The Evolution of Starburst Galaxies

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Abstract.
I review the properties of starburst galaxies in the nearby and distant universe to decipher their evolution as a distinct extragalactic class. The physical processes and environments of massive star-formation appear to be similar out to \( z \sim 4 \), although the modes of triggering are likely quite different, varied, and still evolving. This is argued with the use of a structural system that measures the physical conditions of galaxies. This system provides evidence that starbursts at high-\( z \) are triggered by merging, while nearby starbursts have a host of different triggering mechanisms, none of which, besides merging, are currently known to exist at \( z > 2 \).

1. Introduction

Starburst galaxies are in a fundamental phase of galaxy evolution that possibly all galaxies undergo, and where a large fraction of all stars are produced. Currently \( \sim 25\% \) of star-formation in the nearby universe is occurring in these galaxies [14]. The fraction of star-formation in starbursts at high redshift is almost certainly much greater [18]. The dominate physical processes for forming stars via a starburst are however still poorly understood. Since starbursts have a higher than average star-formation rate, and will exhaust their fuel of gas in less than a Hubble time, these events must be relatively short lived. There must be a method, either externally or internally, that during the evolution of a galaxy triggers the onset of massive amounts of star-formation.

It seems likely that mergers and interactions are primary triggering mechanisms, particularly at high-\( z \). Despite this, there is a lack of conclusive proof that mergers are occurring at \( z > 1 \). In this paper, I present evidence that major mergers are occurring in a significant fraction of all known distant galaxies, triggering the onset of star-formation. At low-\( z \) the situation is more complicated, with higher order dynamical effects triggering starbursts, such as bar instabilities and stochastic star-formation in spiral density waves.

2. Local Starbursts

Our current understanding of starbursts, and to some extent our understanding of high-\( z \) galaxies, is derived from studying starbursts in the local universe. The term starbursts was first coined by Weedman et al. [30] based on the very blue nuclear colors of NGC 7144. Usually the term refers to galaxies bright in the
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Figure 1. Nearby UV-bright starbursts, showing the large diversity of apparent structures.

UV, although in this paper, a starburst is any galaxy where star-formation is higher than average, with $M_{\text{gas}}/\dot{M}_{\text{SF}} < H_0^{-1}$.

Today we recognize several classes of nearby starburst galaxies, that I will divide into UV-bright and dim starbursts. The classical starbursts, the UV-bright ones, have structures, morphologies and SEDs that are dominated by OB stars. Dust extinction is occurring in these systems, but in a patchy or ‘picket-fence’ distribution [5,10]. The other major starburst class are those dominated by dust, and therefore do not emit much light in the UV. These galaxies, the (Ultra)Luminous Infrared Galaxies, (U)LIRGs, are undergoing massive star-formation, although we cannot directly view much of the light originating from the young OB stars due to dust attenuation. These galaxies are re-emitting a large fraction of this absorbed light at far infrared wavelengths, with $L_{\text{FIR}} > 10^{12} L_\odot$ for the ULIRGs.

In this paper, I mainly discuss the properties of UV-bright starbursts seen in the nearby and distant universe. Figure 1 shows six examples of nearby UV-bright starburst galaxies. Anecdotally, these objects look quite different, and one might guess their starbursts were produced in different ways. Markarian 8, NGC 3690 and NGC 7673 are likely merging systems [9], while the remainder are triggered by various processes, including an interaction with NGC 5236 (NGC 5253), an old minor merger (NGC 3310) and perhaps a bar instability or stochastic star-formation (NGC 7678).

Many nearby starburst are not triggered by interactions or mergers. Studies of paired emission line galaxies reveals that the most luminous emission line starbursts are isolated [29]. This is not however the case for ULIRGs, where
nearly all with $L_{FIR} > 10^{12} L_\odot$ have morphological evidence of major mergers [24].

3. **High-\(z\) Starbursts**

It is now nearly certain that many galaxies currently observed at redshifts $z > 1$ are hosts to massive star-formation events. This has been demonstrated by their SEDs (e.g., [18,27,2]) and their structural similarities to low-\(z\) starbursts (e.g., [15,10]). The current paradigm is that UV-bright galaxies at high-\(z\) are analogs to nearby UV-bright starbursts, while galaxies detected in the rest-frame FIR, or observed sub-mm, are dusty galaxies analogous to ULIRGs [21]. Other evidence for the similarity between the gross physical processes in starbursts is the wide variety of dust extinctions for these objects at high and low-\(z\) [2]. High-\(z\) starbursts also have a higher than average star-formation rate compared to nearby starbursts [31]. We know more about high-\(z\) galaxies that are bright in their rest-frame UV than at any other wavelength due to the relative detection sensitivities at optical wavelengths. We have only begun to understand galaxies where star-formation can be viewed at radio [22] and sub-mm wavelengths [21].

UV-bright galaxies are also by far the most numerous high-\(z\) galaxy known [27]. The class of galaxies detected at 850 \(\mu\)m are, because of their high rest-frame FIR flux, potentially highly enshrouded by dust [6,21]. This is further suggested by the very faint UV counterparts to these galaxies [3]; a similar trend is found for nearby ULIRGs [28]. The high 850 \(\mu\)m background flux [13] reveals that there is possibly a large population of these dusty star-forming galaxies that is currently only 25\% resolved into individual objects [21].

