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# Optical SED models of galaxy mergers

**Gregory F. Snyder[1], T. J. Cox[2], Christopher C. Hayward[1], Lars Hernquist[1] and Patrik Jonsson[1]**

[1]Harvard-Smithsonian Center for Astrophysics
60 Garden ST, Cambridge, MA 02138

[2]Carnegie Observatories, Pasadena, CA

email: gsnyder@cfa.harvard.edu

**Abstract.** I discuss recent work in which we construct models of poststarburst galaxies by combining fully three-dimensional hydrodynamic simulations of galaxy mergers with radiative transfer calculations of dust attenuation. The poststarburst signatures can occur shortly after a bright starburst phase in gas-rich mergers, and thus offer a unique opportunity to study the formation of bulges and the effects of feedback. Several additional applications of spatially-resolved spectroscopic models of interacting galaxies include multi-wavelength studies of AGN/starburst diagnostics, mock integral field unit data to interpret the evolution of ULIRGs, and the 'Green Valley'.

Optical spectra of simulated major gas-rich galaxy mergers can be found at
http://www.cfa.harvard.edu/~gsnyder

**Keywords.** galaxies: evolution, galaxies:interactions, galaxies: starbursts, methods:n-body simulations, radiative transfer

## 1. Introduction

Poststarburst (or 'K+A') galaxies are defined by recent but not ongoing star formation (Dressler & Gunn 1983). Detailed studies (Yang *et al.* 2008) of their properties suggest that many of them will evolve into typical ($\sim L^*$) elliptical galaxies, and thus present an opportunity to study the formation of bulges. The merger hypothesis has been proposed as a formation mechanism for poststarburst galaxies by Lavery & Henry (1988).

To evaluate this hypothesis, realistic physical models of K+A galaxies are essential for two reasons: 1) the merger or event rates inferred from wide-area surveys of K+A galaxies depend sensitively on the K+A duration timescales assumed for the underlying event population, and 2) the physical processes responsible for this bulge assembly and/or star formation quenching can be inferred directly from the model components.

In Snyder *et al.* (2011), we utilized hydrodynamic simulations of galaxy mergers coupled with radiative transfer calculations of dust attenuation to reconcile the merger rate inferred from K+A galaxies with that derived from other methods. Here I present a more in-depth look at a handful of these simulations, working toward a detailed observational representation of state-of-the-art galaxy simulations.

The starting point of this analysis is $\sim 40$ gas-rich merger simulations with a variety of initial conditions, from which we selected poststarburst galaxies based on moderate-resolution ($R \approx 1000$) optical spectroscopy, requiring strong Balmer absorption and weak [O II] emission (cf. Zabludoff *et al.* 1996). We generated these spectra with the Monte Carlo dust radiative transfer code Sunrise (Jonsson 2006; Jonsson *et al.* 2010), producing spatially-resolved spectra from multiple viewing angles. Herein I focus on 15 mergers of identical Milky Way-like disks discussed in Cox *et al.* (2006), that differ only in the initial

