

NA65-1720

IN-90

05/11/97

# The Interaction-Activity Connection

Kirk D. Borne<sup>1</sup>

<sup>1</sup>*Hughes STX, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA*

*(Received 22 January 1996)*

A review is presented of the numerous studies that have been undertaken to investigate the likely interaction-activity connection among galaxies. Both observational evidence and theoretical supporting models are reviewed. Some specific examples of “interactive” galaxies from the author’s own research are presented: (a) the collision-induced AGN activity in the radio jet source 3C278; and (b) the collision-induced starburst activity in the spectacular “Cartwheel” ring galaxy. Some comments are offered concerning some of the more promising theoretical investigations that are now taking place. A few words of warning are also offered about the possible misinterpretation of putative collision-induced morphologies among some galaxy samples.

## 1. PRELIMINARY REMARKS

Activity in galaxies has been the subject of increasingly intense study for nearly half of a century ever since the discovery of unusual emission lines in the nuclear spectra of some galaxies by Seyfert (1943), the optical identification of powerful radio sources with certain extragalactic objects (*e.g.*, Baade & Minkowski 1954*a,b*), and the discovery of quasars (Schmidt 1963). The idea that interactions between galaxies may be related to the observed activity was suggested by Baade & Minkowski (1954*b*), with a similar suggestion by Arp (1966). While much work was done on active galaxies following these discoveries, a plausible physical model for this *interaction-activity (I-A) connection* was first elaborated upon (using graphic metaphorical language) in the bold hypotheses of Toomre & Toomre (1972) and Gunn (1977) that interactions could actually “stoke the furnace”, or “feed the monster”, in active galactic nuclei (AGN). Further evidence of tidally-induced activity came to light when Larson & Tinsley (1978) noted that the colors of a subsample of Arp’s (1966) peculiar galaxies were consistent with recent star formation activity when compared against an undisturbed control sample; Sharp & Jones (1980) and Lonsdale, Persson, & Matthews (1984) later confirmed these findings.

In spite of these various suggestions, for a long time, research focussed more on the “personal” activity within active galaxies and not so much on their “social” interactions with their neighbors. Mergers and collisions among galaxies were at best an interesting side issue in the field of active galaxy research — at least, until recently (see the review by Heckman 1990 and the papers in Shlosman 1994).

## 2. OBSERVATIONAL EVIDENCE FOR THE I-A CONNECTION

The study of interacting and merging galaxies has become very active in the last decade, due in large part to the discoveries by IRAS that the most IR-luminous galaxies are nearly all products of galaxy collisions and that these may be the missing link in the chain of evolution from quasars to normal quiescent galaxies (Sanders *et al.* 1988*a,b*). These highly luminous galaxies have a higher space density than quasars, emit >90% of their power in the IR, are rich in the raw materials of star formation, and to a large extent owe their peculiar morphologies to encounters with other galaxies. The physical processes at work here are hypothesized to be the same as those at work in quasars — tidally disturbed galactic gas loses angular momentum in the tidal encounter and falls to the center of the galaxy, where it undergoes violent dissipation (and probably star formation), ultimately collapsing into the galaxy's nucleus, where it either falls into the lurking "monster" or else contributes to the formation of the dense central star cluster that will itself ultimately form the massive central black hole (*i.e.*, the AGN engine; see Norman & Scoville 1988 and also the reviews by Heckman 1991*a,b*).

The evidence for tidal phenomena in a plethora of different active systems is now overwhelming: in quasars (*e.g.*, Stockton & MacKenty 1983, 1987; Yee & Green 1984; Hutchings & Neff 1988, 1990*a*, 1992*b*; Stockton & Farnham 1991; Block & Stockton 1991; Bahcall *et al.* 1995; cf. Smith & Heckman 1990*a*), in AGN (*e.g.*, Dahari 1984; Keel *et al.* 1985; MacKenty 1989; Hummel *et al.* 1990; Hutchings & Neff 1990*b*; MacKenty, Simpson, & McLean 1990; Mazzarella, Bothun, & Boroson 1991; Keel & van Soest 1992; MacKenty *et al.* 1994), in radio-jet galaxies (*e.g.*, Colina & Pérez-Fournon 1990*a,b*; de Juan *et al.* 1993; Colina & de Juan 1995), in powerful radio galaxies (*e.g.*, Heckman *et al.* 1986; Smith & Heckman 1989*a,b*, 1990*b*; cf. Smith & Heckman 1990*a*), in low-luminosity radio galaxies (*e.g.*, de Juan *et al.* 1994), in GHz-peaked-spectrum radio galaxies (Stranghellini *et al.* 1993), in actively star-forming galaxies (= Starbursts; *e.g.*, Joseph & Wright 1985; Bushouse 1986; Kennicutt *et al.* 1987; Kennicutt 1990; Smith & Kassim 1993; Keel 1993; Smith *et al.* 1995), in IR-luminous galaxies (*e.g.*, Sanders *et al.* 1988*a,b*; Lawrence *et al.* 1989; Armus 1989; Melnick & Mirabel 1990; Carico *et al.* 1990; Hutchings & Neff 1991, 1992*a*; Majewski *et al.* 1993; Gallimore & Keel 1993; Leech *et al.* 1994; Liu & Kennicutt 1995*a,b*; Soifer, this volume), and in galaxies with strong central concentrations of molecular gas (*e.g.*, Sargent & Scoville 1991; Scoville *et al.* 1991). The particular importance of IR-luminous galaxies in the grand scheme of cosmology and galaxy evolution has been underscored by the luminosity function studies of Soifer *et al.* (1986), which have indicated that most galaxies have gone through a high-IR luminosity stage. Studies of such objects are consequently of great importance in determining the relationships between this evolutionary stage, the galaxies' star formation histories, and the occurrence of interactions and mergers among galaxies.

A tantalizing discovery of the past decade was the so-called "alignment affect" in distant radio galaxies, wherein their radio, optical, and IR morphologies are all aligned over many decades in wavelength (Chambers, Miley, & van Breugel 1987; van Breugel & McCarthy 1990; Chambers & Miley 1990). Whether this is evidence for jet-induced star formation or for something else, it appears now that the early stages of galaxy formation and star formation within galaxies may be

significantly affected, if not controlled, by galactic activity. While this effect has not been linked with tidal processes, it nevertheless demonstrates once again that the causes and physical development of nuclear and starburst activity are likely related to the formation and early evolution of galaxies, which certainly involved tidal interactions (Kormendy 1989; Kormendy & Sanders 1992).

