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Mergers of Galaxies from an HI Perspective

J. E. Hibbard

NRAO, 520 Edgemont Road, Charlottesville VA 22903

Abstract. H I spectral line mapping studies are a unique probe of morphologically peculiar systems. Not only does HI imaging often reveal peculiarities that are totally unsuspected at optical wavelengths, but it opens a kinematic window into the outer dynamics of these systems that is unmatched at any other wavelength. In this review I attempt to summarize what we have learned from such studies, and what we may hope to learn from them in the future.

1. Introduction

Spiral galaxies, particularly later types, tend to be rich in neutral hydrogen. Much of this gas is found in the outermost regions of the disks, which are the first regions to be perturbed during tidal interactions. As such, the structure of the gas-rich material thrown off in such encounters will bear the spatial and kinematic imprint of the encounter dynamics. Mapping the distribution and line-of-sight velocity of the atomic gas in the 21cm line of neutral hydrogen (H I) is therefore a unique and powerful tool for investigating these violent events. As an example, Figure 1 shows H I observations of the classical on-going disk-disk merger NGC 4038/9, "The Antennae". This figure emphasizes the kinematic and spatial continuity of tidal features. It is this continuity that makes H I observations so powerful for investigating on-going mergers and their evolved remnants. The tails are generally much too faint to map the stellar kinematics, and ionized emission tends to be confined to a few localized regions of star formation. H I mapping is very often the only way to obtain such information.

At present, at least 140 on-going interactions, mergers, or merger remnants have been mapped in the 21cm line of neutral hydrogen. This includes such classes of objects as interacting doubles, major mergers, evolved merger remnants, shell galaxies, ring galaxies, polar ring galaxies, compact groups, and ellipticals with extended H I debris. In the remainder of this review I will highlight some of what we have learned from these observations. It is beyond the scope of this review to summarize the wealth of knowledge obtained on each of the more than 140 systems observed, and I will instead highlight a few global themes. For additional details, the reader is directed to the proceedings edited by Arnaboldi et al. (1997), especially the contributions by van Gorkom & Schiminovich, Morganti et al., Schiminovich et al., and Oosterloo & Iovino. See also the recent H I reviews of mergers by Sancisi (1997), of compact groups by Verdes-Montenegro et al. (1999), of ring galaxies by Appleton & Struck-Marcell (1996), and of polar ring galaxies by Sparke (these proceedings).

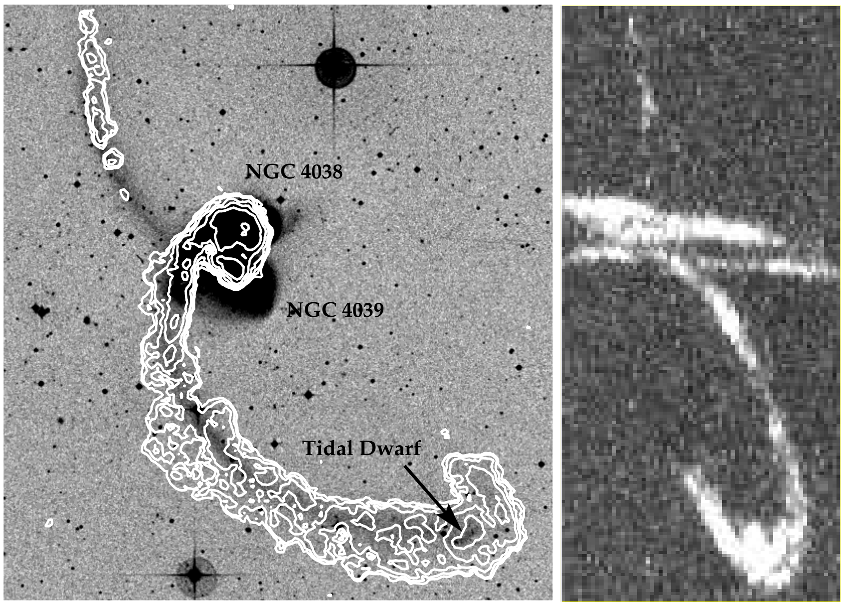

Figure 1. VLA C+D array H I observations of NGC 4038/9 (Hibbard, van der Hulst & Barnes, in preparation). Left: In this and all subsequent figures contours indicate the integrated H I emission and greyscales the optical morphology. Right: H I position-velocity plot, with declination along the y-axis and line-of-sight velocity along the x-axis.

