MERGER-INDUCED STARBURSTS

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Abstract   Extragalactic starbursts induced by gravitational interactions can now be studied from $z \approx 0$ to $\gtrsim 2$. The evidence that mergers of gas-rich galaxies tend to trigger galaxy-wide starbursts is strong, both statistically and in individual cases of major disk–disk mergers. Star formation rates appear enhanced by factors of a few to $\sim 10^3$ above normal. Detailed studies of nearby mergers and ULIRGs suggest that the main trigger for starbursts is the rapidly mounting pressure of the ISM in extended shock regions, rather than high-velocity, $50-100$ km s^{-1} cloud–cloud collisions. Numerical simulations demonstrate that in colliding galaxies the star formation rate depends not only on the gas density, but crucially also on energy dissipation in shocks. An often overlooked characteristic of merger-induced starbursts is that the spatial distribution of the enhanced star formation extends over large scales ($\sim 10-20$ kpc). Thus, although most such starbursts do peak near the galactic centers, young stellar populations pervade merger remnants and explain why (1) age gradients in descendent galaxies are mild and (2) resultant cluster systems are far-flung. This review presents an overview of interesting phenomena observed in galaxy-wide starbursts and emphasizes that such events continue to accompany the birth of elliptical galaxies to the present epoch.

1.   Introduction

This brief review concentrates on three items. First, I report on recent progress in our understanding of the dynamical triggers at work in merger-induced starbursts. Then I address two issues that are often ignored or misunderstood, yet are of fundamental importance to the subject: the large spatial extent of merger-induced starbursts, and the implications of such starbursts for the formation of elliptical galaxies at low and high redshifts.

The basic reason why tidal interactions and mergers help fuel bursts of star formation has been understood for over three decades. Under the headline *Stoking the Furnace?* Toomre & Toomre (1972) wrote: "Would not the violent mechanical agitation of a close tidal encounter—let alone an actual merger— already tend to bring *deep* into a galaxy a fairly *sudden* supply of fresh fuel in the form of interstellar material?" Subsequent numerical simulations that

included gas have fully corroborated this notion (e.g., Negroponte & White 1983; Noguchi 1988; Barnes & Hernquist 1991).

Similarly, many observational studies have established beyond any doubt that mergers invigorate star formation well beyond the levels observed in quiescent disk galaxies. As early as 1970, Shakhbazian pointed out the presence of extraordinary stellar *"superassociations"* with luminosities of up to $M_V \approx -15.5$ in The Antennae. In a landmark paper, Larson & Tinsley (1978) showed that the UBV colors of Arp's peculiar galaxies can best be explained if tidal interactions engender short, but intense bursts of star formation involving up to $\sim 5\%$ of the total mass. Infrared observations confirmed the notion of *super*starbursts in major disk–disk mergers (Joseph & Wright 1985). Since then, a steady stream of papers from surveys (e.g., 2dF: Lambas et al. 2003; SDSS: Nikolic et al. 2004) has continued to support and refine this picture. A nice twist was the discovery—fostered by *HST*'s high resolution—that star clusters and, specifically, globular clusters form in large numbers during galactic mergers (Schweizer 1987; Holtzman et al. 1992; Whitmore et al. 1993).

2.   Gas Supply and Dynamical Triggers

Even after ~ 13 Gyr of evolution, many present-day galaxies still have significant gas supplies available for star formation during interactions and mergers. The median gas fraction of neutral hydrogen alone, expressed relative to the total baryonic mass, is 15%, 10%, and 4% for dIrr, Sc, and Sa galaxies, respectively (Roberts & Haynes 1994). Even more impressive is the median fraction of *all* gas relative to the dynamical mass, $M_{\mathrm{H\,I+H_2}}/M_{\mathrm{dyn}} \approx 25\%$, 15%, and 3% for the same three types of galaxies (Young & Scoville 1991). Since even at high redshifts no galaxy can be more than 100% gaseous, the relatively high gas fractions of local Sc and later-type galaxies tell us that there is less than one order-of-magnitude difference between the fractional gas contents of many local disk galaxies and their high-z counterparts. Hence, the often-heard objection that mergers at $z \approx 2-5$ were completely different from local mergers is weak, and studying local mergers can, in fact, help us understand high-z mergers.

