Research Interests and Plans

Peculiar Galaxies, Near and Far

J. E. Hibbard, National Radio Astronomy Observatory

Abstract

The merger of gas-rich systems provides a stage upon which the drama of modern-day galaxy formation is played out. In these systems we are witnessing the main physical processes believed to be at work when galaxies are formed: violent relaxation, strong gaseous dissipation, and highly elevated rates of star formation. In my research I explore the importance of these processes with detailed multi-wavelength observations of a small but growing number of individual systems. These observations are used in conjunction with numerical simulations to learn as much as possible about the merging process at z=0. However the study of individual peculiar systems is merely academic if these observations do not have relevance to more general questions of galaxy formation and evolution. I plan to explore these aspects on two fronts, by tracking the expected evolutionary fates of merger products, both observationally and numerically, and by investigating the morphological characteristics of peculiar galaxies at higher redshift, especially as compared to their local analogs.

1 Galaxy Mergers in the Local Universe

1.1 Major Mergers

During the past few years I have compiled detailed datasets on fourteen nearly equal mass disk-disk mergers. The primary goal of this research is to explore the fate of gas during the merging process, and to examine the conditions under which super starbursts are initiated. The major component of this work is high quality VLA H I spectral line observations. These data are supplemented by narrow band imaging, optical and NIR broad band imaging, single dish and aperture array CO observations, X-ray imaging, and numerical simulations. The systems include an optically selected sample of double-tailed mergers in progressively advanced stages of merging (Hibbard *et al.* 1994; Hibbard 1995; Hibbard & van Gorkom 1996; Yun & Hibbard 1999; Hibbard, van der Hulst & Barnes in preparation – see Fig. 1) and an IR selected sample of the nearest, most active star forming mergers, the Luminous Infrared Galaxies (LIRGs, $L_{IR} > 3 \times 10^{11} L_{\odot}$; Hibbard & Yun 1996, 1999a,b; Yun, Hibbard & Scoville 1999). The data have been fully reduced and are displayed on my NRAO homepage (*www.cv.nrao.edu/~jhibbard*).

Concerning the fate of gas during disk-galaxy mergers, we find that (1) at least some mergers of gas-rich disks leave gas-poor remnants, removing yet another objection to the hypothesis that spiral galaxies can merge and *eventually* leave an elliptical galaxy in their stead (the "merger hypothesis", Toomre & Toomre 1972); (2) the delayed infall of tidal material occurs over several billion years and should leave observational signatures which will help identify more evolved merger remnants (Hibbard & Mihos 1995); (3) mergers do not present a significantly larger cross-section than field spirals *at a given surface brightness level*, for the simple reason that as the material is pulled over a larger area, it necessarily falls to lower surface brightness. However, mergers *do* have higher surface brightness material at much larger radii than field spirals. This result has important consequences for models which invoke mergers as significant contributors to quasar absorption line systems (Hibbard & Yun 1999b). I will continue to use this dataset in the future, to help constrain numerical models of mergers in order to explore their dynamical evolution.

As regards the fueling of IR luminous starbursts, we find that IR luminosity is very tightly tied to central molecular gas column density (Yun & Hibbard 1999). This relationship holds over two decades in IR luminosity, molecular gas mass and molecular gas column density. This strongly suggest that the amount of star formation is intricately tied to the amount of dissipation experienced by cold ISM of the progenitors. The encounter characteristics that give rise to the highest amounts of gaseous dissipation are at present unknown, but some clues are found in the H I mapping observations of LIRGs (Hibbard & Yun 1996, 1999a,b; Hibbard 1997). From the kinematics of the tidal gas, we find some suggestion that mergers involving at least one retrograde progenitor experience high levels of star formation while their nuclei are still well separated ($dr > 4$ kpc), while prograde encounter geometries have their highest star forming episodes delayed until the merger is almost complete ($dr < 1$ kpc). In retrograde encounters the gas within the disk is not pulled into tidal bridges and tails, as is the case for prograde geometries. Instead, it remains in the disk where large epicyclic motions are excited, leading to higher collision rates and hence to more gaseous dissipation. I plan to test this hypothesis with H I observations of well-separated LIRGs.

