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The Role of Mergers in Galaxy Evolution

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Abstract In the last decade the importance of mergers in the evolution of galaxies has become evident. In this paper we illustrate this importance by showing examples of merging galaxies, both local and at increasing redshift. However before getting carried away by the charms of the hierarchical model in which large galaxies have been built up by successive mergers of smaller objects, it is worth looking at what stellar population synthesis can tell us. Here I show that, using indices which allow us to separate the effects of metallicity and age on the spectra of the stellar populations of galaxies, we can show that the most massive galaxies have the oldest stellar populations, an effect which is enhanced within galaxy clusters and is maximized within the most massive clusters. These measurements imply that a model where mergers (even "dry" mergers) are the main driver for galaxy evolution cannot be giving us anything like a valid picture. The role of mergers must be considerably more subtle than one would infer from the standard semi-analytic models of galaxy evolution within a cosmological framework.

Key words: Galaxies – mergers – chemical diagnostics

1 MERGERS IN THE LOCAL UNIVERSE

There are striking well-known examples of galaxies merging which we can observe in detail in the local universe. Figure 1, an *HST* picture of the central zone of the Antennae (Whitmore et al. 2006), a very well known interacting pair, will illustrate many points relevant to how interactions work in galaxy evolution.

We can see in this composite image how the intense interaction is provoking spectacular bursts of star formation which show up as luminous knots in Hα. The image displays how the gas (whose distribution is mapped well by the dust) is compressed and twisted into lanes and fronts where star formation is stimulated. It is easy to see from examples of this kind that in gas rich galaxies mergers will give rise to major episodes of star formation which, after the merger is complete and a single large galaxy results, will show up as a younger stellar population superposed on the older underlying stars. A recent picture from Spitzer in Figure 2 (Elmegreen et al. 2006) shows, in the near IR, how the pre-merger interaction of gas rich galaxies gives rise to major star formation.

In Figure 3 (Read & Ponman 1998) we show a sequence of merging pairs designed to illustrate what cannot be directly observed, i.e. the sequence of interactive phases which finally lead to a complete merger.

There is no doubt that galaxies do merge and the main question to be addressed here is what is the importance of the merging process in the general scheme of the evolution of galaxies.

2 ARE MERGERS THE MAIN DRIVER OF GALAXY EVOLUTION?

It seems clear that as the universe was denser at earlier epochs, the probability of galaxy mergers should have been greater, so that the role of mergers in galaxy evolution should have been more important at increasing z. This is apparent in the semi-analytical form of Big Bang cosmology, in which modern large

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Fig. 1 Composite *HST* image of the merging "Antennae" galaxies; from BVRI and Hα band equivalent images (Whitmore et al. 2006)

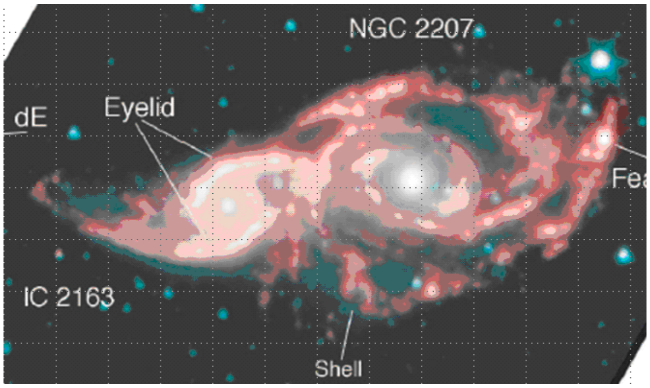


Fig. 2 Composite image of two interacting galaxies prior to their fusion. Data from Spitzer Space Telescope at 3.6, 4.5, 5.8 and 8.0 μm (shorter wavelengths presented as bluer).

galaxies are built up sequentially from smaller sub-units by sequences of mergers.(Navarro, Frenk & White 1995) As it is the dark halos of galaxies which dominate the gravitational masses of all these objects, the theory really deals with dark halos rather than with the baryonic components of the merging units, but in principle the theory ought to describe well the evolution of real galaxies. Figure 4 (adapted from Carretero 2007) gives schematically two alternative scenarios for the evolution of large galaxies, which have become known as the hierarchical and the monolithic scenarios.