Molecular gas masses observed in local mergers and distant quasars support this point of view. Locally, $M_{\mathrm{H_2}}$ ranges from $0.6 \times 10^{10}\ M_\odot$ for an aging merger remnant like NGC 7252 through $1.5 \times 10^{10}\ M_\odot$ for an ongoing merger like The Antennae to $\sim 3 \times 10^{10}\ M_\odot$ for extreme ULIRGs, while $M_{\mathrm{H_2}} \approx 2 \times 10^{10}\ M_\odot$ in a QSO at $z = 2.56$ (Solomon et al. 2003) and also in one at $z = 6.42$ (Walter et al. 2003).

With gas amply available for star formation during mergers at both low and high redshifts, what are the *dynamical triggers* for merger-induced starbursts?
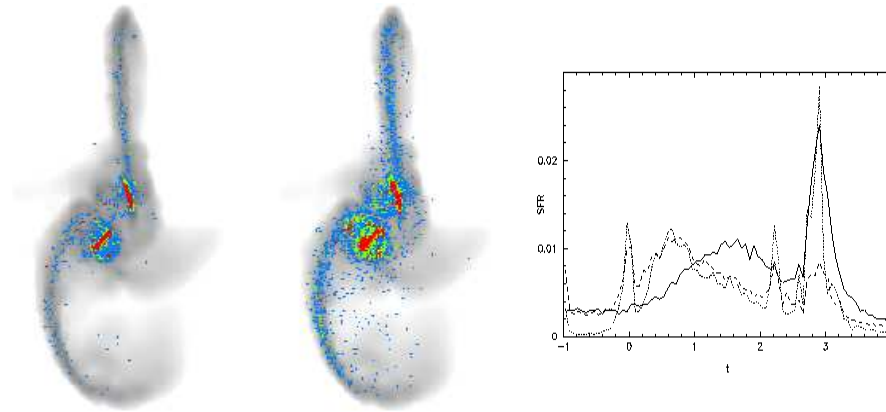
Figure 1.   Simulations of star formation in The Mice for (left) density-dependent and (middle) shock-induced star formation recipes; halftones mark old stars, points mark star formation. (Right) Star formation rate vs. time for density-dependent (*solid line*) and various shock-induced (*dashed & dotted*) star formation recipes (from Barnes 2004).

During disk-galaxy interactions gravitational torques arise between the bars induced in the gas and among the stars. Because the gaseous bar leads, the gas experiences braking, which in turn leads to its infall. The resulting pressure increase in the gas has long been understood to be the root cause of interaction-induced starbursts (Noguchi 1988; Hernquist 1989; Barnes & Hernquist 1991).

Although the vehemence of this pressure increase clearly depends on such factors as the presence or absence of a central bulge (Mihos & Hernquist 1996) and the encounter geometry (Barnes & Hernquist 1996), the small-scale details of the dynamical triggers have been less clear until recently.

It now appears that *shocks* play a very major role, both in affecting the spatial distribution of star formation (Barnes 2004) and in squeezing giant molecular clouds (hereafter GMCs) into rapid star and cluster formation (Jog & Solomon 1992; Elmegreen & Efremov 1997). Questions such as whether cloud–cloud collisions are important and what role magnetic fields play are just beginning to be addressed by observers, as detailed below.

Merger-induced shocks can be fierce. In a simulation of two merging equal-mass disks (Barnes & Hernquist 1996), massive rings of dense gas form around the center of each galaxy and collide, during the third passage, head-on with a relative velocity of $\sim$500 km s^{-1}! This extreme final smash is made possible by the rapid $\sim$90% loss of orbital angular momentum that the two gas rings experience within $\sim$1/4 disk-rotation period.