It is therefore clear from the weight of evidence now in hand that there is an important connection between galaxy interactions (which produce morphologically-peculiar structures) and some forms of galactic activity (see reviews by Hernquist 1989, Stockton 1990, and Heckman 1990, and the papers in Shlosman 1994). Given the vast literature on the demographics of this  $I$ - $A$  connection, from so many research groups (*e.g.*, Adams, Armus, Bushouse, Colina, Dahari, de Juan, Green, Heckman, Hutchings, Illingworth, Joseph, Keel, Kennicutt, Lawrence, Lonsdale, MacKenty, Mazzarella, Miley, Mirabel, Neff, Neugebauer, Sanders, Sargent, Scoville, Soifer, Smith, Sopp, Stanford, Stockton, van Breugel, and Yee; to name a few), there remains very little doubt that somehow the two sets of phenomena are related. However, in spite of this wealth of observational supporting evidence, the precise relationship between interaction and activity is difficult to characterize as several studies have indicated that the majority of active galaxies do in fact show morphological signs of interaction, while other studies have shown that only a minority of all interacting systems are actually endowed with corresponding signs of activity (Smith & Hintzen 1991). This one-sided relationship (or unbalanced dichotomy) was noted very early by Baade & Minkowski (1954b), and by many others since then. Thus, while morphological distortions may be good indicators of potential sites of galactic activity, every interaction does not appear to produce the same type or degree of activity.

The physics and “sociology” of the unbalanced  $I$ - $A$  dichotomy may be related to one very simple observation and one plausible assumption, as described below, under the more general assumption that there is indeed a physical  $I$ - $A$  connection. First, we observe in numerical models that the dynamical effects of a strong encounter are very long-lived (*e.g.*, tidal tails are visible for one to two gigayears following a strong collision). Second, we might plausibly assume that AGN activity has a relatively short duty cycle (*i.e.*, the activity is “turned on” for a fraction of time significantly less than the time that the tell-tale signs of the interaction are still present). Consequently, from these two statements, we can conclude that a dichotomy would be expected in the  $I$ - $A$  connection: only a small fraction of all galaxies that show signs of interaction will also show signs of activity, whereas a large fraction of all active galaxies will show signs of interaction (either through disturbed morphologies, disturbed kinematics, or nearby companions). Care should be taken with such deductions however, and section 7 of this paper issues a warning about overly simple interpretations of such effects.

### 3. NUMERICAL STUDIES OF THE $I$ - $A$ CONNECTION

Several groups have carried out theoretical studies of the problem of inducing galaxy activity via tidal interactions. Some of the more relevant studies have used an  $N$ -body particle dynamics codes modified in various ways to include simplified gas dynamics (*e.g.*, see the review by Noguchi 1990; see also Noguchi & Ishibashi 1986; Byrd *et al.* 1986, 1987; Lin, Pringle, & Rees 1988; Noguchi 1988a,b, 1991,

1992; Hernquist 1989; Olson & Kwan 1990*a,b*; Barnes & Hernquist 1991; Mihos, Richstone, & Bothun 1991, 1992; Wada & Habe 1992; Mihos, Bothun, & Richstone 1993; Hernquist & Weil 1992; Weil & Hernquist 1993; Bekki & Noguchi 1994; Heller & Shlosman 1994; Lamb, Gerber, & Balsara 1994; Mihos & Hernquist 1994*a,c,d,e*, 1996; Hernquist & Mihos 1995; Bekki 1995). The main objectives of typical numerical simulation experiments include:

- Attempting either to find or to exclude appropriate collision scenarios for active galactic systems (*e.g.*, Taniguchi & Noguchi 1991; for a similar study of an isolated system, see also Knapen *et al.* 1995);
- Testing the relevance of interactions to the observed activity (in terms of mass transfer, gas shocking, nuclear gas accumulation, bursts of star formation, burst/activity timescales, potential for chemical enrichment, etc.); and
- Delimiting and parameterizing the range of collision models that lead to potentially active systems.

The results of these studies will then have application in a number of broad areas, including:

- Classifying a wider variety of observed systems in the context of the derived collision model parameter space within which activity is found to accompany interactions; and
- Predicting the expected properties, frequencies, and interrelations of interacting, active, and IR- and/or radio-luminous galaxies both in the local universe and at increasing redshift.

Particle+gas dynamics simulations are the culmination of a series of investigations of ever-increasing complexity and physical reasonableness. Initial models containing purely stellar dynamical effects have been supplanted by similar models containing, in addition, simple hydrodynamic terms. Those models are subsequently modified to follow the gas phase on a galactic scale and to include realistic effects: gas shocking, cloud collisions, angular momentum loss, “star formation”, nuclear gas accumulation, etc. Each of these algorithmic steps has an important role and each can contribute to our understanding of “interactive” galaxies. But, it is at the last step in the code sequence where substantial new ground is being broken and where our ability to test the *I-A* connection reaches its fullest potential.

In the area of interaction-induced starburst activity, additional power of investigation is gained through the application of stellar population synthesis and population evolution algorithms to the numerical model results (*e.g.*, Fritze-Von Alvensleben & Burkert 1995; see also section 6 of this paper).

It has been shown that it is possible to model the optical morphological and kinematic properties of merging and interacting galaxies with straightforward numerical simulation techniques (*e.g.*, Borne *et al.* 1994, and references therein), and that the final collision solutions can be used to derive various physical and orbital parameters of the constituent galaxies (Borne 1990*b*). Galaxy masses, shapes, spins, and orientations, and orbital sizes, shapes, timescales, and orientations can all be deduced to some level, depending on the quality and quantity of available data, with particular dependence on the kinematic data (Borne 1988, 1990*a,b*). Merger remnants like NGC 7252 with a very complicated morphology and very complex kinematics can be reproduced in such simulations, even without including gas dynamical effects (Borne & Richstone 1991; Hibbard & Mihos 1995), and similarly for

other complex collision remnants (*e.g.*, smoke-ring galaxies, as in Theys & Spiegel 1977), though the inclusion of gas dynamics can lead to spectacularly improved results, as shown by Struck–Marcell & Higdon (1993) and Mihos & Hernquist (1994d).

On the whole, simple *stellar dynamical* collision models can do a modestly reasonable job at reproducing the *optical* observations of many interacting and merging galaxies. However, if one also attempts to model the full complement of *radio, infrared, and optical* observations of tidally-disturbed active galaxies, then additional input physics is required and nothing less than a full stars+gas simulation will suffice (as demonstrated by the vast and growing literature referenced earlier). As an example of what new results are being derived from among this rich literature of investigations, I summarize here some of the highlights of the work presented by Bekki & Noguchi (1994) and Bekki (1995):

- They studied the merger of two gas-rich galaxies using a TREESPH simulation algorithm (see Hernquist & Katz 1989).

- The cores of the two galaxies sink to a common center and merge via dynamical friction.

- The mutual orbiting of the two cores “stirs up” (*i.e.*, dynamically heats) the gas clouds.

- Dissipative cloud–cloud collisions drive  $\sim 10^8 M_\odot$  of disk gas into the central 10 pc. This corresponds to a dramatic improvement over the results of earlier models in overcoming the angular momentum barrier that would prevent gas material from being driven into the nucleus of the galaxy.

- Most of the gas infall occurs after the two cores have coalesced (merged).

- A recipe for star formation is included in their models.

- A nuclear starburst is the primary energy source before the cores merge.

- Accretion power (presumably onto an AGN) is the primary energy source after the cores merge.