3 HOW TO USE ABUNDANCE RATIOS TO PROBE HIERARCHICAL VERSUS MONOLITHIC GALAXY FORMATION

One of the most sensitive probes of whole galaxy evolution is to use chemical abundance ratios to test the rate of element formation in different environments and in particular to see how the rate of element formation depends on galaxy mass. Figure 5 (from Carretero 2007) illustrates this point. It shows schematically a

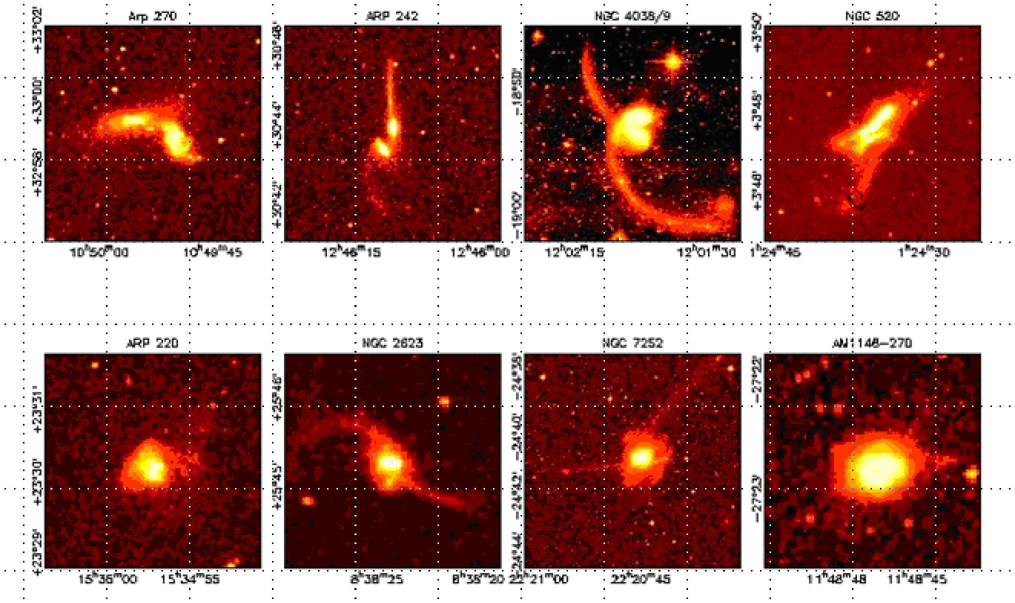
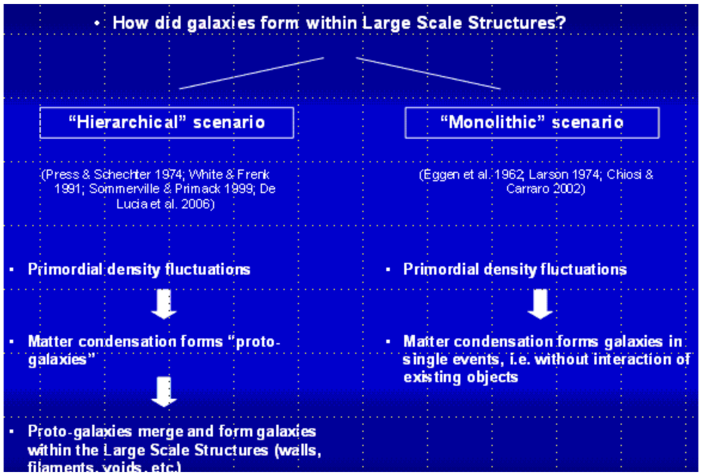


Fig. 3 Sequence of merging galaxies selected to show progressive stages in their fusion, and corroborated morphologically against model simulations.

plot of star formation rate (SFR) against time for a galaxy assumed to have the characteristics of ellipticals in which there is a rather early burst of star formation followed by a steady subsequent decline.

In the graph we show characteristic timescales for the formation of a set of elements whose abundances can be observationally determined. These timescales are determined by a combination of the nuclear processes involved and the mass scales of the stars in which these processes principally occur. A significant amount of physics and astrophysics goes into each of these estimates, but basically the controlling factor is whether the element is produced in supernovae of type II, which mark the death throes of massive stars, or in supernovae of type I, which are caused by accretion onto compact stars of much lower mass, or both. Mg is formed in type II SNe, which occur with high mass stars, and so have short timescales, Fe is produced in type I SNe on long timescales, and both C and N are produced in both, so that the resultant timescale for their production is intermediate. We have also, in Figure 5, superposed idealized plots of the star formation rate (SFR) for three hypothetical star forming sequences, a rapid sequence, and intermediate sequence and a slow sequence. From this figure we can see that it should be possible to use the measured abundances of these elements or their compounds to explore the formation timescales of the stars in galaxies and by implication of the galaxies themselves, under different physical conditions.

