# Star Formation in Interacting Galaxies: A Tale of Compactness

Rafael Martínez-Galarza[(1)*], Christopher Hayward[(2)], Chao-Ling Hung[(1,3)], Laurenne Lanz[(4)], Georgios Magdis[(5)], Howard Smith[(1)], Dimitra Rigoupoulou[(5)], Lee Rosenthal[(1,6)], Aaron Weiner[(1)], Andreas Zezas[(1,7)]

(1) Harvard-Smithsonian CfA; (2) Heidelberg Institute für Theoretische Studien; (3) Institute for Astronomy, University of Hawaii; (4) IPAC, California Institute of Technology; (5) University of Oxford Department of Physics; (6) Haverford College; (7) University of Crete

* jmartine@cfa.harvard.edu

## Summary

A correlation has been found between the dust temperature in star-forming galaxies, their specific star formation rate (sSFR), and their distance from the so-called main sequence (MS) in the SFR-$M_*$ plane (e.g. Magnelli et al., 2014) . We combine hydrodynamical simulations, state-of-the-art radiative transfer models and UV to FIR observations of local interactions and z~0.3 ULIRGs to investigate this correlation in terms of the ISM physics. We show that the compactness of HII regions within these systems correlates with the sSFR of their host galaxies in both simulations and observations, providing some possible physical interpretations for the $T_{dust}$-sSFR correlation. Our results suggest that outliers of the MS have both a larger gas content and a significant difference in their compactness, which points to a different evolution of ISM pressure with time in starburst systems.

## Observations

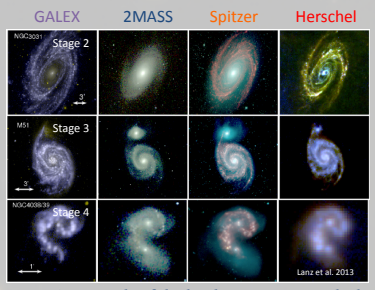



Fig. 1. An example of the local interactions studied, as seen at different wavelengths. Our sample of 31 local galaxies spans four orders of magnitude in dust luminosities and a broad range of interaction probabilities, from weakly (stage 1) to strongly (stage 4) interacting.

Besides the local interactions, we also analyze UV to FIR photometry for a group of luminous (>$10^{11}$ $L_\odot$) stage 4 interactions that we have morphologically selected from the Sloan Digital Sky Survey (SDSS) and Galaxy Zoo and cross checked with the revised IRAC Faint Source Catalogue, as well a small sample of intermediate redshift (z~0.3) Herschel selected ULIRGs from Magdis et al. 2014.

| Type | No. Objects | IR Luminosities |
|---|---|---|
| Local Interactions | 31 | < $10^{11}$ $L_\odot$ |
| Local LIRGs | 6 | > $10^{11}$ $L_\odot$ |
| z~0.3 ULIRGs | 9 | > $10^{12}$ $L_\odot$ |

## Simulations

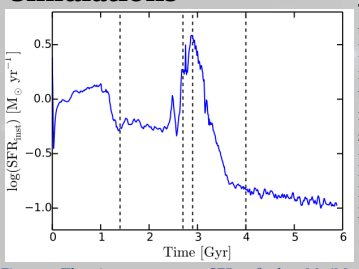



Fig. 2. The instantaneous SFR of the M2/M3 interaction simulation as a function of time. The SFR is enhanced during the first passage at around 1~Gyr and reaches an absolute maximum at coalescence, after about 3~Gyr. Vertical dashed lines indicate four different stages of the interaction.

The simulations are identical to those used in Lanz et al. 2014. A hydrodynamical code (GADGET-3) is combined with a radiative transfer code (SUNRISE) to obtain mock SEDs along the interaction sequence for a set of 4 isolated progenitor galaxies and all their possible paired interactions. The progenitor galaxies are similar to typical Sloan Digital Sky Survey (SDSS) galaxies.

| Progenitor | $M_*$ [$10^{10}$ $M_\odot$] | $M_{gas}$ [$10^{10}$ $M_\odot$] |
|---|---|---|
| M0 | 0.061 | 0.035 |
| M1 | 0.38 | 0.14 |
| M2 | 1.128 | 0.33 |
| M3 | 4.22 | 0.80 |

## Fitting

CHIBURST is a Monte Carlo routine to fit multi-wavelength SEDs of galaxies using a grid of self-consistent, time evolving MAPPINGSIII models (Groves et al. 2008). It computes the SED of a galaxy as a combination of: a starburst population of young (10 Myr) stars; two populations of intermediate age (100 Myr) and old (5 Gyr) field stars; and a population of very young (1 Myr) embedded massive stars. From the galaxy spectral and photometric data, CHIBURST calculates probability distribution functions (PDFs) for the following parameters: stellar mass ($M_*$); SFR over the last 10 million years ($SFR_{10}$); SFR between 10 Myr and 100 Myr ($SFR_{100}$); SFR over the last million years ($SFR_1$); fraction of total luminosity produced in PDRs ($f_{PDR}$); compactness parameter ($\mathcal{C}$); ISM ambient pressure ($P_o/k$), metallicity (Z) and visual extinction ($A_V$).