2. True Fraction of Peculiar Galaxies

H I mapping very often reveals a markedly different dynamical picture of systems than suggested by the distribution of the optical light. Particularly striking examples are: the extensive tidal streamers found connecting the members of the M81 group (van der Hulst 1979, Yun et al. 1994); the 200 kpc rotating H I ring in the M96 group (Schneider et al. 1989); a pair of purely gaseous tidal tails emerging from the E4 galaxy NGC 1052 (van Gorkom et al. 1986), from the E2 galaxy NGC 5903 (Appleton, Pedlar & Wilkinson 1990) and from the Sa galaxy NGC 7213 (Hameed, Blank & Young in preparation); the H I bridge/tail morphology of the "Virgo Cloud" H I 1225+01 (Giovanneli et al. 1991, Chengalur et al. 1995); plumes of H I pulled off the Sb galaxy NGC 678 by the Epec galaxy NGC 680 and the associated intergalactic H I cloud (van Morsel 1988). As a result of these and many similar discoveries, we conclude that the true fraction of peculiar objects must be considerably larger than derived from purely optical studies. Based on H I studies, Sancisi (1997) suggest that at least one in four galaxies has suffered a recent merger or experienced an accretion event.

Even in systems already identified as optically peculiar, H I mapping frequently reveals structures that provide critical insights into their dynamical nature by revealing connections not seen at other wavelengths (e.g., Figure 2). Examples include: tidal H I in QSOs (Lim & Ho 1999); the nearly 200 kpc long tidal plumes emerging from the ring galaxy Arp 143 (Appleton et al. 1987; see Figure 6.) and the IR luminous starburst Arp 299 (Hibbard & Yun 1999); the 275 kpc diameter H I disk around the mildly interacting system Mrk 348 (see Figure 3); the H I tail and counter-arm in the starburst galaxy NGC 2782 (Smith

1991); the extended tidal streamers in the starburst/blowout system NGC 4631 (Weliachew et al. 1978); the extended disk and streamers in the dIrr NGC 4449 (Hunter et al. 1998); two H I tails emerging from the blue compact dwarf II Zw 40 (van Zee et al. 1998). The fact that these features are easily visible in H I but lack optical counterparts is likely due to the fact that in disk galaxies H I is generally more extended than the stars.

It is not clear if H I mapping is the most efficient means for revealing low-level peculiarities. When a similar amount of observing time ($\sim$ few to a dozen hours) is invested in deep optical imaging, some remarkable results have emerged: faint optical loops and streamers have been discovered around what were long thought to be normal unperturbed disk galaxies (see Malin & Hadley 1997, Zheng et al. 1999). While the optical observations do not include the kinematic information provided by H I observations, they may be the only signatures of very evolved interactions, when the H I has faded away or been ionized.

3. Global Dynamics of Merging Systems

As demonstrated by Toomre & Toomre (1972) (and re-affirmed many times since, e.g. Barnes 1998), tidal features develop kinematically. As a result, they have a simple kinematic structure, with energy and angular momentum increasing monotonically with distance along the tail (Hibbard & Mihos 1995). Because of this simple kinematic structure, H I observations provide a uniquely useful constraint on N-body simulations of gas-rich mergers (e.g. Combes 1978, Combes et al. 1988, Hibbard & Mihos 1995, Yun 1997, Barnes 1998). While the primary parameters that are fit in this exercise are the physically uninteresting angles describing the orientations of the disks and the viewing perspective, the model matching gives us the confidence to explore the evolutionary history of mergers beyond the best-fit time. By running the simulations forward in time, we can explore the late-stage merger evolution for clues on the expected morphology of the remnants and the distribution of material at large radii in the halos around the remnants.