One huge untapped advantage for studying high-\(z\) UV-bright starbursts is the ability to study galaxy populations based on structural appearances. The structures of these galaxies (e.g., Figure 2) reveal important information concerning their physical states. If the same quantifiable structural parameters are calibrated on nearby starbursts [9], quiescent galaxies [7,8], and models, they can reveal how distant galaxies were triggered [9]. The results of these preliminary studies show that many of these galaxies are mergers [11].

4. **Dust, Metallicity, and the IMF**

Dust and metallicity effects, and perhaps non-standard initial mass functions (IMFs), are largely responsible for the observational differences between galaxies undergoing massive amounts of star-formation. Dust is a major constituent of starbursts, and it is the dominate process for altering their observable structures and spectral energy distributions [5]. Metallicity can also change the observable properties of starburst galaxies, although current measurements indicate that high-\(z\) galaxies have metallicities similar to many local starbursts [e.g., 16]. These measurements are however difficult and remain uncertain even for the few galaxies studied.

Another question we would very much like to answer is what the IMF of starbursts galaxies are, and if it evolves with redshift, or environment. Derivations of the total masses and star-formation rates of starbursts rely on assumptions about the IMF having some form. If a starburst’s IMF is significantly different
Figure 2. The rest-frame UV and optical morphologies of UV-bright $2 < z < 3$ star-forming galaxies located in the Hubble Deep Field [12]. Reproduced with the kind permission of Mark Dickinson.
than the current canonical forms, derivations of most fundamental parameters are going to be wildly off. Unfortunately, there is no good way at present to directly measure mass functions, besides indirect methods. Preliminary observations indicated that the IMF of starbursts are possibly truncated at lower mass limits, and that high mass stars are overrepresented compared to solar neighborhood Scalo and Salpeter IMFs [e.g., 23], although see [5]. Until we have a better understanding of the dust, metallicity and IMF properties of starbursts, we will be unable to accurately understand the basic physical mechanisms driving star-formation in these galaxies.

5. Starburst Triggering

One fundamental aspect of starbursts that we can study is how they are triggered. Starburst galaxies obviously occur after the initial epoch of galaxy formation, since we see them in the nearby universe. Young stars in local starbursts are typically < 100 Myr old [5]. This observation tells us that galaxy evolution is still occurring, and that existing galaxies undergo physical processes that somehow produce massive star-formation. In the nearby universe, a starburst phase is perhaps an effect of evolution rather than a primary cause. Although, at high-z the starbursting process is likely a major galaxy formation mechanism [26]. Are methods of producing and triggering starbursts the same for nearby and high-z galaxies? By using the physical techniques developed in [7,8,9,4] I will argue that we can begin to answer this fundamental question.

The internal physical processes for producing star-formation are still not understood, and in starbursts the process is certainly non-linear. Increased gas cloud collisions induced by larger cloud cross-sections and higher velocities may account for these processes in interacting or merging systems, particularly in the outer parts of galaxies. Nuclear starbursts are easier to explain due to the localized nature of the star-formation in compact volumes. Barred galaxies
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Figure 4. The implied merger fraction of galaxies as a function of redshift. Based on a combination with the pair fraction data from Le Fèvre et al. [17] and Patton et al. [20], our asymmetry method gives a merger fraction evolution with redshift $f = 0.03(1 + z)^{2.1 \pm 0.5}$.

Also can form starbursts by funneling gas into their centers [19, 25]. In the nearby universe galaxies have evolved such that they contain these high-order bar and spiral structures, leading to a diversity of triggering mechanisms. These structures are however not generally observed at high-$z$ [1].

If we want to make direct evolutionary comparisons to high-$z$ galaxies, it is necessary to calibrate how various parameters correlate with modes of starburst triggering. A basic first step is to find a method to distinguish systems that are merging, since it is likely a major triggering mechanism. This is done by using the asymmetry parameter, a measure that indicates which galaxies are undergoing a major merger [8]. Mergers have asymmetry values $A > 0.35$ [9]. This can be seen in Figure 3a, a plot of the colors and asymmetries for the local starbursts in Figure 1, and a sample of quiescent nearby galaxies. The galaxies that are likely merging, based on comparisons to N-body simulations and internal dynamics [9], have asymmetries consistent with merging, while the non-mergers have asymmetries $A < 0.35$.

Applying this method to high-$z$ galaxies in the HDF, we obtain Figure 3b. This reveals an increased merger fraction at higher redshifts. We can compute the merger fraction evolution with redshift, using our criteria for identifying mergers. The fraction of major mergers increases with redshifts as $f \sim (1 + z)^{2.1 \pm 0.5}$ out to $z \sim 2$ (Figure 4). This indicates it is likely that a high fraction of the star-formation seen at high-$z$ is triggered by the merging of similar sized galaxies. However, only 40% of galaxies at $z > 2$ are consistent with mergers. The remaining starbursts are possibly produced by minor mergers, galaxy interactions, misidentified major mergers, or perhaps some other unknown triggering mechanism. It is unlikely that these galaxies are triggered by mechanisms related to spiral density waves or bars, since these features are not observed at these redshifts [1]. If these observations of the high-$z$ universe are accurate, and
if we are sampling a representative number of high-z objects, then the methods of triggering massive star-formation clearly have evolved.

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