- Retrograde encounters are most effective in fueling the nucleus since clouds on such orbits tend to lose angular momentum and fall into the center, whereas clouds moving on prograde orbits with respect to the orbiting cores tend to gain large amounts of angular momentum and be expelled away from the center.

#### 4. EXAMPLE — AN INTERACTION-INDUCED AGN: 3C278

As an example of interaction-induced nuclear activity, we present here a summary of some recent work on one such source: 3C278, a curved radio-jet source whose host galaxy is strongly interacting with a nearby companion elliptical.

We have developed a numerical simulation algorithm for modeling the propagation and morphology of ballistic radio jets in colliding galaxies (Borne & Colina 1993; hereafter BC). This algorithm has already been used quite successfully to fit the specific two-sided jet morphology seen in 3C278, a Fanaroff-Riley type I (FRI) radio source. The elliptical galaxy NGC 4782 is the host for 3C 278, which shows an east-west oriented two-sided jet with a *C*-shaped structure having very distinct bends in its morphology (see Fig. 1). The jet shape can be explained as a consequence of its interaction with the companion galaxy NGC 4783. According to BC, the observed deflections in the 3C 278 radio jets are primarily induced by the sweeping action of the hot gas in NGC 4783 as it passes by. The binary orbital parameters for the two colliding galaxies (NGC 4782/4783) were determined from

detailed optical imaging and kinematic measurements of the pair (Borne, Balcells, & Hoessel 1988; hereafter BBH), and these orbital parameters were used as input to the radio-jet simulations.

In the BC models the evolution of the radio jets is determined by their response to the time-dependent mechanical forces (*i.e.*, gravity and ram pressure) that act on the constituent jet blobs. Our models constrain the initial jet parameters, the properties of the hot gaseous medium into which the jets are ejected, and the relative importance of gravitational deflection versus ram pressure bending in influencing the jet morphology. From our specific model of the two-sided radio jet structure

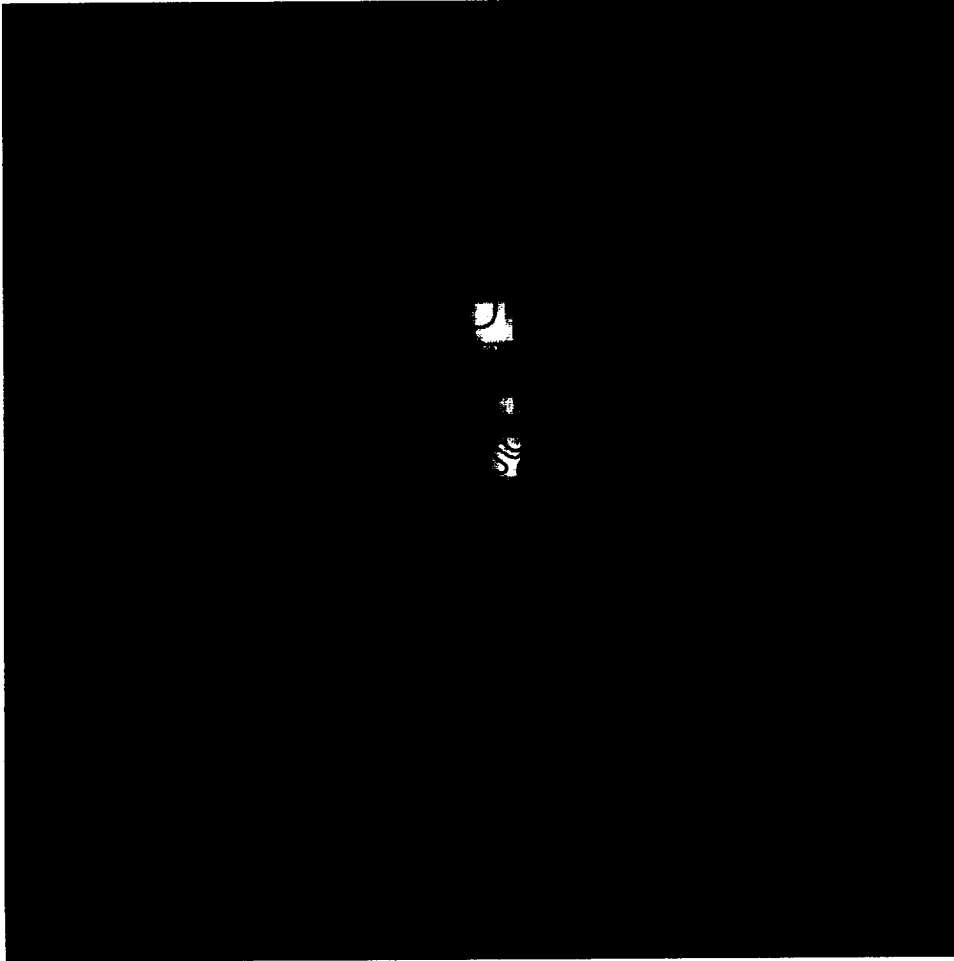


FIGURE 1. ROSAT X-ray image of the NGC 4782/4783 pair of galaxies overlaid with the VLA radio contours of the 3C 278 source (Baum et al. 1988). The radio source is centered on the peak of the stellar distribution. North is up and east to the left. Galaxy NGC 4782 (the host for 3C 278) is the southern elliptical in the image. Clearly noted in the figure are the distinct X-ray features that are referred to in the text.

associated with 3C278, it was determined that ram pressure deflection by the hot ISM is the dominant force affecting the morphology of the radio emission, and it was found that the jet activity began just over 70 million years ago, roughly 50 million years before the pericenter passage of the two galaxies, at which time the galaxies were already substantially overlapping. This kind of study therefore permits us to check in a quantitative way the onset of activity in galaxies being subjected to the (kinematically observed) tidal shocks that are produced in deeply penetrating galaxy collisions. Such shocks are seen in NGC 4782 (the host for 3C278) and in NGC 4783 (BBH), thereby directly supporting the *I-A* connection for this particular class of active galaxies (see de Juan *et al.* 1993, 1994; and Colina & de Juan 1995).

In order to verify the predictions of our hot gas-deflection model for the 3C278 radio jet and consequently to validate the physical parameters that relate to the interaction-induced nuclear activity, we have obtained deep ROSAT HRI imaging of the X-ray emitting gas associated with NGC 4782/4783 (Colina & Borne 1995). The HRI image presented in Figure 1 shows several remarkable features, observed for the first time in a pair of close colliding galaxies: (1) the detection of hot gas in the two galaxies NGC 4782 and NGC 4783 with their emission peaks displaced with respect to the stellar luminosity peaks; (2) a high-surface brightness *bridge* along the line joining the two galaxy nuclei; (3) tidal-like *tails* emerging from the X-ray nuclei of the two galaxies; and (4) a *sheet* of gas at the interaction interface between the two galaxies. All of these remarkable features reveal the complexity of structure that develops in the hot gas distribution when both hydrodynamical and tidal forces come into play during collisions between ellipticals with hot gas components. These results also substantiate the major role played by the hot ISM, and its asymmetries, in the propagation and entrainment of radio jets in colliding radio host ellipticals. Further, our observations validate the general concept of gas mass redistribution during galaxy encounters, which is the fundamental basis for expecting an *I-A* connection among galaxies.