Because much of the tidal material remains bound to the remnant, it will eventually reach an apocenter, turn around, and move back inwards in the potential. There will therefore be a constant rain of tidal material back onto the remnant. Material which falls back while the potential is still violently relaxing will scatter and be mixed throughout the remnant body. Material which returns after the potential has relaxed will wrap coherently, forming shells, loops and other "fine structures" (Hernquist & Spergel 1992). Because of its high energy and angular momentum, the material which falls back later will fall back to larger and larger radii, forming loops rather than shells. At late times, the material outside of the loops will have a low density and may be ionized by the intergalactic UV field (Corbelli & Salpeter 1993, Maloney 1993) or the remnant itself (Hibbard, Vacca & Yun 1999). We would therefore expect evolved disk merger remnants to exhibit partial rings of H I with a rotational signature (since the loops correspond to turning points where the radial velocity goes to zero), lying outside the remnant body. This is exactly what has been found around a number of shell galaxies (Schiminovich et al. 1995; Fig. 2b–d).

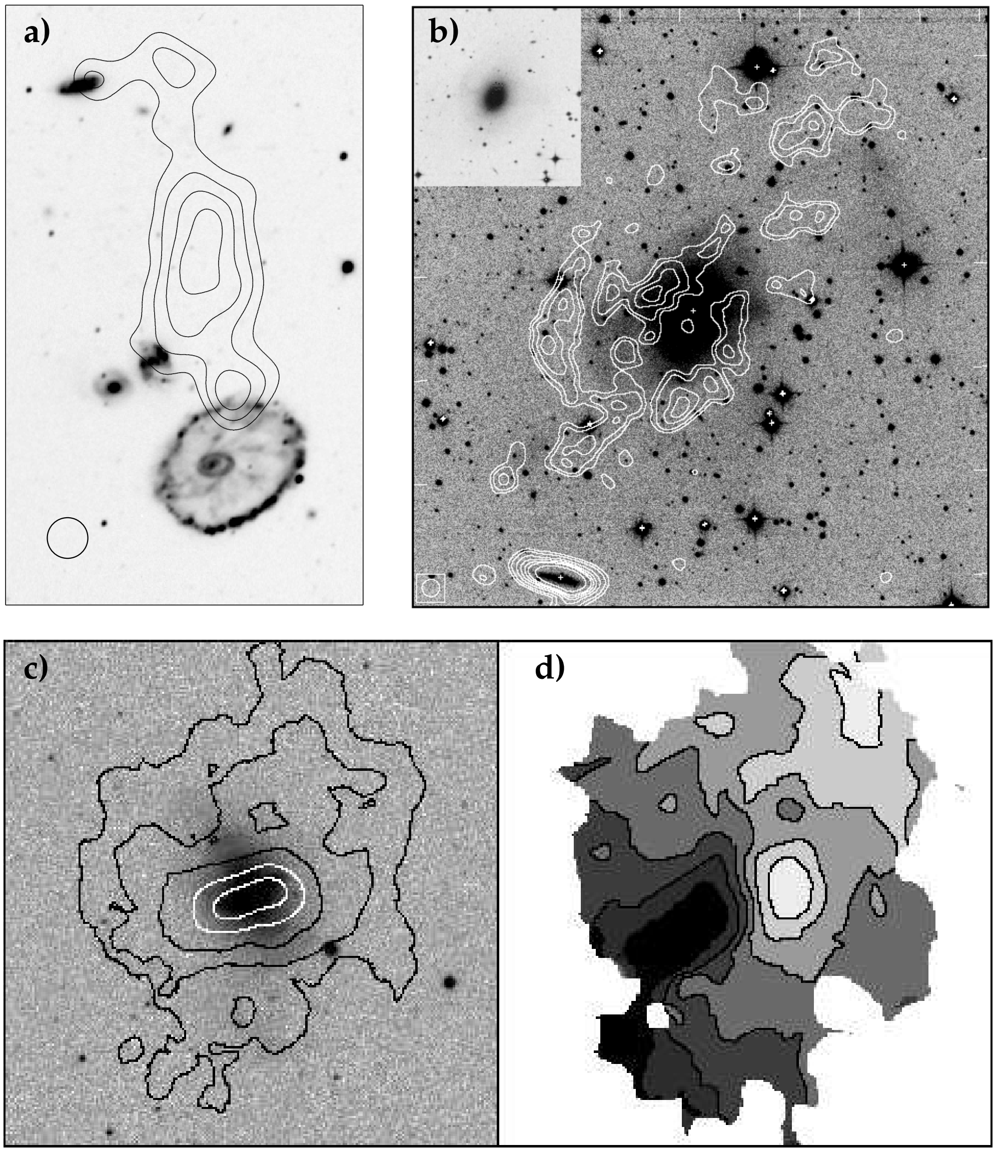

Figure 2. (a) VLA D-array observations of the Cartwheel Ring Galaxy (Higdon 1996). The H I plume reveals a connection between the ring and the northernmost galaxy. Prior to this observation it was not clear which of the three galaxies in the field collided with the ring galaxy. (b) VLA C+D-array observations of the shell elliptical NGC 2865 (Schiminovich et al. 1995). Inset shows the main body of the galaxy. The H I has rotational kinematics. (c) & (d) VLA B+C array observations of the proto-typical shell galaxy Arp 230 (Schiminovich, van Gorkom & van der Hulst, in preparation). Left: integrated H I. Right: H I velocity field, showing that the outer H I is arranged into a rotating disk.