## Fits to simulated interactions

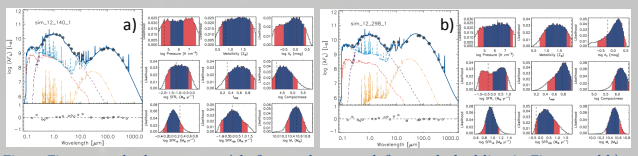
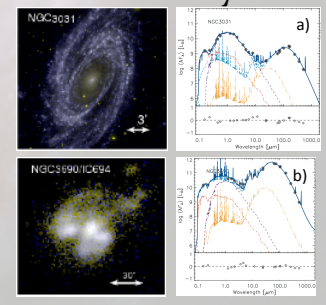



Fig. 3. Fits to mock photometry: a) before coalescence, leftmost dashed line in Fig. 2 and b) at coalescence, third dashed line in Fig. 2, for the interaction M2/M3. Shown are the mock photometry (black diamonds), best fit model (solid blue), and contributions from SFR10 (light blue), SFR100 (red) $M_*$ (purple) and SFR1 (yellow), as well as the PDFs in the panels to the right.

The relative contribution of FIR (8-1000 μm) emission to the total (0.1-1000 μm) luminosity tends to increase with the combined mass of the interacting galaxies, an indication that more massive interactions have larger sSFRs near the coalescence phase. This is however not always the case. In fact, our results show that the largest fractional FIR luminosities happen preferentially in interacting pairs where both galaxies have equal masses. There is also a trend for the FIR bump to peak at shorter wavelengths (i.e. warmer dust temperatures) in those systems where the FIR emission is larger. The most remarkable change in the SEDs as the interactions evolve in time is the relative contribution of FIR emission (coming from the HII-PDR regions) to the bolometric luminosity of the system, which peaks during coalescence. The contribution of optical and NIR emission from the oldest field stars remains rather constant along the interaction, whereas the UV emission follows the FIR emission, although it significantly decreases in the relaxation phase after coalescence.

## Fits to observed systems




| Parameter | Value |
|---|---|
| log $\mathcal{C}$ | 4.1 - 4.7 |
| log SFR10 [$M_\odot$/yr] | -0.2 – 0.1 |
| log $M_*$ [$M_\odot$] | 10.4 – 10.7 |
| $f_{PDR}$ | 0.5-0.8 |

| Parameter | Value range |
|---|---|
| log $\mathcal{C}$ | 6.2 - 6.6 |
| log SFR10 [$M_\odot$/yr] | 2.1 – 2.3 |
| log $M_*$ [$M_\odot$] | 10.4 – 10.9 |
| $f_{PDR}$ | 0.7 – 1.0 |

Fig. 4. Examples of two local interactions in: a) stage 1 and b) stage 4, and their CHIBURST-derived parameters. Strong interactions have larger $\mathcal{C}$, sSFR, $f_{PDR}$, and smaller relative contributions from older stellar populations. By comparing the SEDs of unresolved observations with those of simulated systems, we can associate them with particular stages of the interaction. For example, if NGC 3690 was spatially unresolved, we could tell from its derived compactness that this is a system approaching coalescence.

## The sSFR-Compactness Correlation

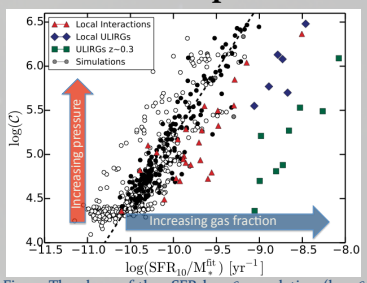



Fig. 5. The slope of the sSFR-log $\mathcal{C}$ correlation (log $\mathcal{C}$ = 1.5 × log sSFR + ε, dashed line) remains constant for all our galaxy samples, but its normalization ε changes from sample to sample. Fractional gas mass can only partially account for the shift of the correlation between populations. We propose that an offset in log $\mathcal{C}$ is also needed to explain the shift. Dots are simulations before (black) coalescence and after (white) coalescence.

The compactness parameter relates to the typical ISM pressure and cluster mass of the HII regions:

$$\log \mathcal{C} = \frac{3}{5}\log\left(\frac{M_{cl}}{M_\odot}\right) + \frac{2}{5}\log\left(\frac{P_0/k}{\mathrm{cm}^{-3}\ \mathrm{K}}\right)$$

Since the hydro simulations do not include feedback from the clusters ($M_{cl}$), the vertical offset in compactness in this correlation can be interpreted in terms of a change in the ISM ambient pressure ($P_o/k$).

Interestingly, the shift only occurs above certain sSFR, which posses the question of whether outliers of the main sequence (those in the so-called starburst mode) are high sSFR systems where $P_o/k$ evolves differently.

## References

Hayward et al. 2014, 2014arXiv1402.0006H
Lanz et al. 2013, ApJ 769, 90L
Lanz et al. 2014, ApJ 785, 39L
Magdis et al, 2014, submitted
Groves et al. 2008, ApJS 176, 438G

*This research was funded by the National Aeronautics and Space Administration Grants NNX14AJ61G and NNX10AD68G to the Smithsonian Astrophysical Observatory.*