I have used the H I data to constrain numerical simulations for a number of systems. Neutral hydrogen observations are uniquely suited for such studies, since tidal tails are extracted early in the encounter from the gas-rich outer parts of the disks and develop kinematically thereafter. The morphology and kinematics of such features will therefore bear the imprint of the encounter history, and the complete velocity mapping provided by the VLA observations allows us to constrain their true space velocities. Detailed matches have been obtained for the well-known mergers NGC 7252 (Hibbard & Mihos 1995) and NGC 4676 ("The Mice", Hibbard & Barnes in preparation). While the primary output of such modeling efforts are the rather mundane encounter geometry parameters (such as viewing angles, progenitor disk inclinations and pericentric separations), the real strength of these efforts is that they allow us to go beyond the specifics of a particular solution and examine their past and future dynamical evolution of the merger. This issue will be address below (§1.3).

Simulations can also lead to insights that observations may be at a loss to provide. As an example, I reproduce in Fig. 2 the observations and preliminary modeling efforts for the confusing system Arp 299. The observations reveal an amazing "bifurcated" tidal structure, with a single optical tail (top left figure), but two distinct parallel H I tidal filaments (labelled "inner filament" and "outer filament" in the top middle panel). Despite detailed observations (Hibbard & Yun 1999a), we were at a complete loss to explain this bifurcated tidal morphology. However, with the help of summer student Greg Stinson (Carleton College), we were quite easily able to match the simple velocity structure of the tail (illustrated in the position-velocity plot in the top right panel of Fig. 2), which is characteristic of tidal tails in general. We found that we could match either the morphology and kinematics of the outer tidal filament and N clump (middle row in Fig. 2), or the kinematics of the inner filament and morphology of the stellar tail (bottom row in Fig. 2). However we were unable to match both features simultaneously with a single disk orientation and viewing angle. This leads us to suspect that the progenitor giving rise to this feature was initially warped (as is often the case for disk galaxies; Bosma 1991). In this case, the outer, optically fainter regions would be pulled off along one plane (resulting in the outer tidal filament), while the regions from smaller radii would move primarily in a different plane (resulting in the inner filament). A similar explanation may account for the less extreme bifurcated structures seen in other tidal tails that have heretofore remained unexplained (e.g. M81 Yun *et al.* 1994; NGC 2535/6 Kaufman *et al.* 1997; NGC 4038 Hibbard, van der Hulst & Barnes, in preparation).

This example shows how simulations allow us to make much better use of our H I velocity data, particular for such disturbed systems. I have no doubt that we could not have arrived at the above conclusion without the aid of the numerical models. In the future I plan to work on automating the model matching procedure as much as possible in order to reduce the time it takes to arrive at such solutions. This will enable us get the most out of our spectral line data cubes and to explore the dynamics of many more systems. This software will be made available to the astronomical community to encourage similar studies.

1.2 Merger Remnants

Ever since Toomre & Toomre (1972) first proposed the merger hypothesis, scientist have tried to refute it (eg. Ostriker 1980), so far to no avail. However, while the discovery of dense gaseous cores in the centers of merger remnants was once heralded as a great success for the merger hypothesis (Kormendy & Sanders 1992), recent numerical work which includes formalisms for hydrodynamics and star formation suggest that such clumps might offer an embarrassment of riches. In particular, the models of Mihos & Hernquist (1994, 1996) suggests that mergers inevitably experience so much gaseous dissipation that they will produce dense gas cores that, once turned into stars, will form remnants with a sharp "spike" in their luminosity profiles, unlike the $r^{1/4}$ de Vaucoleurs profile associated with normal ellipticals. They conclude that "mergers of gas-rich galaxies may not have contributed greatly to the population of present-day ellipticals".