Meanwhile, the loosely bound tidal material in the outer regions continues to travel outward. This material has radial periods $\sim$ many Gyr and azimuthal periods even longer than this (Hibbard 1995). As a result, the tidal material will not give rise to a smooth, spherical halo of material; instead there will be specific regions of higher column density material with a low filling factor extending to very large radii. At late times, the atomic gas will be too diffuse to be detected in emission, and may anyways be largely ionized by the intergalactic UV field. Therefore the tidal features mapped in H I are likely the denser neutral peaks of a more extended distribution. This material should be detectable in absorption against background sources (Carilli & van Gorkom 1992).

4. Galaxy Transformation: Spirals to Ellipticals

The evidence that at least some mergers of gas-rich disk galaxies can make elliptical-like remnants is very strong (e.g. Schweizer 1998). Whether these merger remnants are true ellipticals or anomalous in some manner is still a matter of debate (see van den Marel & Zurek, these proceedings). H I observations addressed one important aspect of this question: do mergers get rid of the atomic gas of the progenitors? It has often been stated that H I will be ejected into the tidal features, but in fact at least as much (and likely much more) outer gas should be sent into the inner regions as is found in the tidal tails (see Fig. 15 of Toomre & Toomre 1972). It was therefore reassuring to find that progressively more advanced merging systems have less and less atomic gas in the bodies of the remnants (Hibbard & van Gorkom 1996).

It was not clear how most of the original atomic gas was removed from the inner regions, or how they remain largely H I free in light of the H I which continues to fall back from the tidal regions. Recent observations have shed some light on this subject, by showing that two processes — galactic superwinds and ionization by continued star formation — can have a strong effect on the observability of tidal H I (Hibbard, Vacca & Yun 1999). Superwinds are likely to be important in helping the most gas-rich systems get rid of much of their cold gas reservoirs, but the wind phase is short lived, and would not explain the continued removal of returning tidal H I. Simple calculations suggest that the UV flux from on-going starformation is sufficient to ionize diffuse H I in the tidal regions (see also Bland-Hawthorn & Maloney 1999).

