Galaxy Wars: Stellar Populations and Star Formation in Interacting Galaxies
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Star Formation History in Merging Galaxies

Li-Hsin Chien

Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822

Abstract. Galaxy interactions are known to trigger starbursts. Young massive star clusters formed in interacting galaxies and mergers may become young globular clusters. The ages of these clusters can provide clues about the timing of interaction-triggered events, and thus provide an important way to reconstruct the star formation history of merging galaxies. Numerical simulations of galaxy mergers can implement different star formation rules. For instance, star formation dependent on gas density or triggered by shocks predicts significantly different star formation histories. To test the validity of these models, multi-object spectroscopy was used to map the ages of young star clusters throughout the bodies and tails of a series of galaxy mergers at different merger stages (Arp 256, NGC 7469, NGC 4676, Arp 299, IC 883, and NGC 2623). We found that the cumulative distribution of ages becomes shallower as the stage of merger advances. This result suggests a trend of cluster ages as a function of merger stage. In NGC 4676 we found that two clusters have ages of about 170 Myr, suggesting that they likely formed during its first passage. Their locations in the tidal tails are consistent with the spatial distribution of star formation predicted by shock-induced models. When comparing the ages and spatial distribution of clusters in NGC 7252 to our model, we found that some clusters are likely to form during the prompt starburst at first passage, as predicted by simulations with shock-induced star formation. These simulations show that the shock-induced mechanism is an important trigger of star formation and that using the ages of clusters formed in the starbursts can effectively determine the star formation history of merging galaxies.

1. Numerical Simulations of Galaxy Mergers With Star Formation

Galaxy collisions provide a natural laboratory for probing how star formation is affected by major rearrangements in the structure and kinematics of galactic disks. Many observational studies have been devoted to investigating these phenomena and helped to establish the link between galaxy interaction and induced star formation (e.g. Kennicutt 1998; Sanders & Mirabel 1996). However, the triggers of star formation in interacting galaxies are still not fully understood. Studies have suggested two mechanisms to describe the star formation enhancement— density-dependent (e.g. Schmidt 1959; Kennicutt 1998) and shock-induced (e.g. Jog & Solomon 1992; Scoville et al. 1986) star formation rules. Numerical models implementing these rules suggest that simple density-dependent rules cannot offer a complete description of star formation in merging galaxies (Mihos et al. 1993), and that the two rules predict significantly different star formation histories (Barnes 2004).

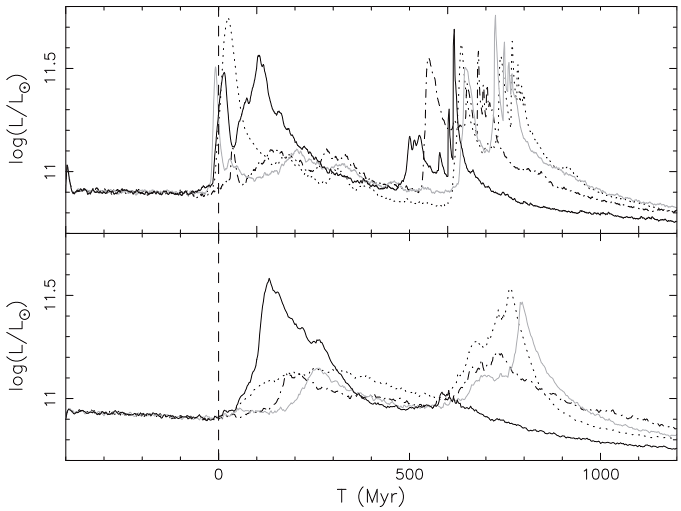

Figure 1. Bolometric luminosities as functions of time. Top: shock-induced and Bottom: density-dependent simulations. Different lines indicate galaxy pairs colliding with different geometries: Black dotted line as DIRECT encounter, light gray line as POLAR, black dash-dotted line as INCLINED and black solid line as RETROGRADE (see Barnes 2002). Vertical dashed line represents the first passage at $T = 0$.