The X-ray emission peaks associated with NGC 4782 and NGC 4783 are displaced with respect to the peaks of the optical luminosity distributions by  $\sim 7''$  (1.9 kpc) and  $\sim 4''$  (1.1 kpc), respectively. The detailed BBH orbital models for the motion of NGC 4782/4783 indicate that NGC 4782 is currently moving to the southwest while NGC 4783 is moving to the northeast. The central displacements of the X-ray emission peaks are in the same direction as the tidal distensions seen in the optical isophotes of the two galaxies, which is in the direction opposite to the motion of the galaxies in the BBH models. These displacements are consistent with the idea that (a) both the X-ray emitting gas and the stellar mass distribution are tidally distended by the gravitational interaction and that (b) the hot ISM in each galaxy is being “pushed back” by ram pressure from the incoming hot gas of the passing companion galaxy.

A high-surface brightness *bridge* is seen in the ROSAT image. This region of high surface brightness, located between the two colliding galaxies, is expected as a consequence of the compression of the hot interstellar media of the two galaxies in precisely this region where the interaction of the two ISM is most intense.

The best BC model capable of explaining the positions and angles of the bends in the 3C 278 radio jets predicts the presence of dense hot X-ray emitting gas with these distinct properties: (1) it should be displaced with respect to the center of the 3C 278 radio source (*i.e.*, away from the nucleus of NGC 4782); and (2) it should

be asymmetric with respect to the east and west jet. The predictions of the BC model are in close qualitative agreement with what is observed in the ROSAT/HRI image. In particular, the prediction that the east jet should be encountering a more dense and asymmetric hot gas component than the west jet is beautifully shown in the VLA/HRI overlay image in Figure 1. The success of the interaction model for explaining the optical, radio, and X-ray characteristics of 3C278 therefore supports the idea that the radio activity was indeed induced by the redistribution and transfer of gas mass into the galactic nucleus during the collision, thus providing direct physical evidence for the *I-A* connection.

## 5. EXAMPLE — AN INTERACTION-INDUCED STARBURST: THE CARTWHEEL RING GALAXY AM0035-335

As an example of interaction-induced starburst activity, we present here a summary of some recent work on one such source: the “Cartwheel” ring galaxy, number AM0035-335 from the Arp & Madore (1987) catalog of southern peculiar galaxies.

Of the many types of interacting and merging galaxies known, the rare and beautiful smoke-ring galaxies are among the most straightforward to interpret dynamically. Since the pioneering models of Lynds & Toomre (1976) and Theys & Spiegel (1977) it has become accepted that many “classical” ring galaxies are formed from a head-on collision between a small intruder galaxy and a larger disk system. The ring forms as gas and stars are crowded into an expanding wave that moves radially through the disk. The passage of the wave triggers vigorous star formation in the rings and provides us with a remarkably simple example of density wave-induced star formation (Jeske 1986; Appleton & Struck-Marcell 1987*a,b*; Struck-Marcell 1990; Gerber 1993; Struck-Marcell & Higdon 1993; Gerber & Lamb 1994; Mihos & Hernquist 1994*d*). Recent ground-based observations of rings (Marcum, Appleton, & Higdon 1992; Marston & Appleton 1995; Higdon 1995) reveal stellar evolutionary effects in and behind the expanding rings that strongly support the collisional picture. The Cartwheel ring galaxy presents unusually strong density wave-induced starburst activity in the wake of the collision event that formed the ring.

Unlike many regions of massive star formation found in astronomy, the site of the youngest (most massive) stars in rings is continually expanding, leaving behind in its wake a trail of evolving stars. The high spatial resolution of the Hubble Space Telescope (HST) provides an exciting opportunity to investigate the properties of massive OB associations formed in this expanding wave and provides a glimpse into the formation sequence of the most massive stars found in nature. The most dramatic changes are likely to occur on the leading edge of the expanding wave where the most massive stars will be found. These H II regions are dominated by stars more massive than  $10 M_{\odot}$ , whose lifetimes are typically less than a few times  $10^7$  years. If such stars were born on the edge of a ring expanding at typically 100 km/s into the surrounding disk, then the extremely massive O stars would exist in a band only 0.3 kpc wide. At the typical distance of a ring galaxy (100 Mpc) this corresponds to about  $0.6''$ . It is therefore evident that, in order to investigate the formation and distribution of the most massive stellar associations within such H II regions, we require the very high angular resolution of the HST. Furthermore,



since the number of nearby “canonical” smoke-ring galaxy candidates is quite small (*i.e.*, the best of the nearest examples have redshifts in the range  $cz \approx 6000 - 9000 \text{ km s}^{-1}$ ), analysis of the crucial questions related to star-formation behavior across the expanding ring density wave demands HST resolution. A number of these systems show remarkable fine-scale structure in ground-based images (*e.g.*, the Cartwheel has a dazzling array of knots and spokes), but most of the details in those structures are simply unresolved from the ground (*e.g.*, the distinction between a single super star cluster versus a collection of clusters). The real business of measuring spatial (hence temporal) variations in the density wave-induced star formation is occurring on scales that only HST can begin to resolve.

We have used the HST to obtain several blue-band and I-band images of two ring galaxies: the Cartwheel ring galaxy and II Zw 28. A detailed description of the Cartwheel galaxy results are presented elsewhere in this volume by Lucas *et al.* (see also Borne *et al.* 1996*a,b*; and Struck, Appleton, Borne, & Lucas 1996). Figure 2 presents a  $B - I$  image of the Cartwheel galaxy, as derived from the HST images; the colors are shown in a very exaggerated form in order to highlight the true  $B - I$  color variations, which are nevertheless quite strong and dramatic throughout the galaxy.

In our images of the Cartwheel, fine structure is observed down to the resolution limit of the HST images and very blue compact objects (perhaps massive young star clusters) are found throughout the starbursting regions. The primary ring around the galaxy is full of blue star-forming knots, which are well resolved in our images. The “spokes” of the Cartwheel, which are interior to the primary ring, are clearly visible, though their structure is somewhat more amorphous than that of the outer ring, suggesting that indeed the massive star formation behind the expanding density wave has subsided and the stellar associations that comprise the spokes are dispersing as they age. There is a well defined secondary ring around the nucleus (which is seen in numerical simulations at late times following the collision event), and there is a lens (or disk) interior to that ring. This region is heavily reddened and clearly full of dust. The images reveal a very fine structure in the dust distribution around and interior to the secondary ring. A sharp point-like nucleus is seen within the inner disk. Of the two nearest companions, the eastern-most companion shows some evidence of interaction, shows no evidence for star formation or gas, and appears to be an S0 galaxy. On the other hand, the western-most of the two near companions is very disturbed, shows strong evidence for star formation and gas, and appears to be a disrupted late-type barred spiral or irregular. As to which galaxy produced the Cartwheel ring, a distant third companion is seriously implicated by recent HI 21cm maps as being the “bullet” that penetrated the Cartwheel progenitor (Higdon, this volume; and Higdon 1995).