Photoionization is an attractive mechanize for explaining tidal features which are gas rich in the outer radii, but gas poor at smaller radii (e.g., the northern tail of The Antenna, Fig. 1; Arp 105 Duc et al. 1997; NGC 7252 Hibbard et al. 1994). The dynamics of tail formation require that the gas-rich outer radii of the progenitor disks extend all the way back into the remnant (see Fig. 2 of Toomre & Toomre 1972). The geometry of a preliminary numerical fit to the NGC 40389/9 data (Hibbard, van der Hulst & Barnes, in preparation) suggest that the northern tail has an unobstructed sightline to the numerous starforming regions in the disk of NGC 4038, while the southern tail does not, explaining why it remains gas rich along its entire length. This process may explain how merger remnants remain gas poor in the presence of the continued return of tidal H I. Such an on-going process is required if remnants are to evolve into normal ellipticals in terms of their atomic gas content.

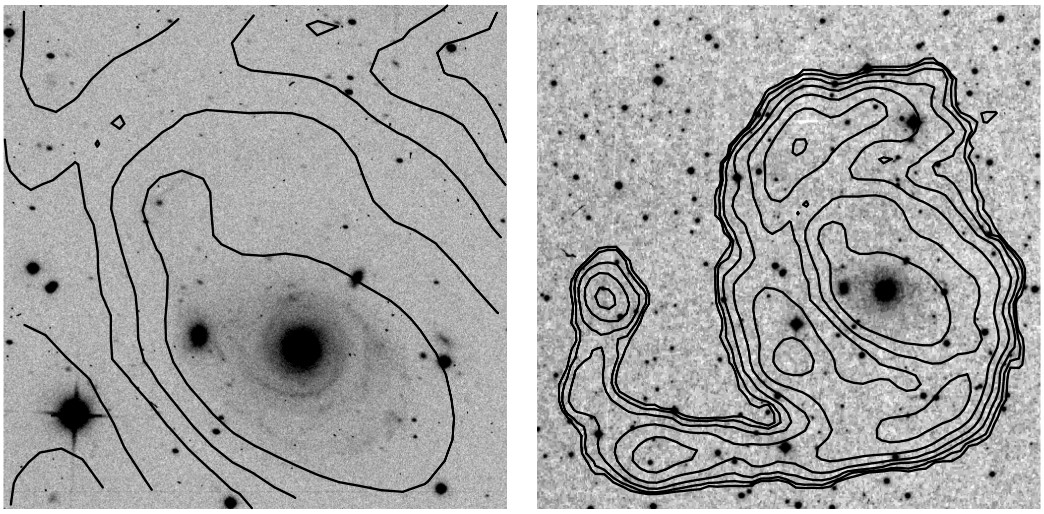

Figure 3. VLA D-array observations of Mrk 348 (Simkin et al. 1986). Left: Full field of view (image is 300 kpc on a side). Right: close-up of inner regions and companion (image is 100 kpc on a side).

5. Galaxy Transformation: Other Beasts

Is the ultimate evolutionary product of disk-disk mergers an elliptical with fine structure? Here again H I observations provided evidence for unexpected merger products. In particular, a number of on-going mergers and merger remnants are found to have large gaseous disks with rotational kinematics. Particularly good examples are Arp 230 (Fig. 2c&d), NGC 520 (Hibbard & van Gorkom 1996), and MCG -5-7-1 (Schiminovich, van Gorkom & van der Hulst in preparation). The very faint loops and streamers imaged around normal disk galaxies (Malin & Haley 1997, Zheng et al. 1999) support the idea that some disk systems may have had a violent origin or experienced a major accretion event.

Finally, there are some systems which simply do not seem to conform to the standard interaction picture. One such example is Mrk 348 (Fig. 3). The main difficulty with the tidal interpretation for this system is that the scale of the H I is tremendous (diameter ~280 kpc), and two thirds of the neutral hydrogen ($1.4 \times 10^{10} M_\odot$ out of a total of $2.1 \times 10^{10} M_\odot$) lies outside of the highest contour in Fig. 3, i.e., outside the region containing both the companion and all of the optical light of the disk. It simply does not seem possible that the small companion seen in Fig. 3b could have raised this much material to such large radii. It may be that the progenitor was a very gas-rich low surface brightness galaxy like Malin 1 (Impey & Bothun 1989, Pickering et al. 1997). A more intriguing possibility is that the neutral gas may have condensed out of an extensive halo of ionized gas. In this regard it is interesting to consider the NGC 4532/DDO 137 system, which has a very irregular distribution of H I lying mostly outside of the optical galaxies. Hoffman et al. (1999) suggest that the H I clumps are simply neutral peaks in sea of mostly ionized hydrogen. The existence of such a sea of baryons may mean that full scale galaxy formation continues to the current epoch.