Fig. 1 shows bolometric luminosities as functions of time for merger simulations using the two star formation rules and a sample of encounter geometries (Barnes 2002). Bolometric luminosity is a good tracer of the star formation rate (SFR) since it comes largely from young massive stars. Different encounter geometries yield different star formation histories, but the choice of star formation rules is clearly a more important factor. In shock-induced simulations (top), a global burst is triggered by large-scale shocks during the first passage at $T = 0$; later bursts of star formation, concentrated within the central regions, occur with the second passage and merger at $\sim 500 - 600$ Myr. In contrast, density-dependent models (bottom) generally predict a rather gradual increase within the central regions of the galaxies following the first passage; only the low-inclination passage (RETROGRADE) shows a starburst before the galaxies fall back together and merge.

2. Young Star Clusters In A Series of Merging Galaxies

Violent interactions often trigger starbursts which lead to the formation of young massive star clusters. These are likely to become young globular clusters (YGCs) if they are still gravitationally bound after ~ 40 Myr (Schweizer 1999). The ages of these YGCs can be interpreted to yield the timing of interaction-triggered events, providing a powerful way to reconstruct the star formation history of merging galaxies. Chien et al. (2007) obtained spectra of 12 young clusters in NGC 4676 using LRIS on Keck. These spectra yielded reliable approximations for cluster age and metallicity. Among the ages obtained, two are ~ 170 Myr,

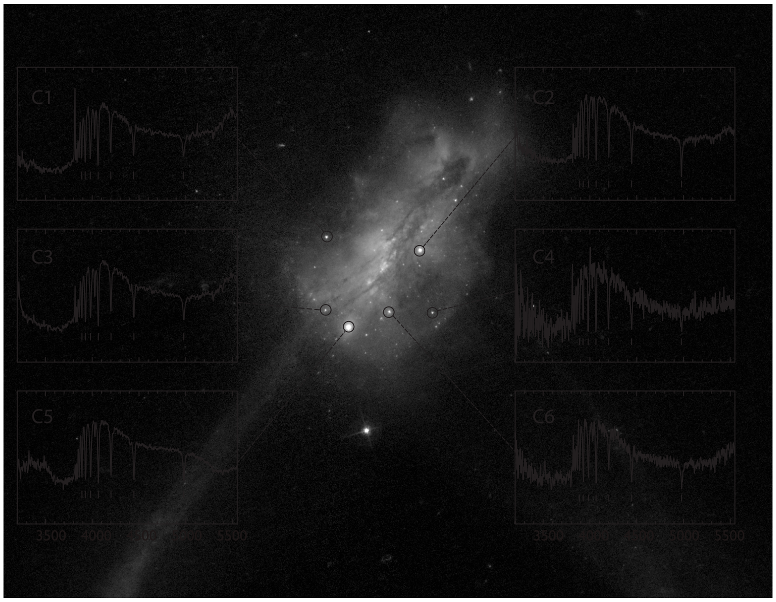

Figure 2. ACS/WFC F435W image of IC 883 and spectra of 6 young clusters obtained with LRIS on Keck. Spectra are plotted as relative flux vs. observed wavelength (Å). Markers in the spectra are the Balmer series.

which suggests that they likely formed during the first passage of NGC 4676 (Barnes 2004). These two objects are located in the tidal tails of the pair, which is consistent with the spatial distribution of star formation predicted by shock-induced models (Barnes 2004).

We have also obtained ages of clusters in a series of merging galaxies, ranging from early stages (Arp 256, NGC 7469) through merging (Arp 299) to fully merged (NGC 2623, IC 883) systems. For example, Fig. 2 shows spectra of 6 young clusters in the merged system IC 883. Based on our age results, we compare the age distribution of clusters in each galaxy (including NGC 4676) according to their stage of merger (Fig. 3). We found more than 70% of the observed clusters have ages less than 10 Myr in the first two mergers, Arp 256 and NGC 7469, indicating strong on-going star formation in these galaxies. The ages are distributed more evenly out to about 260 Myr in the last two merger remnants, IC 883 and NGC 2623, which may suggest that some of these clusters formed during the first or second passages. This result suggests a trend of cluster ages as a function of merger stage: the cumulative distribution of ages becomes shallower as the stage of merger advances. These age distributions provide a crucial way to discriminate between the alternate star formation histories predicted by the two rules described in Sec. 1. A detailed analysis of ages and metallicities of young star clusters in these galaxies is in preparation.