The HST imaging observations of the Cartwheel ring demonstrate a wealth of sharp features: star-forming knots, stellar clusters, arclets, bubble-like regions, and holes in the ring (blast regions?). The arclets, bubbles, and holes may be similar to the vast multi-supernova-driven arc reported by Vader & Chaboyer (1995) for NGC 1620. The knots and clusters (young globular clusters?) appear similar to those that many authors have now reported in HST images of other interacting and merged galaxies. These clusters are apparently forming in the shocked gas components of the constituent gas-rich galaxies involved in the collisions. For a discussion of these observations and their interpretation, refer to Holtzman *et al.* (1992), Whit-

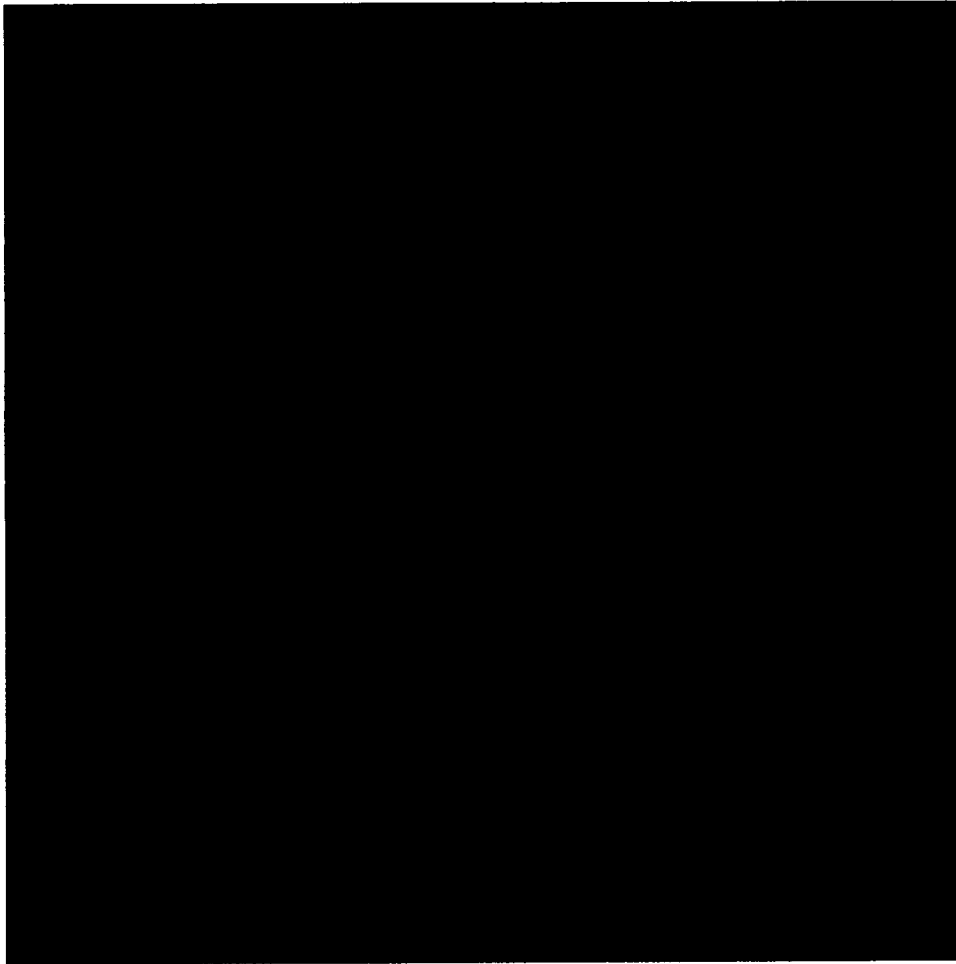


FIGURE 2. Exaggerated true-color representation of the true B-I color variations in the HST images of the Cartwheel ring galaxy. Blue shades identify regions with small B-I, and red shades correspond to regions with large B-I. North is to the upper left, and east is to the lower left. Note the very red inner ring and core region, the diffuseness and intermediate color of the spoke region, the very blue regions of the outer ring, the radial color gradients across the outer ring (especially the different color gradients on the north and south sides), and the azimuthal color gradients around the outer ring (especially the intense star formation in the southern section of ring). Note also the distinct differences in the colors (hence star formation rates) in the two nearby companion galaxies. The red companion (an S0 galaxy) shows a very faint tidal tail extending to the east, on the side opposite the blue IRR companion. The blue companion shows a sharp blue ridge of star formation to the northwest, on the side opposite the S0 companion. These latter two effects are consistent with a mutual interaction between these two companions, not necessarily involving an interaction with the Cartwheel galaxy. The intruder "bullet" galaxy that generated the Cartwheel's ring morphology is likely a third more distant companion to the north (not shown here; but see Higdon, this volume).

more *et al.* (1993, 1995), Shaya *et al.* (1994), Conti & Vacca (1994), Whitmore & Schweizer (1995), Whitmore (this volume), and Zepf (this volume). We believe that we are seeing a very rich population of similar objects throughout the outer Cartwheel ring, all of which (in addition to the bubbles and arcs) are a consequence of the interaction-induced starburst activity in this system.

## 6. PROMISING NEW DIRECTIONS

Section 3 provided a detailed list of the many theoretical studies related to the *I*-*A* connection (*i.e.*, the triggering of galactic activity through galaxy-galaxy collisions). The more advanced of these include some combination of N-body stellar dynamics and SPH (smoothed particle hydrodynamics): for example, the TREESPH simulation algorithm of Hernquist & Katz (1989). Significant advancements in our understanding of interaction-induced starbursting systems in particular are now being made by various groups who are including additional stellar population synthesis results and stellar evolution tracks in their studies (*e.g.*, Fritze-Von Alvensleben & Gerhard 1994*a,b*; Fritze-Von Alvensleben & Burkert 1995; Mihos & Hernquist 1994*b*). The work of Fritze-Von Alvensleben and her research group (see Fritze-Von Alvensleben, this volume) is quite promising and is already providing new insights into the ages and dynamical histories of these highly “interactive” systems, especially for the young star clusters discovered in HST images of interacting galaxies.

## 7. CAVEAT EMPTOR

As a pilot observational study of the interaction-activity connection, Borne & Scott (1990) investigated the environmental properties of the most intensely active and tidally disturbed sample of “nearby” galaxies, the ultraluminous IRAS galaxies. We report here the results of that study and point out a simple erroneous conclusion that could easily have been derived from our results.

We examined the digitized all-sky scans that were used to produce the STScI Guide Star Catalog in order to determine the projected density of non-stellar objects around the galaxies comprising the Ultraluminous IR Galaxy Sample and the Warm Ultraluminous IR Galaxy Sample (Sanders *et al.* 1988*a,b*). Each of the 19 galaxies identified in the combined sample appears to be undergoing a major starburst event. Furthermore, from the distorted appearances of most of the galaxies, the starburst has apparently been triggered by a recent interaction with another galaxy (see also Soifer, this volume). The spatial frequency of galaxies in the neighborhoods of these IR-bright galaxies can therefore provide some indication of the likelihood and frequency of such collisions.