We recently investigated this question observationally by using the observed molecular gas column densities and optical luminosity profiles of on-going or late-stage mergers to predict the luminosity profiles of the evolved remnants (Hibbard & Yun 1999c). We find that even under the most optimistic estimates (normal IMF, no mass ejection, 100% efficiency of turning gas into stars, fading the present population by 1 mag), the resulting luminosity profiles of the prototypical merger remnants NGC 3921 and NGC 7252 should still be characterized by an $r^{1/4}$ law. In view of previous optical work on these systems (Schweizer 1982, 1996; Hibbard 1995), it seems well established that they will evolve into normal ellipticals as regards their optical properties. We suggest that the necessarily ad-hoc numerical formalisms used in the simulations to model the effects of gas-dynamics, star formation, and feedback are still in their infancy and their results should be viewed with some caution.

However, we do find that the systems with the highest molecular gas surface densities (which, given the relationship between IR luminosity and gas column density mentioned above, means the most IR luminous systems such as Arp 220) would indeed produce luminosity spikes at small radii ($r < 0.5$ kpc), *if* all of their molecular gas is turned into low-mass stars. However, this does not preclude a merger origin for elliptical galaxies since (1) About 10% of the Nuker sample ellipticals (Byun et al. 1996) show central spikes in their radial light profiles, and (2) it is possible that much of the gas in such systems is blown into intergalactic space by the mass-loaded superwinds found emanating from such objects (Heckman, Lehnert & Armus 1993). An outstanding question that I am pursuing with W. Vacca (IRTF) is whether such spikes are found in the slightly more evolved remnants of the ultraluminous IR galaxies. If so, the frequency of such cores can be used to constrain the number of ULIR mergers in the past. If not, it would suggest that much of the central molecular gas of such systems is transformed into something other than low-mass stars.

1.3 "King Gap" Objects

At the discussion following Toomre's presentation of his merging sequence (Toomre 1977), Ivan King inquired about the objects between late stage mergers, such as NGC 3921 and NGC 7252, and ellipticals. The detailed observational work to uncover and characterize these so-called "King Gap" objects has been led by F. Schweizer and collaborators (Schweizer 1998 and references therein), who identify as the prime candidates for such evolved merger remnants the "shell" or "fine structure" ellipticals (e.g. Malin & Carter 1983).

This hypothesis has been significantly supported by H I observations of shell galaxies and dynamical studies of merger remnants. Dynamical studies on the very late stage evolution of merging galaxies ($t - t_{merge}$ >1 Gyr; Hibbard & Mihos 1995, Hibbard 1995) demonstrate that much of the tidally ejected material remains bound to the remnant and falls back over several billion years. The orbits of this material converge and the radial component of its velocity decreases as it reaches its inner turning point, leading to a density enhancement. The diffuse tidal gas is expected to obtain sufficient column density to be imaged only at these turning points (Hibbard 1995), and the natural result of very late stage tidal evolution should be partial rings of H I with rotational kinematics. H I studies of shell galaxies have revealed just such features at large radii around shell galaxies (Schiminovich et. al. 1997 and references therein). The quantities and kinematic continuity of the H I argue against its origin via accretion events.

In the future I will extend this work to investigate the conditions under which elliptical galaxies (the supposed ultimate product of of major mergers) contain cold gas. It has long been argued that cold gas around ellipticals has an external origin (e.g. Knapp *et al.* 1985). The studies mentioned above suggest that major mergers do indeed contribute in some cases. The fact of the matter is that any sign of peculiarity (which includes the presence of atomic gas in elliptical galaxies) is often taken as proof of a merger origin. My interest is to fully investigate the expected fates of merging encounters, both observationally and numerically, in order to confirm or refute this assumption. Although remnant tidal H I might be responsible for the cold gas in a number of cases, it is equally or perhaps even more interesting to study the cases in which a tidal origin is not as likely. In particular, we wish to investigate whether we can identify any systems which might be accreting gas from the IGM or which contain cold gas left over from its formation.