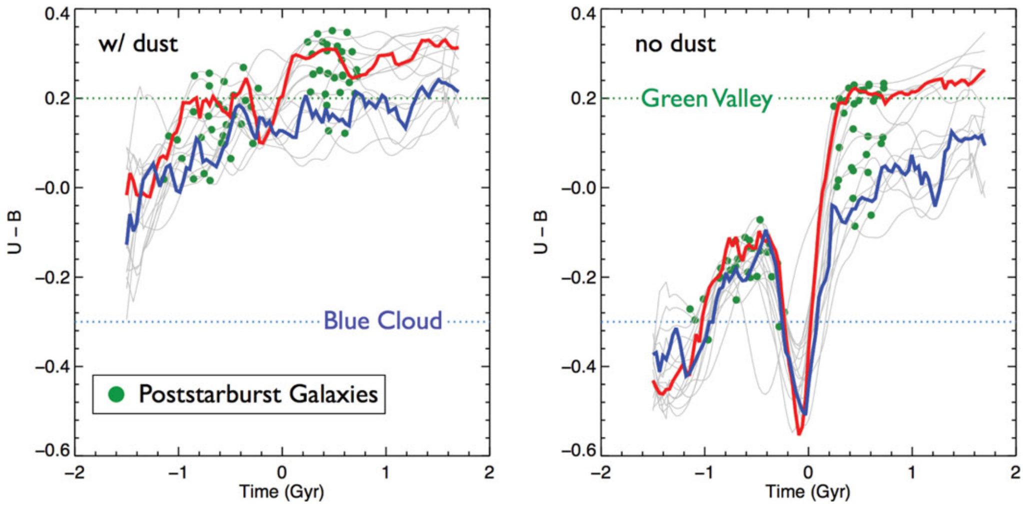


**Figure 1.** Time evolution of U-B colors of galaxy mergers. The dotted gray curves show the evolution of 15 major mergers of identical Milky Way-like disks. These mergers vary only in the initial relative orientation of the disk spin vectors. From Figure 8 of Snyder *et al.* (2011) we subdivide this set of mergers into two classes: "strong burst" (8) and "weak burst" (7), where the former are defined as likely forming a K+A galaxy for longer than 100 Myr occurring after the final merger ($t = 0$). The two solid curves show the median of each subclass, with the redder remnant forming from the "strong burst" class in both panels. Filled circles represent snapshots for which we identify the galaxy as a K+A from at least one of seven viewing angles. The left panel is our calculation of the colors including attenuation by dust, where for the right panel we have turned off attenuation by dust in the diffuse phase of the ISM, so that these colors reflect the *intrinsic* stellar populations. We find that K+As form redder remnants regardless of the presence of dust, but also that dust causes even the intrinsically bluest remnants to enter the 'Green Valley' of U-B color.

relative orientation of their angular momentum vectors. These simulations were run with a version of GADGET2 (Springel 2005) that includes a two-phase ISM/star-formation model Springel & Hernquist (2003) and thermal coupling of AGN feedback into the local ISM (Springel *et al.* 2005). Our goal is to determine what are the physical causes of K+A formation, and whether or not they are likely predecessors of red-and-dead galaxies.

## 2. Findings

We find a wide diversity of outcomes, which is not surprising given recent work showing that even major gas-rich mergers can result in a very disk-like remnant (e.g. Robertson *et al.* 2006; Hopkins *et al.* 2009b). Likewise, the merger of identical disks gives rise to a long-lived K+A galaxy only when the dynamics of the final merger lead to a short, intense starburst that is "complete" in the sense that the gas is either mostly consumed or expelled. We find that merger-induced K+A galaxies are indeed likely to evolve into redder remnants, as shown in Figure 1, whether or not dust is considered. Furthermore, the difference in their final colors arises almost exclusively to differences in the merger properties *during coalescence*, either strong AGN feedback and/or gas consumption, because at $t < 0$ (pre-merger), the intrinsic color evolution (right panel) of strong or weak K+A-inducing mergers are identical.

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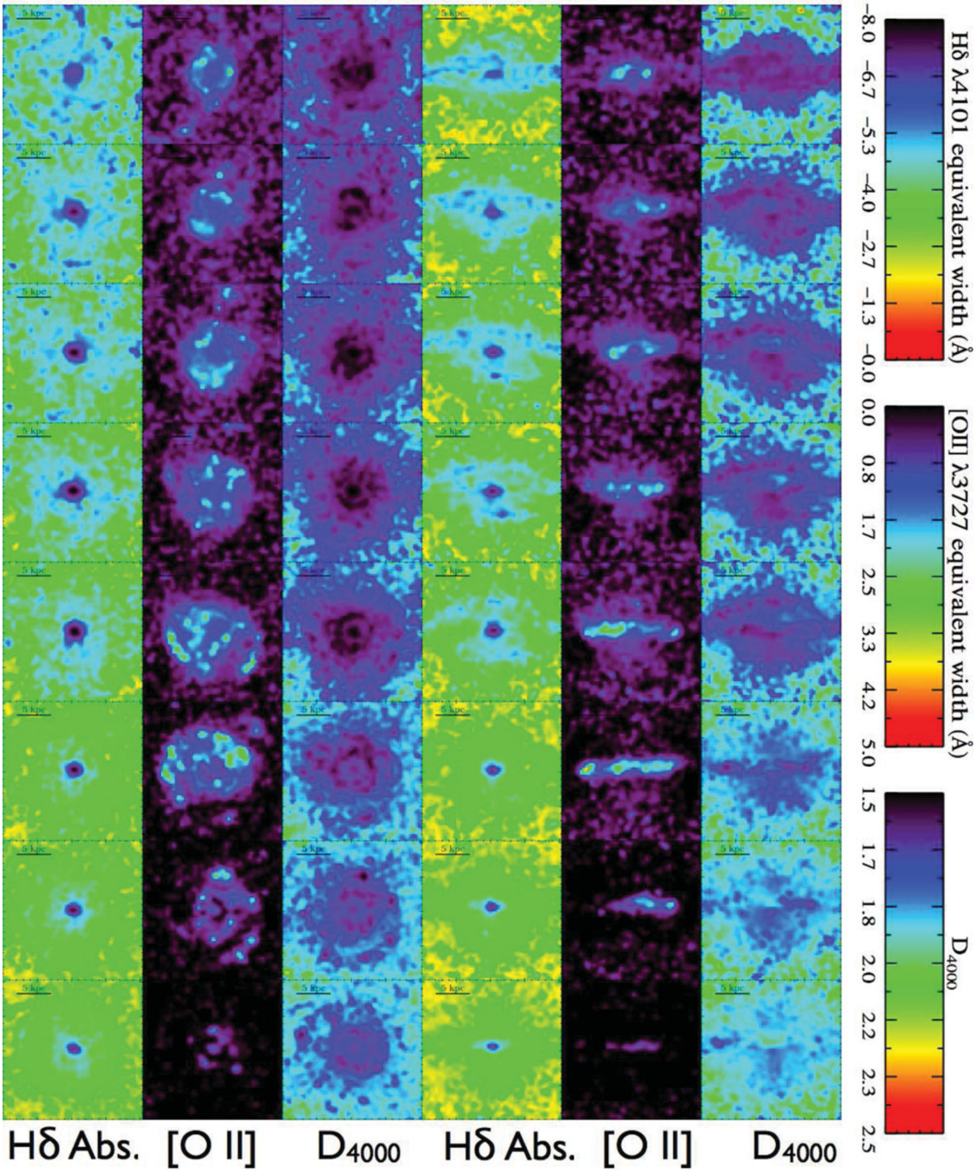


