order to match 24μm resolution.

4. PAH Emission (Or Lack Thereof) in Stripped Gas

Stellar continuum light at 3μm shows that the outer disk is undisturbed (Figure 4) - slight irregularities in the eastern disk contours are attributable to point sources. However, PAH emission is confined to the inner stellar disk - very little is detected at 8μm in the stripped extraplanar HI. The ratio of 8μm emission to HI is a factor of 6 lower in the tail of extraplanar HI than it is in the main body of the galaxy. Either there are no PAHs in the stripped gas, or (more likely) there is insufficient heating from star formation and stellar continua for the extraplanar PAHs to emit at 8μm.

The upturn at the leading edge of the galaxy (Figure 5) provides confirmation that at least some stripped dust is still associated with the galaxy but is not sufficiently heated to emit at 8μm. A plume of optical dust extinction extends further away from the stripping boundary than 8μm emission (Figure 5b; optical dust extinction is white), so either this particular cloud lacks sufficient PAHs to emit at 8μm, or insufficient heating is taking place to excite emission. Since no star formation is detected in the same area as the dust extinction, the latter seems more likely. Similarly, there is very little star formation in the stripped gas in the tail region - although the tail contains 10% of the galaxy's HI, it accounts for only 1% of the total star formation. Based on the lack of 24μm and Hα emission, we can conclude that little star formation is taking place in the stripped gas, so although the presence of PAHs in the stripped gas cannot be established with certainty, there is unlikely to be sufficient heating for 8μm emission.

5. Summary

Spitzer data of NGC 4330 have revealed the strength and location of star formation regions, as well as the distribution of the heated ISM, giving us new insights into the ram pressure stripping process. Relatively high Hα/24μm flux ratios indicate star-forming regions with little dust obscuration at the leading edge of the ICM-ISM interaction. No IR emission at any wavelength is detected in the extraplanar HI tail, indicating that there is not sufficient stellar continuum emission or star formation to excite dust grains in the stripped gas. The striking upturn feature at the galaxy's leading edge is clearly visible at 8μm, 24μm, and Hα, indicating that dense, star-forming gas is being pushed out of the disk along with the less dense HI. However, there is no evidence of star formation in the plume of optically detected dust that extends beyond the upturn and appears to have been swept out of the disk by the ICM-ISM interaction. In NGC 4330, pressure from the ICM has not triggered a dramatic increase in star formation, either at the leading edge of the ICM-ISM interaction or in the stripped gas.

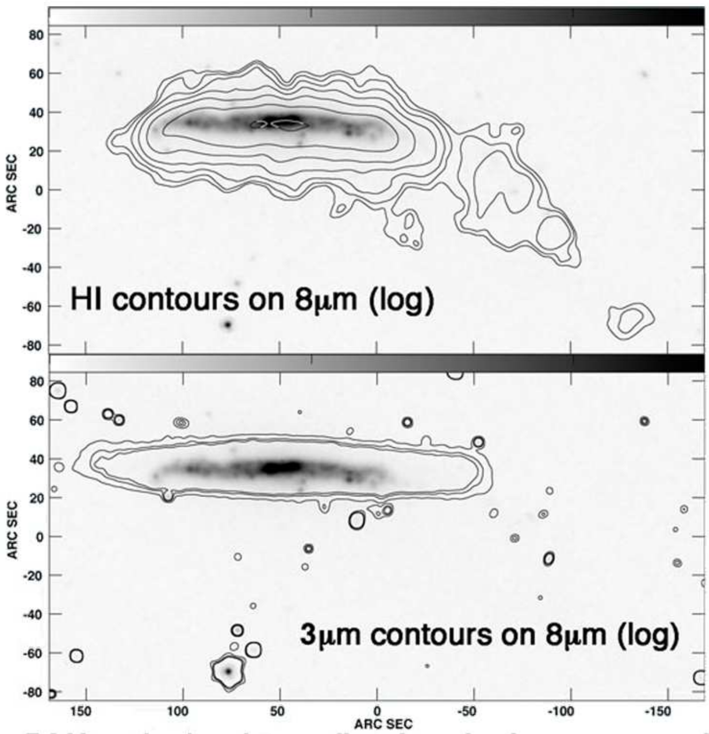

Fig. 4.— a) HI contours show where the ISM has been stripped from the disk; 8μm log stretch in greyscale shows where the ISM is sufficiently heated to excite PAHs. In the stripped gas, there is insufficient heating to excite PAHs, indicating a lack of star formation activity or heating from strong stellar continua. HI contour levels 2, 4, 8, 16..., $\times 10^{19}$cm^{-2}. b) Same greyscale image but with 3μm contours; 3μm emission comes primarily from stellar continua, and indicates the extent of the undisturbed stellar disk. Lowest 3μm contour is 0.03$\times$ peak flux.