To this end, I am collaborating with various collaborators on their existing VLA observations of peculiar ellipticals: a sample of H I rich shell galaxies (with J. van Gorkom of Columbia and D. Schiminovich of Caltech); a sample of IRAS bright Ellipticals (with M. Rupen of NRAO and summer student K. Bunker of NCSU), and a sample of shell galaxies selected according to their X-ray rather than H I properties (with A. Sansom of UCLan) (see the "HI in Early Type Galaxies" link on my homepage). In order to to examine the correlation between H I content and a systems intrinsic properties (e.g. cold and hot gas content), external properties (e.g. the number of nearby spirals or the local galaxian density), or evolutionary indicators (e.g. presence of shells or post-burst population), we will incorporate available H I data on a wide variety of ellipticals. By observing objects in a range of evolutionary stages (from on-going mergers to very late stage mergers to systems which may have nothing at all to do with merging) and a wide variety of environments (from field to group to cluster to compact group), we hope to be able to discriminate between evolutionary and environmental effects and to identify and isolate the important processes involved during elliptical galaxy formation and evolution.

2. Cosmological Relevance of Interacting Galaxies

One of the most exciting advances in observational cosmology made possible by the superior spatial resolution of the Hubble Space Telescope (HST) is the identification of the "Faint Blue Excess" with a rapidly evolving population of galaxies with irregular and/or peculiar morphologies at intermediate to high redshifts. However, the nature of this population is not at all understood. They may be higher redshift manifestations of what are locally known to be disturbed and interacting galaxies, or simply normal Hubble types which have been made to look peculiar due to the effects of band-shifting and the loss of surface brightness sensitivity (Hibbard & Vacca 1997 and references therein). Alternatively, they may be composed of entirely new classes of galaxies, or proto-galactic clumps. Only by assessing the relationship between these remote peculiar galaxies and their nearby analogs will we be able to take the first steps towards understanding their true nature.

To this end, I have obtained UBV images for a subset of 70 peculiar galaxies drawn from a complete sample of peculiar galaxies (see Figure 3). I have obtained $BVRK$ data on all systems using the UH 88″ telescope, and my collaborators (L. Armus from IPAC & C. Liu from Columbia) have contributed $U-$band data from the Palomar 60$''$ and Steward 90$''$ telescopes. We will double the size of this sample with UBVRIJHK imaging on the VATT with collaborator R. Windhorst and students at ASU. Further, we plan on submitting a Cycle 9 HST proposal to obtain F300 snapshots of a subsample of these galaxies. These images will be used to simulate HST $R-$ and I-band observations of peculiar galaxies at redshifts from z=0.3 – 1.6 and then compared to observations of peculiar galaxies in the Hubble Deep Field (HDF), Medium Deep Survey, and Groth-Westphal strip. This comparison will enable us to quantitatively assess whether peculiar galaxies at intermediate redshifts, when the universe was only two-thirds of its present age, are similar to those seen around us today. Similarities would suggest similar progenitor types and encounter characteristics, while differences will provide insight into the dynamical processes giving rise to this intriguing population.

As a pilot study to this project, we have taken four nearby peculiar galaxies for which we have sensitive ground-based B&V images and with publically available HST FOC images ($\lambda = 2200\AA$). These data are used to simulate how these systems would appear at redshifts between 0.5—2.5. The results of this exercise are shown in Figure 4 for two of the four systems (from Hibbard & Vacca 1997). The technique used is similar to that described in Giavalisco *et al.* (1996), with the exception that the final images are embedded within a subsection of the Hubble Deep Field F814 mosaic so that a direct comparison can be made with actual galaxies at these redshifts. These observations show that the peculiar nature of these systems remains discernible out to intermediate redshifts, but that at the highest redshifts the morphology of these double systems can appear either as a single concentrated knot (NGC 1614) or as several very luminous knots very close together ($r < 5$ kpc; Arp 299). We conclude that meaningful morphological comparisons can only be made to redshifts z <1.5.