In Figure 6 we show the result of one detailed investigation of the rates of element formation in three clusters of galaxies. The observations are of three chemical components: Fe, the CN combination, and Mg, all ratioed against H, and these abundances measured in galaxies with a range of masses in each cluster. The velocity dispersion parameter, σ, is used as a proxy parameter for galaxy mass, with the larger values of σ corresponding to larger masses. We can see that although there is an overlap of masses, the three clusters span different ranges of galaxy mass, with the lowest masses in A115, intermediate masses in A655 and the highest masses in A963. As well as the element abundances, in Figure 5 we have plotted ages estimated from the same spectra (see Carretero et al. 2007 for details). There are immediate overall conclusions from the age estimates, which have implications for the possible importance of mergers in the production of these galaxies. Firstly there is a tendency, albeit not a strong tendency, for the stellar populations of the most massive galaxies to be older than those of the less massive galaxies. Secondly the absolute ages of all the galaxies, and especially the most massive ones, tend to be greater than 10 Gyr, with values ranging



- How did galaxies form within Large Scale Structures?

“Hierarchical” scenario

(Press & Schechter 1974; White & Frenk 1991; Sommerville & Primack 1999; De Lucia et al. 2006)

- Primordial density fluctuations
- Matter condensation forms “proto-galaxies”
- Proto-galaxies merge and form galaxies within the Large Scale Structures (walls, filaments, voids, etc.)

“Monolithic” scenario

(Eggen et al. 1962; Larson 1974; Chiosi & Carraro 2002)

- Primordial density fluctuations
- Matter condensation forms galaxies in single events, i.e. without interaction of existing objects

Fig. 4 Schematic flow charts showing how galaxies may have formed according to the two main proposed scenarios: the hierarchical and monolithic models. In the hierarchical scenario mergers dominate the evolutionary build-up of large galaxies, starting from the presence of primordial fluctuations in the local density of the universe. In the monolithic scenario the fluctuations give rise directly to large galaxies without the intermediate process of smaller galaxy formation followed by mergers. The cosmologists strongly favour the hierarchical scenario as it seems to come naturally and directly from their global models. However many specialists in stellar population analysis within galaxies are not at all convinced by this, and the main point of this article is to illustrate the basis of these doubts.

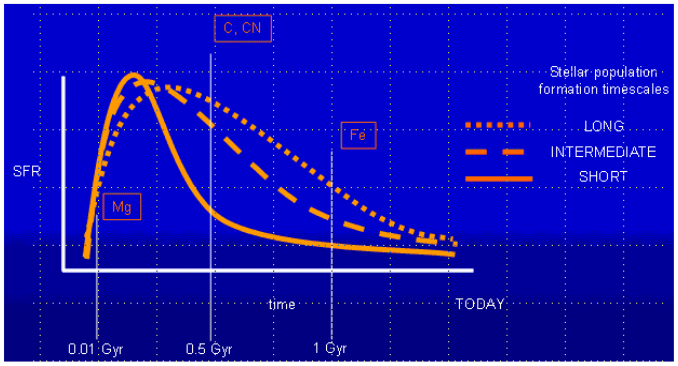


Fig. 5 Schematic plots of formation of specific observable elements and compounds as functions of time to show how observations of these can allow us to estimate the timescales of formation of the stellar populations in galaxies (from Carretero 2007).

up to 12 Gyr. These ages are high in any case, and cast doubt on the direct predictions of the standard semi-analytical models of galaxy formation in dark matter dominated cosmologies, but most surprising is that the massive galaxies appear to contain older stars than the less massive galaxies. This certainly does not, at first sight tally with models where mergers were the dominant route to galaxy growth, as in such scenarios the smaller galaxies should have formed earlier. In fact there are now a number of studies in the literature which show that smaller galaxies tend to have younger stellar populations than larger galaxies,