We measured the number of non-stellar objects in fields 30-arcmin square centered on each of the galaxies in these samples, and in two similarly-sized adjacent fields (one each to the immediate west and east of the primary field). We found that *there is no significant difference in the local projected galaxy density around the 19 starbursting ultraluminous IR galaxies from that in the adjacent fields.* We also found that *these galaxies inhabit a wide range of environments, from low- to high-density:* with a range of projected densities  $\approx 20 - 260$  non-stellar objects per square degree, down to our limiting instrumental magnitude. These conclusions might lead one to conclude (erroneously) that interactions played a minor role in

the formation of such systems. But, this is not the best interpretation of the results and it is actually a misleading conclusion about the significance (or lack thereof) of interactions in producing the observed starburst activity.

If the galaxy density around these strongly starbursting galaxies had in fact been higher than that of the adjacent fields, then the interaction hypothesis for the origin of the starbursts would *apparently* have been supported. However, if that were true, then it would be hard to understand how these galaxies could have avoided until the present epoch a rapid gas-exhausting starburst event of the type that they are now experiencing. Conversely, if the galaxy density around these starburst galaxies had been significantly lower than in the adjacent fields, then galaxy-galaxy collisions would have been very rare indeed, making it extraordinarily difficult to explain their apparently tidally disturbed morphologies and *young* starburst ages. But, if their local galaxy densities were basically similar to that of the surrounding field galaxy population (as is actually observed), then each of these galaxies could have maintained a dense ISM until late times, at which point a single *random* collision would produce both its very disturbed morphology and the currently observed “once-in-a-lifetime” major starburst event, thereby permitting the galaxy to be included in the present Ultraluminous IR Galaxy Samples.

Given the insignificant difference in the projected galaxy densities around these disturbed ultraluminous IR galaxies compared to that in adjacent fields, and given the wide range of local galaxy densities in the neighborhoods of these galaxies, we conclude that galaxy interactions may indeed be responsible for these starburst events (as already implied by their disturbed morphologies) and that such events are occurring at the present epoch in a random, environment-independent manner. This conclusion contradicts the superficial initial interpretation of the results, which would have suggested that the absence of a systematically enhanced density of companions around these galaxies necessarily precludes their formation via tidal interaction processes. In this and similar studies, one must therefore beware of deriving overly simple conclusions based solely on the presence or absence of companions (or on the presence or absence of a distorted morphology) without additional evidence or without the application of additional physical parameters.

## 8. SUMMARY REMARKS

The study of interacting galaxies has become very diversified and very productive in recent years. One of the clear results of these manifold studies is the apparent causal connection between some interactions and various forms of activity within the participating galaxies. This Interaction-Activity (*I-A*) connection now has overwhelming observational support. Considering the preponderance of active galaxies in high-redshift samples of galaxies (selected on the basis of high IR or radio flux), deeper observational analysis and investigation of this *I-A* connection holds promise for offering tremendous insight into the formation and evolution of galaxy-scale structures throughout the universe (*e.g.*, Mihos 1995).

Theoretical investigations of the *I-A* connection provide a general frame of reference from which to study both the physical processes involved in generic collisions between galaxies and the generation of activity in various specific classes of objects (*e.g.*, starburst galaxies, ultraluminous IRAS galaxies, low- and high-luminosity radio galaxies, high-redshift radio galaxies, and quasars). Since such objects are

strong emitters in various wavebands, they are visible to large distances and are therefore very relevant to general investigations of the evolution and structure of galaxies, as well as being applicable to studies of large-scale structure.

The power and realism of the theoretical, numerical models that are being applied to studies of the *I-A* connection are now quite impressive and the models are rich in physics (dynamical, hydrodynamical, and chemical). Such studies are consequently helping to answer some of the fundamental questions that have arisen from the wealthy accumulations of observations on active galaxies: *Is activity in galaxies actually triggered by tidal interactions?* And: *What is the validity and relevance of the I-A connection for the origin, structure, and evolution of galaxies in the universe?*

## ACKNOWLEDGEMENTS

This research was supported in part by NASA ROSAT grant NAG5-1920 and by NASA HST grant GO-05410.01-93 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555. Partial travel support to this conference was supported under NASA Contract NAS5-30960. The author is grateful to G.Longo and the conference organizers for additional travel support. The Cartwheel galaxy investigations were carried out in collaboration with R.Lucas, P.Appleton, C.Struck, A.Schultz, and L.Spight. The 3C 278 investigations were carried out in collaboration with L.Colina. The author is especially grateful to G.Longo for his patience in accepting this paper well past the submission deadline.

## REFERENCES

- Appleton, P., & Struck-Marcell, C. 1987*a*, ApJ, 318, 103  
Appleton, P., & Struck-Marcell, C. 1987*b*, ApJ, 323, 480  
Arp, H. C. 1966, ApJS, 14, 1  
Arp, H. C., & Madore, B. F. 1987, A Catalogue of Southern Peculiar Galaxies and Associations (Cambridge: Cambridge University Press)  
Armus, L. 1989, PhD Thesis, University of Maryland  
Baade, W., & Minkowski, R. 1954*a*, ApJ, 119, 206  
Baade, W., & Minkowski, R. 1954*b*, ApJ, 119, 215  
Bahcall, J. N., Kirhakos, S., & Schneider, D. P. 1995, ApJ, 447, L1  
Barnes, J. E., & Hernquist, L. E. 1991, ApJ, 370, L65  
Baum, S. A., Heckman, T. M., Bridle, A., van Breugel, W., & Miley, G. 1988, ApJS, 68, 643  
Bekki, K. 1995, MNRAS, 276, 9  
Bekki, K., & Noguchi, M. 1994, A&A, 290, 7  
Block, D. L., & Stockton, A. 1991, AJ, 102, 1928  
Borne, K. D. 1988, ApJ, 330, 38  
Borne, K. D. 1990*a*, in "Dynamics and Interactions of Galaxies", ed. R. Wielen (Berlin: Springer), p. 196  
Borne, K. D. 1990*b*, in "Paired and Interacting Galaxies", IAU Colloquium #124, eds. J. W. Sulentic, W. C. Keel, & C. M. Telesco (NASA), p. 537  
Borne, K. D., Balcells, M., & Hoessel, J. G. 1988, ApJ, 333, 567 (BBH)  
Borne, K. D., Balcells, M., Hoessel, J. G., & McMaster, M. 1994, ApJ, 435, 79