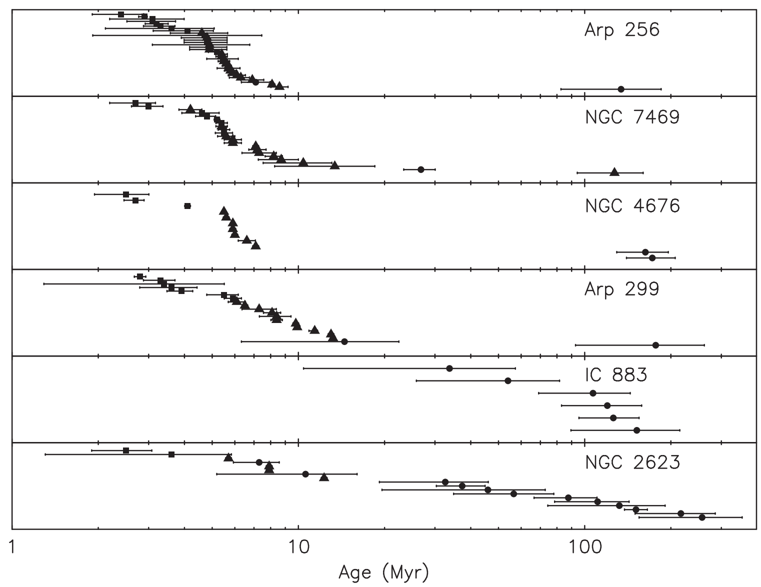

Figure 3. Observed cluster age distribution of each galaxy. For a given panel clusters are plotted according to their age, with the youngest aligned at the top and the oldest at the bottom. Solid squares represent clusters with their spectrum dominated by the Balmer emission lines; circles are those dominated by the Balmer absorption lines, and triangles are those that have composite Balmer features.

3. Combining Observations with Simulations

Using interactive software (Barnes & Hibbard 2009) to match dynamical models to the observed morphology and kinematics of mergers, we built new models of NGC 7252 with the two star formation rules described above (Chien & Barnes 2009). In our models, this proto-elliptical galaxy formed by the merger of two similar gas-rich disk galaxies which fell together ~ 620 Myr ago. Fig. 4 shows the spatial distribution of stellar particles of different ages using the two rules. Although on-going star formation occurs in the central regions in both simulations, the shock-induced simulation predicts that the products of past interaction-induced star formation are also dispersed around the remnant and along the tails.

In addition to comparing our simulations with the observed kinematics and morphologies, we performed a detailed analysis of cluster ages in NGC 7252 (Fig. 5). Schweizer & Seitzer (1998, hereafter SS98) found 6 young clusters which lie between $3 - 15$ kpc ($\sim 10 - 35''$) from the center of NGC 7252 and have ages of $\sim 400 - 600$ Myr, indicating that they formed early in the recent merger; the ages of these clusters are plotted in Fig. 5. From the top panel we see that the shock-induced simulation (gray) produces a prompt burst at first passage ~ 620 Myr ago while SFR rises more gradually in the density-dependent simulation (black) and peaks ~ 100 Myr later. Some of the cluster ages have a wide uncertainty; both of our simulations successfully reproduce the range of