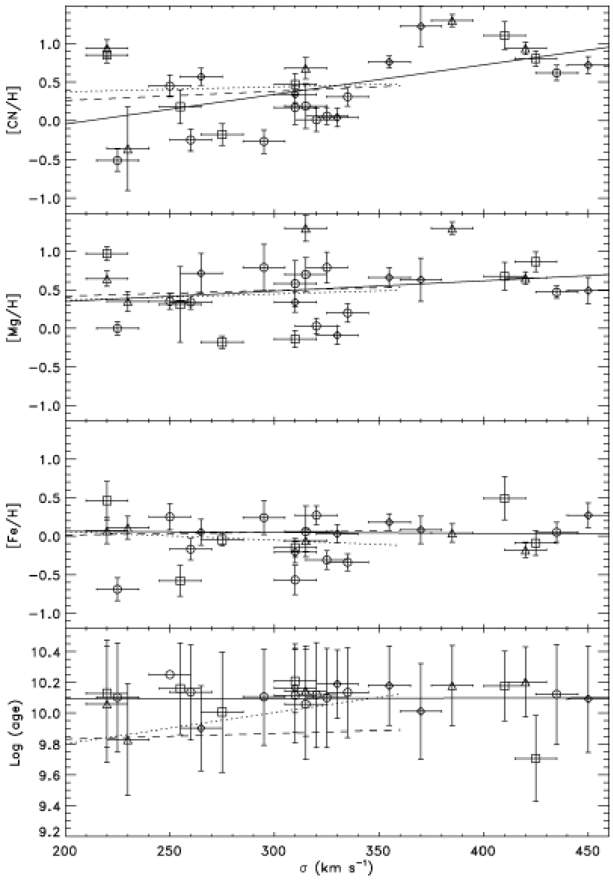


Fig. 6 The relative abundances [CN/H], [Mg/H], [Fe/H] and the mean luminosity-weighted ages plotted as functions of the stellar velocity dispersions for the galaxies in three clusters. Diamonds: galaxies in cluster A115, Open circles: galaxies in A655, Open squares: galaxies in A963, and open triangles (from Carretero et al. 2007).

suggesting that they have probably formed later, which has been dubbed "downsizing". An attempt has been made to support the hierarchical model by appealing to the phenomenon of "dry" mergers. A dry merger is one in which the stellar populations of both the merging galaxies are already in place when the merger occurs. Both galaxies have used up essentially all of their star forming gas before merging, so that there is no significant star formation induced by the merging process. The stellar population in the merged object has the age of the populations in the merging components, so the large galaxy produced gives a measured age which is greater, and possibly much greater, than the age given by the epoch of the merger. This process would indeed yield massive galaxies whose stellar population ages are those of the smaller objects from which they formed by merging. However the scenario has a basic flaw if it is used to explain why massive galaxies in general have older populations than smaller ones. For this to be the case those galaxies undergoing dry mergers would somehow have to be selected in such a way that massive galaxies formed from dry mergers and not from gassy star-forming mergers. There are ways in which this could be envisaged, which entail that in the densest regions even the least massive galaxies form more quickly and convert all their gas into stars more quickly, and are then ready for dry merging processes. However it is reasonable to assume that large galaxy formation process itself takes place more rapidly, including the transformation of gas to stars, in a dark matter halo with a deeper potential well, and more available baryons.

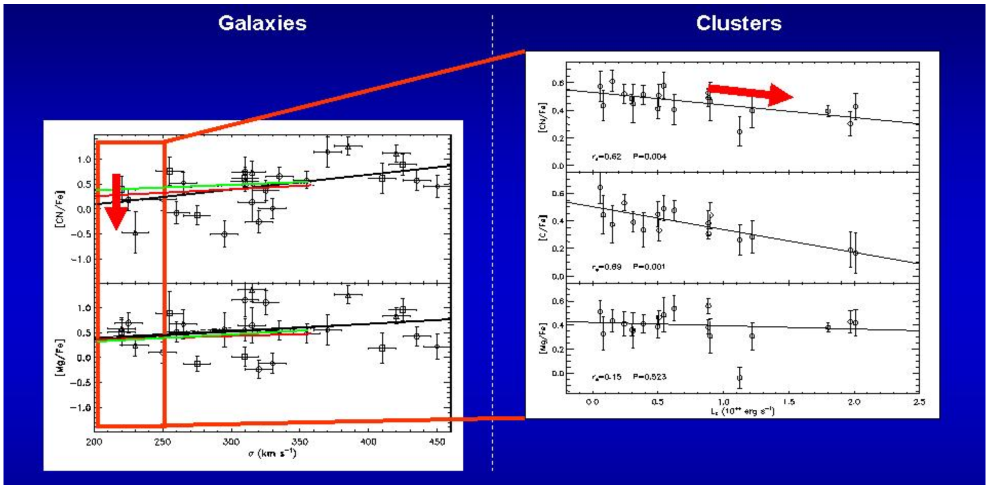


Fig. 7 (a) Left panel. Plots of [CN/Fe] and [Mg/Fe] against galaxy mass, represented by the velocity dispersion σ of the stellar population for selected galaxies in clusters of varying mass. (b) Right panel. Plots of [CN/Fe], [C/Fe], and [Mg/Fe] against cluster mass, represented by the X-ray luminosity Lx of the cluster (from Carretero, 2007). See text for discussion.