- Borne, K. D., & Colina, L. 1993, *ApJ*, 416, 157 (BC)
- Borne, K. D., Lucas, R. A., Appleton, P., Struck, C., Schultz, A. B., & Spight, L. 1996a, in "Science with the Hubble Space Telescope – II", eds. P. Benvenuti, F. D. Macchetto, & E. J. Schreier, in press
- Borne, K. D., Lucas, R. A., Appleton, P., Struck, C., Schultz, A. B., & Spight, L. 1996b, in preparation
- Borne, K. D., & Richstone, D. O. 1991, *ApJ*, 369, 111
- Borne, K. D., & Scott, J. 1990, in "Massive Stars in Starbursts: Contributed Papers," a Space Telescope Science Institute Workshop, p. 5
- Bushouse, H. 1986, *AJ*, 91, 255
- Byrd, G. G., Sundelius, B., & Valtonen, M. 1987, *A&A*, 171, 16
- Byrd, G. G., Valtonen, M. J., Valtaoja, L., & Sundelius, B. 1986, *A&A*, 166, 75
- Carico, D. P., Graham, J. R., Matthews, K., Wilson, T. D., Soifer, B. T., Neugebauer, G., & Sanders, D. B. 1990, *ApJ*, 349, L39
- Chambers, K. C., Miley, G. K., & van Breugel, W. 1987, *Nature*, 329, 604
- Chambers, K. C., & Miley, G. K. 1990, in *Evolution of the Universe of Galaxies*, ed. R. G. Kron (San Francisco: ASP), p. 373
- Colina, L., & Borne, K. D. 1995, *ApJ*, 454, L101
- Colina, L., & de Juan, L. 1995, *ApJ*, 448, 548
- Colina, L., & Pérez-Fournon, I. 1990a, *ApJS*, 72, 41
- Colina, L., & Pérez-Fournon, I. 1990b, *ApJ*, 349, 45
- Conti, P. S., & Vacca, W. D. 1994, *ApJ*, 423, L97
- Dahari, O. 1984, *AJ*, 89, 966
- de Juan, L., Colina, L., & Pérez-Fournon, I. 1993, *ApSS*, 205, 209
- de Juan, L., Colina, L., & Pérez-Fournon, I. 1994, *ApJS*, 91, 507
- Few, J. M. A., Madore, B. F., & Arp, H. C. 1982, *MNRAS*, 199, 633
- Fosbury, R. A. E., & Hawarden, T. G. 1976, *MNRAS*, 178, 473
- Fritze-Von Alvensleben, U., & Burkert, A. 1995, *A&A*, 300, 58
- Fritze-Von Alvensleben, U., & Gerhard, O. E. 1994a, *A&A*, 285, 751
- Fritze-Von Alvensleben, U., & Gerhard, O. E. 1994b, *A&A*, 285, 775
- Gallimore, J. F., & Keel, W. C. 1993, *AJ*, 106, 1337
- Gerber, R. A. 1993, PhD Thesis, University of Illinois
- Gerber, R. A., & Lamb, S. A. 1994, *ApJ*, 431, 604
- Gunn, J. E. 1977, in "Active Galactic Nuclei", eds. C. Hazard & S. Mitton (Cambridge: Cambridge University Press), p. 213
- Heckman, T. M. 1990, in "Paired and Interacting Galaxies", IAU Colloquium #124, eds. J. W. Sulentic, W. C. Keel, & C. M. Telesco (NASA), p. 359
- Heckman, T. M. 1991a, in "Massive Stars in Starburst Galaxies", eds. C. Leitherer, N. Walborn, T. Heckman, & C. Norman (Cambridge: Cambridge University Press), p. 289
- Heckman, T. M. 1991b, in "Testing the AGN Paradigm", proceedings of a University of Maryland Symposium
- Heckman, T. M., Smith, E. P., Baum, S. A., van Breugel, W. J. M., Miley, G. K., Illingworth, G. D., Bothun, G. D., & Balick, B. 1986, *ApJ*, 311, 526
- Heller, C. H., & Shlosman, I. 1994, *ApJ*, 424, 84
- Hernquist, L. 1989, *Nature*, 340, 687
- Hernquist, L., & Katz, N. 1989, *ApJS*, 70, 419
- Hernquist, L., & Mihos, J. C. 1995, *ApJ*, 448, 41

- Hernquist, L., & Weil, M. L. 1992, *Nature*, 358, 734
- Hibbard, J. E., & Mihos, J. C. 1995, *AJ*, 110, 140
- Higdon, J. L. 1995, *ApJ*, 455, 524
- Holtzman, J. A. *et al.* 1992, *AJ*, 103, 691
- Hummel, E., van der Hulst, J. M., Kennicutt, R. C., & Keel, W. C. 1990, *A&A*, 236, 333
- Hutchings, J. B. 1987, *ApJ*, 320, 122
- Hutchings, J. B., & Neff S. G. 1988, *AJ*, 96, 1575
- Hutchings, J. B., & Neff S. G. 1990a, *AJ*, 99, 1715
- Hutchings, J. B., & Neff S. G. 1990b, in "Paired and Interacting Galaxies", IAU Colloquium #124, eds. J. W. Sulentic, W. C. Keel, & C. M. Telesco (NASA), p. 383
- Hutchings, J. B., & Neff S. G. 1991, *AJ*, 101, 434
- Hutchings, J. B., & Neff S. G. 1992a, *AJ*, 103, 1746
- Hutchings, J. B., & Neff S. G. 1992b, *AJ*, 104, 1
- Jeske, N. A. 1986, PhD Thesis, University of California at Berkeley
- Joseph, R., & Wright, G. 1985, *MNRAS*, 214, 87
- Keel, W. C. 1993, *AJ*, 106, 1771
- Keel, W. C., Kennicutt, R. C., Hummel, E., & van der Hulst, J. M. 1985, *AJ*, 90, 708
- Keel, W. C., & van Soest, E. T. M. 1992, *A&AS*, 94, 553
- Kennicutt, R. C. 1990, in "Paired and Interacting Galaxies", IAU Colloquium #124, eds. J. W. Sulentic, W. C. Keel, & C. M. Telesco (NASA), p. 269
- Kennicutt, R. C., Keel, W. C., van der Hulst, J. M., Hummel, E., & Roettiger, K. A. 1987, *AJ*, 93, 1011
- Kormendy, J. 1989, *ApJL*, 342, L63
- Kormendy, J., & Sanders, D. B. 1992, *ApJL*, 390, 53
- Knapen, J. H., Beckman, J. E., Heller, C. H., Shlosman, I., & De Jong, R. S. 1995, *ApJ*, 454, 623
- Lamb, S. A., & Gerber, R. A. 1992, in "The Evolution of Galaxies and their Environment", proceedings of the 3rd Teton Conference (NASA), p. 225
- Lamb, S. A., Gerber, R. A., & Balsara, D. S. 1994, *ApSS*, 216, 337
- Larson, R. B., & Tinsley, B. M. 1978, *ApJ*, 219, 46
- Lawrence, A., Rowan-Robinson, M., Leech, K., Jones, D.H.P., & Wall, J.V. 1989, *MNRAS*, 240, 329
- Leech, K. J., Rowan-Robinson, M., Lawrence, A., & Hughes, J. D. 1994, *MNRAS*, 267, 253
- Lin, D. N. C., Pringle, J. E., & Rees, M. J. 1988, *ApJ*, 328, 103
- Liu, C. T., & Kennicutt, R. C. 1995a, *ApJ*, 450, 547
- Liu, C. T., & Kennicutt, R. C. 1995b, *ApJS*, 100, 325
- Lonsdale, C. J., Persson, S. E., & Matthews, K. 1984, *ApJ*, 287, 95
- Lynds, R., & Toomre, A. 1976, *ApJ*, 209, 382
- MacKenty, J. 1989, *ApJ*, 343, 125
- MacKenty, J. W., Simkin, S. M., Griffiths, R. E., Ulvestad, J. S., & Wilson, A. S. 1994, *ApJ*, 435, 71
- MacKenty, J. W., Simpson, C., & McLean, B. 1990, in "Paired and Interacting Galaxies", IAU Colloquium #124, eds. J. W. Sulentic, W. C. Keel, & C. M. Telesco (NASA), p. 165