**Figure 2.** Time evolution of three resolved stellar population diagnostics after a simulated gas-rich major galaxy merger. We show two viewpoints: one from which a relic star-forming disk can be seen roughly face on (left three columns), and the other from which this disk is inclined (right three). The topmost row shows the remnant 100 Myr after the peak star formation rate of the starburst, and each subsequent row is 70 Myr later, ending 600 Myr post-merger. The burst relic is the clear peak in the Balmer absorption maps (as this is a K+A galaxy at these times). We see low levels of [O II] emission in an extended, rotating disk, comprised of star-forming gas that survived the merger (cf. Lotz *et al.* 2008). This demonstrates one way in which merger outcomes are diverse.

In some cases it is thought that the rapid quenching required to make a poststarburst galaxy is induced by heating from an accreting supermassive black hole, or "AGN feedback". However, Wild *et al.* (2009) found that the rapid truncation of star formation in merger-induced K+A galaxies does not require such feedback. Instead, the starbursts

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themselves consume most of the available cool gas, while subsequent AGN or starburst winds remove the small amount of gas and dust that happens to remain. We found that the Balmer absorption features may be strengthened by this "un-screening" process, because light from the young stars formed during the burst can become less attenuated.

This is a statement primarily about *local analogues*, and so significantly more massive and gas-rich progenitors may require powerful AGN or starburst winds to create the objects of e.g. Tremonti *et al.* (2007). Furthermore, modeling enhancements such as stellar gas recycling that allow simulations with more stable gas-rich progenitors and more realistic evolution of the gas reservoir throughout the merger, may be required to faithfully reproduce such observations. In either case, how can we determine the effect of starburst or AGN-powered outflows on the gas reservoir of galaxies? And what is the expected spatial structure of the gas, dust, and stars in recent merger remnants?

Recent observational work on the evolution of merger remnants has sought to leverage geometric information, such as the spatial extent of different stellar populations and their kinematics. Sunrise is naturally extensible to the spectro-imaging techniques required to perform these studies, and so we demonstrate this with spatial maps of three diagnostics in Figure 2, which follows a remnant for $\approx 600$ Myr or so after the merger. We clearly see the strong, spatially-concentrated central burst in the A-star tracer Balmer absorption, from either viewing angle. In addition, we see a surviving, star-forming disk. For simplicity, we have ignored dust attenuation; from the edge-on perspective only, this disk would obscure the central starburst relic almost completely (it would not necessarily be classified K+A) if dust were included.

## 3. Outlook

Here we have focused primarily on the optical regime of the SED. However, clearly much information can be learned by analyzing merger-induced evolution at all wavelengths. In addition, now that models including toy prescriptions of complicated physics such as feedback can be constructed and compared "apples-to-apples" with sophisticated observations, it may be possible to further constrain their parameter space.

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**Discussion**

Crocker: Do I understand correctly that the photons from the stellar population you model have no dynamical effect on the gas? If yes, is that a concern?

Snyder: Yes, and this is a concern. Ideally we would perform coupled hydro/radiative transfer simulations to understand the effect of stellar/AGN winds, but our current methods do not treat this.

Chakrabarti: How does the emission in the poststarbust phase depend on SFR prescriptions?

Snyder: We haven't yet looked into this - it will be interesting to see what a more realistic treatment with molecular gas and shocks will do to the story.

Moustakas: Did I understand correctly that you don't need AGN feedback to quench the star formation because of the inclusion of radiative transfer, and do you find any evidence of high-velocity fossil winds?

Snyder: The conclusion about AGN feedback doesn't depend on the radiative transfer, it is mostly about the fact that merger histories can give low-enough star formation without it (though the AGN does reduce it further). We do not look into winds since our simulations do not include kinetic feedback - that is definitely something to check.