Even during milder encounters shock-induced star formation may dominate. Because of the ubiquity of shocks in mergers involving gas, Barnes (2004) proposes a new star formation recipe that, in addition to the local gas density ρ_{gas},

includes the local rate $\dot{u}$ of mechanical heating due to shocks and PdV work:
$$\dot{\rho}_* = C_* \cdot \rho_{\text{gas}}^n \cdot \max(\dot{u}, 0)^m \, .$$
Assuming that energy dissipation balances the heating rate, setting $m > 0$ and $n = 1$ yields purely *shock-induced* star formation, while setting $m = 0$ and $n > 1$ yields *density-dependent* star formation (with Schmidt's law as a special case). Barnes compares simulations run for these two limit cases of star formation with observations of The Mice (see Fig. 1 here, and color figs. 3 & 4 in his paper) and shows convincingly that shock-induced star formation is *spatially more extended* and *occurs earlier* during the merger, which is in significantly better accord with the observations.

One long-standing question has been whether high-velocity cloud–cloud collisions $(50 - 100$ km s$^{-1})$ contribute significantly to the triggering of starbursts (Kumai, Basu, & Fujimoto 1993) or not. To address this issue, Whitmore et al. (in prep.) measured Hα velocities of the gas associated with young massive clusters in The Antennae, using *HST*/STIS and positioning the $52''$ long slit of STIS along different groups of clusters. From many clusters in 7 regions the measured cluster-to-cluster velocity dispersion is $<10 - 12$ km s^{-1}, which argues *against* high-velocity cloud–cloud collisions as a major trigger of starbursts. Instead, the squeezing of GMCs by the general pressure increase in the ISM (Jog & Solomon 1992) appears favored.

The role of magnetic fields in triggering starbursts in mergers remains unclear at present, but is beginning to be studied observationally. Chyży & Beck (2004) have used the VLA to produce detailed maps of radio total power and polarization in NGC 4038/39 (see Chyży's poster paper). The derived mean total magnetic field of $\sim$20 μG is twice as strong as in normal spirals and appears *tangled* in regions of enhanced star formation. The field peaks at $\sim$30 μG in the southern part of the Overlap Region, suggesting strong compression where the star formation rate is highest. The crucial question to address over the coming years is whether the enhanced magnetic field observed in mergers merely traces compression, or whether it contributes to the triggering of starbursts.

3.   Spatially Extended Starbursts

Interaction-induced starbursts tend to be spatially extended $(\sim 10 - 20$ kpc) for most of their duration. Only relatively late in a merger do they become strongly concentrated.

For example, any good *HST, Spitzer,* or *Chandra* image of NGC 4038/39 shows that enhanced star formation extends over a projected area of $\sim 8 \times 11$ kpc (Fig. 2). In the optical, Hα and blue images are best at showing the extended nature of the starburst. In the infrared, a *Spitzer*/IRAC image at 8 μm emphasizes the warm dust associated with star formation throughout the two disks, glowing especially bright in the optically obscured disk contact ("Over-
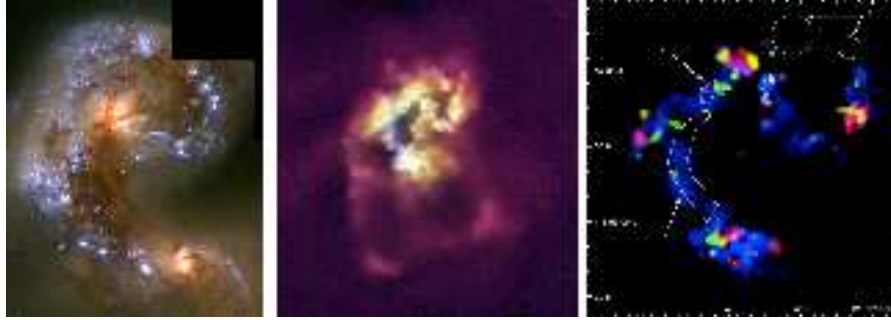
Figure 2. Extended starburst in NGC 4038/39, as imaged by (left) *HST* ($\sim 8 \times 11$ kpc field of view) and (middle) *Chandra*. (Right) Metallicity map for hot ISM, showing spotty chemical enrichment (from Whitmore et al. 1999; Fabbiano et al. 2004; and Baldi et al. 2005).