This work is based on observations made with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory (JPL), California Institute of Technology under NASA contract 1407. Support for this work was provided by NASA and through JPL Contract 1255094.

REFERENCES

Abramson, A. et al. 2008, *in preparation*

Calzetti, D. et al. 2007, ApJ, 666, 870

Chung, A. et al. 2008, *in preparation*

Chung, A. et al. 2007, ApJ, 659, L115

Kenney, J.D.P., Wong, O.I., Abramson, A., Howell, J.H., Murphy, E.J., & Helou, G.X. 2008, *these proceedings*

Koopmann, R.A. & Kenney, J.D.P. 2004, ApJ, 613, 866

Murphy, E.J. et al. 2008, ApJ, 638, 157

Murphy, E.J., Kenney, J.D.P. Helou, G., Chung, A. & Howell, J.H. 2008, *these proceedings*

Murphy, E.J., Kenney, J.D.P., Helou, G., Chung, A. & Howell, J.H. 2008, ApJ, *in press*

Vollmer, B., Cayatte, V., Balkowski, C., & Duschl, W.J. 2001, ApJ, 561, 708

Wong, O.I. & Kenney, J.D.P. 2008, *these proceedings*

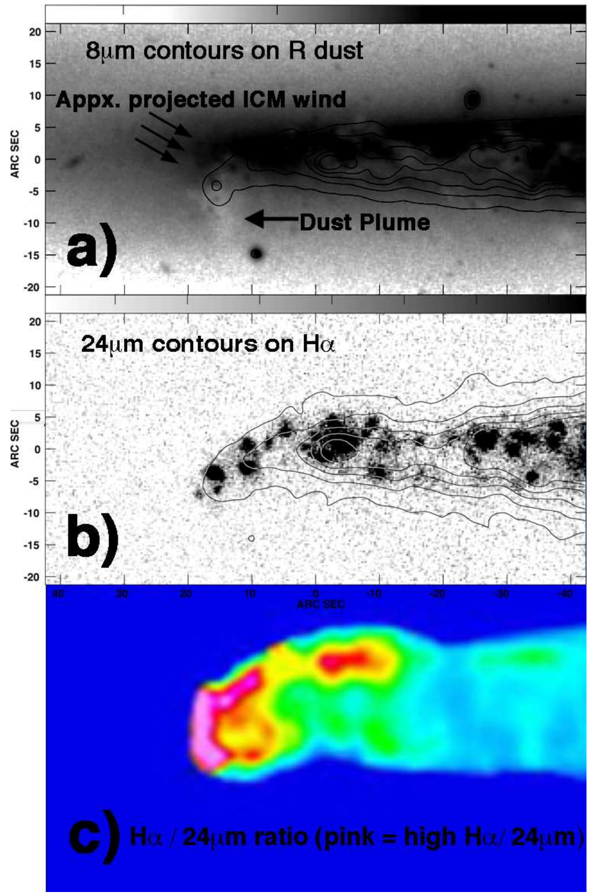

Fig. 5.— a) Optical dust extinction (white) extends further downwind than 8μm emission. This upturn feature is visible in some form at every wavelength that traces the ISM or star formation as a bend away from the disk. The projected wind direction indicated in the figure is roughly parallel to the HI tail on the other side of the galaxy and is confirmed by preliminary simulations (Vollmer et al., in prep). b) The upturn is clearly visible in 24μm and Hα, indicating that the dense, star-forming ISM is also being pushed out of the disk along with the more diffuse HI. 24μm contours at 5% of peak $\times$ 2, 4, 8,... c) The Hα-to-24μm ratio is high in the upturn, where dust that would otherwise block Hα emission has been stripped away.