- Majewski, S. R., Hereld, M., Koo, D. C., Illingworth, G. D., & Heckman, T. M., 1993, *ApJ*, 402, 125
- Marcum, P. M., Appleton, P. N., & Higdon, J. L. 1992, *ApJ*, 399, 57
- Marston, A. P., & Appleton, P. N. 1995, *AJ*, 109, 1002
- Mazzarella, J. M., Bothun, G. D., & Boroson, T. A. 1991, *AJ*, 101, 2034
- Melnick, J., & Mirabel, I. F. 1990, *A&A*, 231, L19
- Mihos, J. C. 1995, *ApJ*, 438, 75
- Mihos, J. C., Bothun G. D., & Richstone, D. O. 1993, *ApJ*, 418, 82
- Mihos, J. & Hernquist, L. 1994*a*, *ApJ*, 425, L13
- Mihos, J. & Hernquist, L. 1994*b*, *ApJ*, 427, 112
- Mihos, J. & Hernquist, L. 1994*c*, *ApJ*, 431, L9
- Mihos, J. & Hernquist, L. 1994*d*, *ApJ*, 437, 611
- Mihos, J. & Hernquist, L. 1994*e*, *ApJ*, 437, L47
- Mihos, J. & Hernquist, L. 1996, *ApJ*, in press
- Mihos, J. C., Richstone, D. O., & Bothun G. D. 1991, *ApJ*, 377, 72
- Mihos, J. C., Richstone, D. O., & Bothun G. D. 1992, *ApJ*, 400, 153
- Noguchi, M. 1988*a*, *A&A*, 201, 37
- Noguchi, M. 1988*b*, *A&A*, 203, 259
- Noguchi, M. 1990, "Proceedings of the 2nd Teton Conference" (Dordrecht: Kluwer), p. 323
- Noguchi, M. 1991, *MNRAS*, 251, 360
- Noguchi, M. 1992, *Astron. Herald*, 85, 330
- Noguchi, M., & Ishibashi, S. 1986, *MNRAS*, 219, 305
- Norman, C., & Scoville, N. 1988, *ApJ*, 332, 124
- Olson, K. M., & Kwan, J. 1990*a*, *ApJ*, 349, 480
- Olson, K. M., & Kwan, J. 1990*b*, *ApJ*, 361, 426
- Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988*a*, *ApJ*, 325, 74
- Sanders, D. B., Soifer, B. T., Elias, J. H., Neugebauer, G., & Matthews, K. 1988*b*, *ApJ*, 328, L35
- Sargent, A., & Scoville, N. 1991, *ApJ*, 366, L1
- Schmidt, M. 1963, *Nature*, 197, 1040
- Scoville, N., Sargent, A. I., Sanders, D. B., & Soifer, B. T. 1991, *ApJ*, 366, L5
- Seyfert, C. K. 1943, *ApJ*, 97, 28
- Sharp, N., & Jones, B. 1980, *Nature*, 283, 275
- Shaya, E. J. *et al.* 1994, *AJ*, 107, 1675
- Shlosman, I., ed. 1994, in "Mass-Transfer Induced Activity in Galaxies" (New York: Cambridge Univ. Press)
- Smith, D. A., Herter, T., Haynes, M. P., Beichman, C. A., & Gautier, T. N., III 1995, *ApJ*, 439, 623
- Smith, E. P., & Heckman, T. M. 1989*a*, *ApJS*, 69, 365
- Smith, E. P., & Heckman, T. M. 1989*b*, *ApJ*, 341, 658
- Smith, E. P., & Heckman, T. M. 1990*a*, *ApJ*, 348, 38
- Smith, E. P., & Heckman, T. M. 1990*b*, in "Dynamics and Interactions of Galaxies", ed. R. Wielen (Berlin: Springer), p. 450
- Smith, E. P., & Kassim, N. E. 1993, *AJ*, 105, 46
- Smith, E. P., & Hintzen, P. 1991, *AJ*, 101, 410



- Soifer, B. T., Sanders, D. B., Neugebauer, G., Danielson, G. E., Lonsdale, C. J., Madore, B. F., & Persson, S. E. 1986, *ApJ*, 303, L41
- Stockton, A. 1990, in "Dynamics and Interactions of Galaxies", ed. R. Wielen (Berlin: Springer), p. 440
- Stockton, A., & Farnham, T. 1991, *ApJ*, 371, 525
- Stockton, A., & MacKenty, J. 1983, *Nature*, 305, 678
- Stockton, A., & MacKenty, J. 1987, *ApJ*, 316, 584
- Stranghellini, C., O'Dea, C. P., Baum, S. A., & Laurikainen, E. 1993, *ApJS*, 88, 1
- Struck, C., Appleton, P. N., Borne, K. D., & Lucas, R. A. 1996, *Nature*, submitted
- Struck-Marcell, C. 1990, *AJ*, 99, 71
- Struck-Marcell, C., & Higdon, J. L. 1993, *ApJ*, 411, 108
- Taniguchi, Y., & Noguchi, M. 1991, *AJ*, 101, 1601
- Theys, J. C., & Spiegel, E. A. 1976, *ApJ*, 208, 650
- Toomre, A., & Toomre, J. 1972, *ApJ*, 178, 623
- Vader, J. P., & Chaboyer, B. 1995, *ApJ*, 445, 691
- van Breugel, W. J. M., & McCarthy, P. J. 1990, in *Evolution of the Universe of Galaxies*, ed. R. G. Kron (San Francisco: ASP), p. 359
- Wada, K., & Habe, A. 1992, *MNRAS*, 258, 82
- Wakamatsu, K., & Nashida, M. T. 1987, *ApJ*, 315, L23
- Weil, M. L., & Hernquist, L. 1993, *ApJ*, 405, 142
- Whitmore, B. C., Schweizer, F., Leitherer, C., Borne, K., & Robert, C. 1993, *AJ*, 106, 1354
- Whitmore, B. C., & Schweizer, F. 1995, *AJ*, 109, 960
- Whitmore, B. C. *et al.* 1995, *ApJ*, 454, 73
- Yee, H., & Green R. 1984, *ApJ*, 280, 79