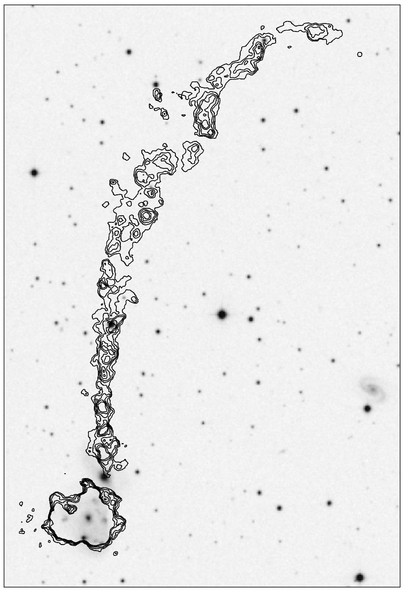

Figure 4. VLA B+C+D-array observations of the Ring Galaxy Arp 143 (Higdon & Appleton, in preparation; see also Appleton et al. 1987). This purely gaseous tidal tail contains a wealth of structure on 5″ scales, with peaks up to $10^{21}\mathrm{cm}^{-2}$. The present observations do not have the velocity resolution to address whether individual clumps are self gravitating.

6. Galaxy Formation: Tidal Dwarf Galaxies

As the name implies, "tidal dwarf galaxies" are concentrations of stars entrained within tidal tails and believed to be gravitationally bound (Schweizer 1978). These systems have received considerable observational attention recently (e.g. Duc 1995, Hunsberger et al. 1996). However, because the inter-clump tidal material is so faint, H I mapping studies provide the *only* means of determining whether the local luminosity enhancements are kinematically distinct from the surrounding material, and this has only been done for a few systems (Hibbard et al. 1994; Hibbard & van Gorkom 1996; Duc et al. 1997).

Within tidal tails there is a wealth of substructure on many scales. It ranges from small, dense gaseous knots within purely gaseous features (e.g., Figure 6.), to small luminosity enhancements within optical tidal tails (e.g. Hutchings 1996, Hunsberger et al. 1996), to dwarf-sized condensations of gas and stars fully embedded within a tidal tail (e.g. NGC 7252, NGC 3921 Hibbard & van Gorkom 1996; NGC 4038/9 Fig. 1a); and finally to separate (and often separately classified) optical dwarfs entrained within mostly gaseous tidal features (e.g., M81/NGC 3077, van der Hulst 1979; NGC 4027, Phookun et al. 1992; NGC 520/UGC 957, Hibbard & van Gorkom 1996; Arp 105, Duc et al. 1997; NGC 5291, Malphrus et al. 1997). An outstanding question is whether there is an evolutionary link between any/all of these categories of structures.

7. Timing of Starbursts

The 100 kpc scale tidal features imaged in H I emanating from starbursting systems suggest that the interaction and starburst timescales are quite different. For example, the starburst in the IR luminous merger Arp 299 has an age of <30 Myr while the 180 kpc tail was launched about 700 Myr ago (Hibbard & Yun 1999). Similarly, the tails of the Antennae (Fig. 1) suggest an interaction timescale of $\sim$ 500 Myr. This object has a population of star-clusters with