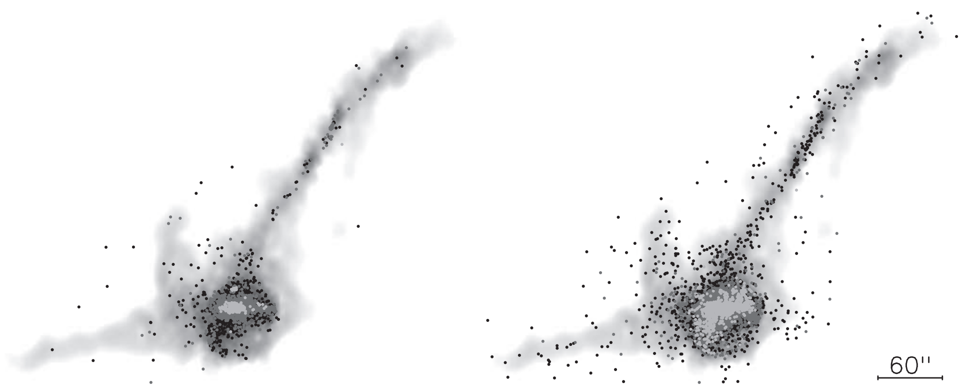

Figure 4. Best match of the simulations of NGC 7252 (Chien & Barnes 2009). Left: density-dependent and Right: shock-induced simulations. Old stellar particles are shown in grayscale. Light gray points are stellar particles with ages < 100 Myr, dark gray with $400 - 500$ Myr and black with $500 - 600$ Myr. The same number of points are displayed in both images.

cluster ages, although cluster S105 and W6, with ages of 580 and 600 Myr, are more consistent with the prompt starburst at first passage in the shock-induced simulation.

However the spatial distribution of the observed clusters strongly discriminates between our models. To compare with the locations of the SS98 clusters ($10'' < r < 35''$), the bottom panel of Fig. 5 shows the age distribution of star particles, located within this annulus, from our simulations. The density-dependent simulation (black) produces a gradually declining distribution of ages, with almost all interaction-induced star formation within the very central regions; for example the predicted SFR shows a broad peak around ~ 500 Myr ago but only a small portion of star particles within this annulus have such ages. In contrast, the histogram from the shock-induced simulation (gray) shows many more star particles in this annulus and a sharp peak around the first passage ~ 620 Myr, suggesting that star formation occurs in more dispersed regions away from the centers and that a high portion of star particles within this annulus formed during the starburst in the first passage. This result may explain the distribution of ages observed in SS98, which indicates that shocks can be an important trigger of formation of these clusters.

In summary, we show that besides the established role of density-dependent mechanism in enhancing the star formation rate in interacting galaxies, the shock-induced mechanism is another important trigger of star formation and that using the ages of clusters formed in the starbursts can effectively pin down the timing of interaction-triggered events and determine the star formation history of merging galaxies.

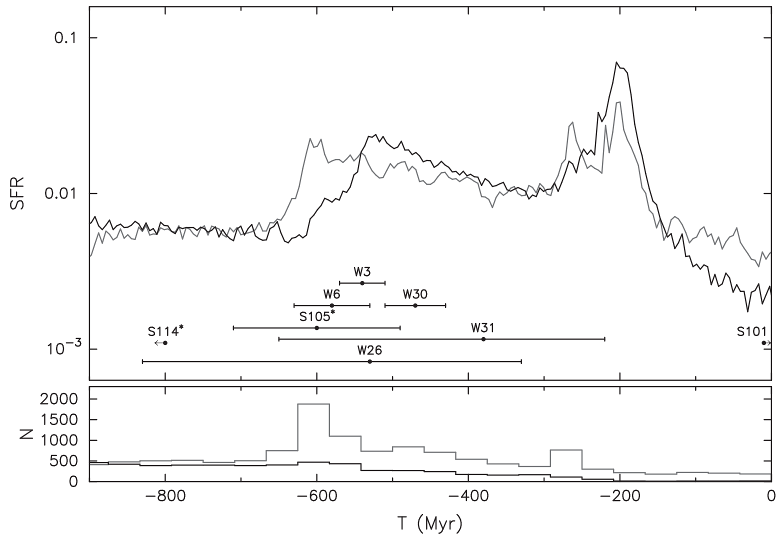

Figure 5. Comparison of age distribution of stellar populations. Top Panel: Global star formation history (in simulation units) of NGC 7252 shown from 900 Myr ago to present ($T = 0$). Black line represents density-dependent and gray shock-induced simulations. Cluster ages from Schweizer & Seitzer (1998) are plotted as dots with their uncertainties. Cluster S101 has an age upper limit of 10 Myr and cluster S114 has an age of $\sim$ 1 Gyr. Note that clusters S105 and S114 have possible ages of $\sim$ 200 and $\sim$ 40 Myr respectively. Bottom Panel: Histograms of number of stellar particles formed in the simulation, located within $10''$ to $35''$ from the center, measured at present time.

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