lap") region (Wang et al. 2004). And in X-rays, a deep *Chandra* image displays not only two disks filled with superbubbles of hot gas (typical diameter ~ 1.5 kpc, $T \approx 5 \times 10^6$ K, $M \approx 10^{5-6} M_\odot$), but also two giant, 10 kpc-size loops extending to the south (Fig. 2, middle panel). Their nature remains unclear (wind-blown?, or tidal ejecta?). These various images illustrate that early in a merger the extended starburst heats the ISM in a chaotic manner, rather than leading to well-directed bipolar superwinds.

An interesting consequence of the extended starburst in NGC 4038/39 is the *spotty chemical enrichment* of the hot ISM, observed for the first time in any merger galaxy (Fabbiano et al. 2004; Baldi et al. 2005). The high S/N ratio of the *Chandra* emission-line spectra permits the determination of individual Fe, Ne, Mg, and Si abundances in ~ 20 regions. Figure 2 (3rd panel, = color Fig. 3 in Fabbiano et al.) shows a metallicity map, with various shades of gray marking individual elements. The α-elements are enhanced by up to $20-25\times$ solar and follow an enhancement pattern distinctly different from Fe, as one would expect if they were recently produced by SNe II. A question for future study is how such spotty chemical enrichment may affect stars still to form.

Another important consequence of the large spatial extent of merger-induced starbursts is that newly-formed stars decouple from the inward-trending gas continuously and at many different radii. This process differs sharply from the widely held misconception that such starbursts occur mainly in the central kiloparsec, where they are being fueled by infalling gas. As a result of this extended star formation, radial age gradients in merger remnants are weak (e.g., Schweizer 1998). This is also the likely reason why in ellipticals age gradients are near zero, and mean metallicity gradients are only $\sim 40\%$ per decade in radius (Davies et al. 1993; Trager et al. 2000; Mehlert et al. 2003).

The strongest evidence linking extended starbursts to merger remnants and ellipticals is the wide radial distribution of the resultant star clusters. In both
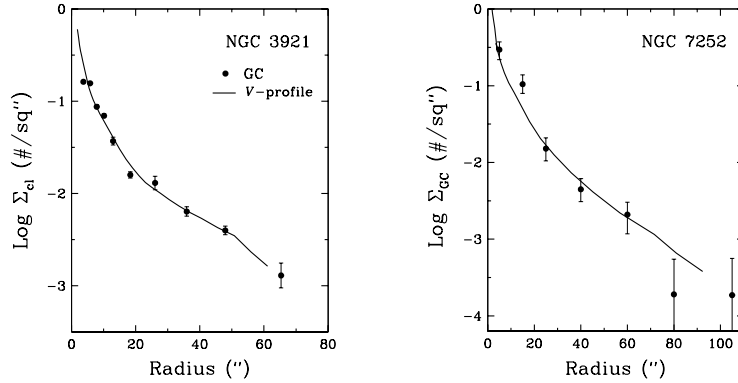
Figure 3. Radial distributions of second-generation globular clusters (*data points*) and background *V*-light (*lines*) in the merger remnants NGC 3921 (Schweizer et al. 1996) and NGC 7252 (Miller et al. 1997). The far-flung cluster distributions are remnant signatures of extended starbursts.

remnants (Fig. 3) and Es, second-generation metal-rich globular clusters track the underlying light distribution of their host galaxies with surprising accuracy. It is true that they tend to be more centrally distributed than metal-poor globulars, but only by little. Typically, half of them lie within $R_{\text{eff}} \approx 3-5$ kpc from the center. This is consistent with some additional gaseous dissipation, but completely inconsistent with nuclear-only ($\lesssim 1$ kpc) starbursts. Hence wide-flung globular-cluster systems are signatures of ancient extended starbursts.