Another important consideration is that much effort is being expended on the development of automated classification techniques in order to deal with the large numbers of galaxies expected from the various on-going optical surveys (Abrahams *et al.* 1996; Naim *et al.* 1997; Wu *et al.* 1996; Lahav *et al.* 1996). However, the majority of these algorithms are being evaluated on high redshift galaxies that have been classified by eye, a technique which has been shown to give very inconsistent results even among experts (Naim & Lahav 1997), or upon local samples with poor signal to noise (Lahav *et al.* 1996). These shortcomings can be circumvented or at least quantified by applying the same algorithms to a set of low-z galaxies with known morphological classifications, after degrading by the appropriate factor and shifting into the corresponding rest wavelength (e.g. Wu *et al.* 1996). Several efforts are underway to obtain suitable images of complete samples of normal galaxies, but these samples will contain very few peculiar galaxies. Therefore they may be inadequate for quantifying the range of morphologies found at high redshift, where peculiars are believed to account for up to 40% of the total population (e.g. Abraham *et al.* 1996; van den Bergh *et al.* 1996). With Katherine Wu (UCSC) I will address these concerns using the large sample of peculiar galaxies described above.

REFERENCES

Abraham et al. 1996, MNRAS, 279, L47.
Bosma, A. 1991, in “Warped Disks and Inclined Rings around Galaxies”, edited by S. Casertano, P. Sackett & F. Briggs (Cambridge Univ. Press, Cambridge), p. 181
Byun, Y. -I., Grillmair, C. J., Faber, S. M., Ajhar, E. A., Dressler, A., Kormendy, J., Lauer, T. R., Richstone, D., & Tremaine, S. 1996, AJ, 111, 1889
Giavalisco, M., Livio, M., Bohlin, R.C., Macchetto, F.D. & Stecher, T.P. 1996, AJ, 112, 369.
Heckman, T. M., Lehnert, M. & Armus, L. 1993, in “The Evolution of Galaxies and their Environment”, edited by H. A. Thronson and J. M. Shull (Kluwer, Dordrecht), p. 455
Hibbard, J.E., 1995, Ph.D. Thesis, Columbia University.
Hibbard, J.E., & Mihos, J.C. 1995, AJ, 110, 140.
Hibbard, J.E. & van Gorkom, J.H. 1996, AJ, 111, 655.
Hibbard, J.E., Guhathakurta, P.G., van Gorkom, J.H., Schweizer, F. 1994, AJ, 107, 67.
Hibbard, J.E. & Yun, M.S., 1996, in “Cold Gas at High Redshift”, eds. M. Bremer, H. Rottgering, P. van der Werf & C.L. Carilli (Dordrecht: Kluwer), p. 47.
Hibbard, J. E. 1997, in “Star Formation, Near and Far”, edited by S. S. Holt & L. G. Mundy (AIP, NY), p. 259

Hibbard, J.E. & Yun, M.S., 1999a, AJ, submitted, HI in Arp 299.
Hibbard, J.E. & Yun, M.S., 1999b, AJ, in preparation, HI in LIR
Hibbard, J.E. & Yun, M.S., 1999c, AJ, submitted, Structure of Merger Remnants
Hibbard, J.E. & Vacca, W.D. 1997, AJ, 114, 1741.
Kaufman, M., Brinks, E., Elmegreen, D. M., Thomasson, M., Elmegreen, B. G., Struck, C. & Klaric, M. 1997, AJ, 114, 2323
Knapp, G. R., Turner, E. L., & Cunniffe, P. E. 1985, AJ, 90, 454
Kormendy, J., & Sanders, D. B. 1992, ApJ, 390, L53
Lahav, O., Naim, A., Sodre, L., Jr. & Storrie-Lombardi, M.C. 1996, MNRAS, 283, 207.
Malin, D. F., Carter, D. 1983, ApJ, 274, 534
Mihos, J. C., Hernquist, L. 1994, ApJ, 437, L47
Mihos, J. C., Hernquist, L. 1996, ApJ, 464, 641
Naim, A., Ratnatunga, K.U. & Griffiths, R.E. 1997, ApJ, 476, 568
Naim, A. & Lahav, O. 1997, MNRAS, 286, 969
Ostriker, J. P. 1980, Comments on Astrophysics, 8, 177
Schiminovich, D., van Gorkom, J, van der Hulst, T., Oosterloo, T. & Wilkinson, A. 1997, in *The Nature of Elliptical Galaxies*, ASP Conf. No. 116, edited by M. Arnaboldi, G. S. Da Costa and P. Saha, p.362
Schweizer, F. 1982, ApJ, 252, 455
Schweizer, F. 1996, AJ, 111, 109
Schweizer, F. 1998, in "Galaxies: Interactions and Induced Star Formation", Saas-Fee Advanced Course No. 26, R. C. Kennicutt Jr., F. Schweizer and J. E. Barnes (Springer, Berlin), p. 105
Toomre, A. & Toomre, J. 1972, ApJ, 178, 623.
Toomre, A. 1977, in *"The Evolution of Galaxies and Stellar Populations"* eds. B.M. Tinsley & R.B. Larson, (Yale Univ. Observatory: New Haven) p. 401.
van den Bergh, S., et al. 1996, AJ, 112, 359.
Wu, K., Faber, S. & Lauer, T. 1996, in "HST and the High Redshift Universe" (37th Herstmonceux Conference), eds. N.R. Tanvir, A. Aragon-Salamanca, and J.V. Wall, 1996
Yun, M. S., Ho, P. T. P., & Lo, K. Y. 1994, Nature, 372, 530
Yun, M.S., & Hibbard, J.E. 1999, AJ, submitted, CO in Toomre Sequence Mergers
Yun, M.S., Hibbard, J.E. & Scoville, N. Z. 1999, AJ, in preparation, HI in Arp 220