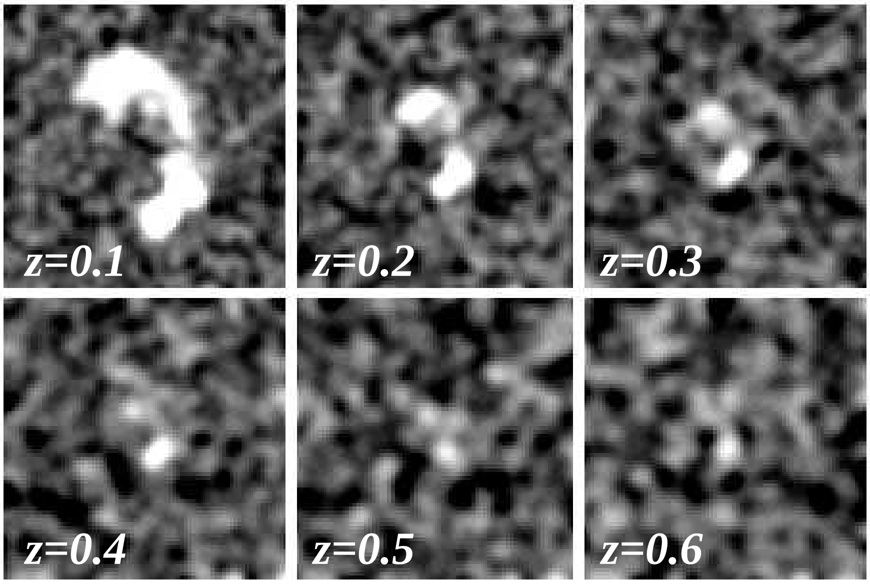

Figure 5. Simulated deep HI image with expanded VLA: The IR luminous merger Arp 299 (Hibbard & Yun 1999), as viewed at redshifts from z =0.1 to 0.6 (H_o=75, q_o =0.1).

an age of $\sim$ 500 Myr as well as a population that is currently forming massive stars (Whitmore & Schweizer 1995). These observations suggest that interaction induced starbursts are not isolated to either first periapse (when the tails are launched) or the final merger, but rather are episodic (cf Noguchi 1991). While the closeness of the nuclei of the ultraluminous IR mergers suggests that the most intense starbursts occur when the progenitor nuclei are coalescing, it does not necessarily follow that the bulk of the stars are formed during this short-lived phase.

This fact has important repercussions for the expected observational characteristics of merger remnants. If most of the interaction-induced starformation takes place at the moment of final coalescence, the burst population is expected to be confined to the inner few 100 pc of the remnant, leaving an anomalously bright central core (Mihos & Hernquist 1994) with the characteristics of a younger, more metal enriched population. The lack of such signatures in shell galaxies is taken to mean that they could not have formed via major mergers (Silva & Bothun 1998). However, if much of the post-interaction population formed over the whole $\sim$ 1 Gyr timescale of the merger, then the "burst" population will be spread more widely through the remnant, leaving much more subtle observational signatures.

8. Conclusion

H I spectral line mapping is a powerful diagnostic tool for investigating interacting and peculiar galaxies. In concert with numerical simulations, such observations provide insight into the transformation and formation of galaxies, the distribution of material in the halos of galaxies, the timing of interaction-induced starbursts, and the possible evolutionary products of mergers.

An important outstanding questions is whether many normal systems formed via mergers. While a merger origin for most galaxies is a generic result of hierarchical structure formation scenarios, there are continued claims that merger remnants will differ from normal ellipticals (Mihos & Hernquist 1994, van den Marel & Zurek, these proceedings). H I observations can help address this question by identify evolved remnants of gas-rich mergers via the amounts and structure of any remaining tidal H I. Once identified, the structure of these remnants should be compared to ellipticals. If they are indeed different, then this might mean that the Hubble Sequence evolves with redshift, such that the merger of present day spirals evolve into ellipticals with different characteristics than present day ellipticals, and conversely that present day ellipticals had progenitors which differed in some manner from present day disk galaxies.

With future cm wave facilities we should be able to address the cosmological aspect of this question. For instance, an expanded VLA (cooled low frequency receivers, greatly expanded correlator) will be able to detect H I out to redshifts $\sim$1. We should be able to image the gas-rich tidal features out to redshifts of $z \sim$0.5 (Figure 5). We will thus be able to constrain the number density of gas-rich mergers at these redshifts, which will tell us how large the population of gas-rich merger remnants should be at the present epoch.

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