4. Cosmological Implications

In 1972, Toomre & Toomre put forth the bold hypothesis that most giant ellipticals might be the remnants of major disk–disk mergers. Toomre (1977) elaborated on this idea, proposing a sequence of 11 increasingly merged disk pairs and refining the argument that from the current merger rate one could expect between 1/3 and all local ellipticals to be remnants of ancient mergers. Much evidence has since accumulated to support this hypothesis.

Yet, beginning with the 1996 release of the *Hubble Deep Field* data, a new generation of astronomers has begun to study galaxy formation directly at high redshifts, often with remarkable success, but too often also making claims about elliptical formation that run afoul of the merger hypothesis and its strong supporting evidence in the local universe. For example, claims about (1) an "E formation epoch" ending around $z \approx 2$ and (2) constant comoving space densities of ellipticals since then abound, but are clearly mistaken.

Few astronomers would contest that disk–disk mergers are occurring locally ($z \approx 0$) and forming remnants remarkably similar to young ellipticals. Evidence that some field Es contain intermediate-age stellar populations is also

increasingly being accepted. What remains controversial is how most older ellipticals formed, say the majority that formed during the first half of the Hubble time and now appear uniformly old, crammed as they are into a small, 0.3-dex logarithmic-age interval. Did they form by major disk mergers as well, or did they form by a process more akin to "monolithic collapse"?

First, the similarities between recent, $\lesssim 1$ Gyr-old merger remnants like NGC 3921 or NGC 7252 and giant Es (e.g., Toomre 1977; Schweizer 1982, 1996; Barnes 1998) are worth re-emphasizing. The above two remnants currently have luminosities of $\sim 2.8\, L_V^*$ and will still shine with $\sim 1.0\, L_V^*$ after $10-12$ Gyr of evolution. They feature $r^{1/4}$-type light distributions, power-law cores, $UBVI$ color gradients, and velocity dispersions typical of Es. Both also possess many young, metal-rich halo globular clusters. They show integrated "E+A" spectra indicative of $b \gtrsim 10\%$ starbursts (Fritze-von Alvensleben & Gerhardt 1994), as do many other similar young merger remnants in the local universe (Zabludoff et al. 1996). Hence, claiming that E formation ceased around $z \approx 2$ is as mistaken as would be any claim that star formation ceased then. Local starbursts and merger remnants tell a different story.

Second, although the age distribution of local E and S0 galaxies is clearly weighted toward old ages, it does show a tail of youngish galaxies, especially in the field, with luminosity-weighted mean population ages of $\sim 1.5-5$ Gyr (Gonzalez 1993; Trager et al. 2000; Kuntschner et al. 2002). Hence, in the field E+S0 formation has clearly not ceased yet.

Third and to astronomers' surprise, massive disk galaxies not unlike the Milky Way have been discovered at $1.4 \lesssim z \lesssim 3.0$ (Labbé et al. 2003) and thus *were available for major mergers at the epoch of peak QSO formation*. These galaxies seem to represent $\sim$half of all galaxies with $L_V \geq 3L_V^*$ at those redshifts. Complementing such IR–optical observations, Genzel et al. (2003) have found a large disk galaxy at $z = 2.8$ whose rapidly rotating CO disk indicates a dynamical mass of $\gtrsim 3 \times 10^{11}\, M_\odot$. Even more surprising is a massive *old* disk galaxy at $z = 2.48$ that shows a pure exponential disk ($\alpha \approx 1.7$ kpc) and no bulge, has a luminosity of $\sim 2L_V^*$, and has not formed stars for the past ~ 2 Gyr (Stockton et al. 2004). This galaxy indicates that massive Milky-Way-size disks were available for E formation through major mergers even at $z > 3$.