FIGURE CAPTIONS

Figure 1: VLA C+D-array H I column density contoured upon a false-color representation of an optical CCD image of NGC 4038/9, "The Antennae" (from Hibbard, van der Hulst & Barnes in preparation). The large image shows the VLA data mapped at a resolution of $\theta \sim 20''$, emphasizing the richness of structure within the tidal tails, while the inset shows the H I data mapped at a resolution of $\theta \sim 10''$. This exquisite dataset will be used to constrain the encounter geometry for the system, which will be the starting point for more detailed studies into the triggering of the formation of super star-clusters within the disks and the formation of a tidal dwarf galaxy at the end of the southern tail. With Mike Rich (UCLA), Jane Charlton (PSU) and Brad Whitmore (STScI), I have HST cycle 6 and 7 WFPC observations of 3 regions along the tails of this system.

Figure 2: Top Row: $B-$band (left) and VLA C+D array H I observations (middle panel = sky plane; right panel = declination—velocity plot) of the luminous IR merger Arp 299 (from Hibbard & Yun 1999a). Specific features are labelled in the middle panel. The bifurcated tidal morphology consists of the inner and outer filaments of gas which connect at the northern clump. No such bifurcation is evident in the optical data, with the optical tail aligning with the inner H I filament. Middle Row: preliminary N-body match to the morphology and kinematics of the outer tidal filament and northern clump (left panel= sky plane; right panel= declination—velocity projection). The clean components from the H I data are drawn as large grey circles, while the simulation particles are the small green points. Bottom Row: preliminary N-body match to the morphology and kinematics of the inner tidal filament. The fact that we can rather easily find reasonable matches to either the outer or inner filament using different encounter geometries, but not to both filaments with a single encounter, leads us to conclude that such bifurcated structures arise from a progenitor with a warped outer disk.

Figure 3: An example of systems from the UGC peculiar galaxy sample. The images shown here are 600 sec exposures with the UH 88″ telescope at f/10 in the R-band. More images and a list of the program galaxies and observations already in hand can be viewed at Hibbard 1996 under "Survey".

Figure 4: Simulated observations of the peculiar galaxies Arp 299 and NGC 1614 embedded into a region of the Hubble Deep Field (HDF). Ground-based B&V images have been used to simulate HDF observations in the F814 filter at redshifts of z =0.53 and 0.88. Archival HST FOC observations have been used to simulate observations at redshifts of z=1.51 and 2.49 (Hibbard & Vacca 1997). At z=1.51 the FOC observation is redshifted into the F606 filter, but for the ease of this comparison we show this case along with the others in the F814 band, after correcting for the different noise levels. These images show that a merger of two normal spiral progenitors can display very different morphologies at high redshift: NGC 1614 appears as a single concentrated knot, while Arp 299 appears as several very luminous knots very close together ($r < 5$ kpc).