With this high-z availability of disks and the above evidence that disk mergers continue to form E-like remnants to the present epoch, it is instructive to revisit Toomre's (1977) argument that most ellipticals may be merger remnants. Figure 4 shows, to the left, his original sketch of the merger rate $\dot{N}(t)$ as a function of time t and, to the right, a modern version of it, in which I have plotted the rate and computed number of remnants vs. $(1 + z)$. From the ~ 10 ongoing disk–disk mergers among $\sim 4000+$ NGC galaxies and their mean age of ~ 0.5 Gyr, Toomre argued that there should be *at least* 250 remnants among these NGC galaxies, had the rate stayed constant, and more likely
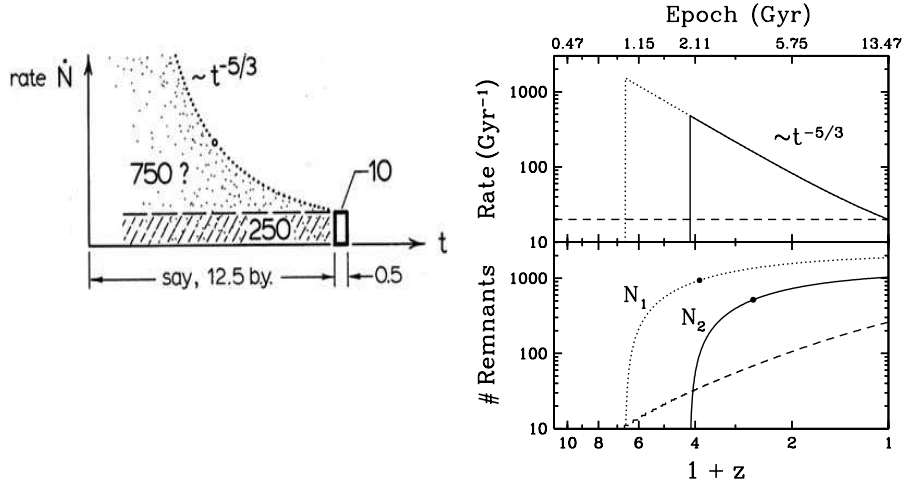
Figure 4. Merger rates and numbers of merger remnants as functions of cosmic epoch. (Left) Toomre's (1977) original sketch and (right) a modern version of it. For details, see text.

~750 remnants if the merger rate declined as $t^{-5/3}$ (assuming a flat distribution of binding energies for binary galaxies). The latter number being close to the number of Es in the catalog, he suggested that *most* such galaxies may be old merger remnants.

The top panel of the modern diagram shows the same rate, $\dot{N} \propto t^{-5/3}$, plotted vs. $(1+z)$ assuming that major disk merging began 1 Gyr (*dotted lines*) or 2 Gyr (*solid*) after the big bang, with the corresponding numbers of remnants labeled N_1 and N_2 in the bottom panel. Dashed lines mark the case of constant $\dot{N}(t)$ for comparison, and epochs for the standard λCDM cosmology are given at the top. Notice that major disk mergers beginning at 1 Gyr ($z \approx 5.6$) would produce more remnants than needed to explain all Es among present-day NGC galaxies, while such mergers beginning at 2 Gyr ($z = 3.15$) would produce just about the right number. Interestingly, half of the N_2 remnants would already have formed at $z = 1.64$ (*dot* on N_2 curve), which may explain why observers are having a hard time deciding whether the comoving space density of Es changes from $z \approx 1.5$ to 0 or not.

In summary, with massive disk galaxies already present at $z \gtrsim 3$, major disk mergers must have contributed to a growing population of elliptical galaxies ever since. Like star formation, E formation through major mergers is an ongoing process in which gaseous dissipation and starbursts play crucial roles.

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