In other words, monolithic formation may dominate, at least for the largest galaxies. This does not mean that mergers do not play a role, but it is almost certainly less important than would be inferred from the direct use of semi-analytical cosmological models which include galaxy formation as one of their by-products. In other words, the standard model cosmologies are much better at predicting large scale phenomena than those associated with the formation and subsequent evolution of galaxies, a conclusion which should not be surprising, given the huge differences of scale involved.

4 HOW TO USE ABUNDANCE RATIOS TO PROBE THE EFFECTS OF CLUSTER MEMBERSHIP ON GALAXY EVOLUTION

As we are dealing with the use of abundance ratios to explore galaxy formation processes we will show an example of just what can be learned from an abundance diagram using two parameters which indicate the mass of the object observed. For the galaxies in the sample we use σ, the line of sight velocity dispersion of their stellar populations, as a measure of their masses. For clusters we can use the X-ray luminosity as an overall mass measure (REF). In Figure 7(a) (Carretero 2007) we first show plots of the [CN/Fe] and [Mg/Fe] ratios as functions of σ for a set of clusters, similar to the plot in Figure 6 but for a larger number of clusters.

However the use we will make of these data here relates to the properties of galaxy formation in clusters of different masses. For this purpose we have selected the galaxies in a restricted mass range, indicated by a range in σ between $200\,\mathrm{km\,s^{-1}}$ and $250\,\mathrm{km\,s^{-1}}$, and, in Figure 7(b)(Carretero 2007) we have plotted the abundance ratios against the masses of their parent clusters, as indicated by their X-ray luminosities, obtained from Ettori et al. (2002), Donahue et al. (2003) and Shimuzu et al. (2003). The results are clear and of interest. The ratio [CN/Fe] falls clearly with increasing cluster mass, (the [C/Fe] ratio falls similarly, as is shown, but the conclusions about galaxy evolution are similar for the two indices), while the [Mg/Fe] ratio remains constant, within the observational limits, and at a positive value, 0.4. The results for the CN and C indices show that galaxy formation, for the range of galaxy masses chosen, occurs more quickly in more massive clusters. Although the diagram does not go on to cover galaxies in higher mass ranges, we can quote the results here: this difference in formation timescale does not appear to apply to galaxies with higher masses, i.e. the effect decreases as the mass range goes above $\sigma = 300\,\mathrm{km\,s^{-1}}$ and can no longer be detected, at least using the CN or C abundance indices. We would need to find and use an index sensitive to formation timescales of a few hundred Myr in order to probe this situation further for the most massive galaxies, but all we can say here is that they form rather quickly even in the less massive clusters. This qualitative conclusion is refined when we consider the [Mg/Fe] index, in which the stellar populations of the ellipticals observed over the full range of cluster masses and the full range of galaxy masses are shown to have been formed on timescales of less than 1 Gyr, and in any case much more quickly than the predictions in the semi-analytical cosmological models, in which galaxies are assembled entirely via mergers between smaller units.

5 CONCLUSIONS

It is obvious from observation that galaxy mergers are common, even in the local universe, and that the frequency of mergers must have been higher at higher redshift. This undeniable phenomenon has been brought into focus in the context of cosmological models, particularly in the "semi-analytic" models which attempt to describe the early stages of galaxy formation and evolution in the context of the standard ΛCDM model cosmology. In these models galaxies form from the density fluctuations inherent as quantum fluctuations in the inflationary early universe. The dark matter halos first give rise to small small baryonic structures and when the halos combine by merging the resulting larger structures tend towards the galaxies we see today. In these models the smaller the galaxy the earlier it should have formed, and Milky Way sized galaxies should have taken several Gyr to evolve as the result of a series of mergers. The examples given in this article based on the use of element abundances to set the ages and relative formation rates of observed galaxies suggest strongly that this simple picture cannot be correct. The stars in large galaxies are on average older than those in smaller galaxies, and this is not obviously easy to explain in terms of merger driven evolution, although it could be possible with dry mergers. Furthermore, the ages of the stellar populations in large galaxies set their formation times at less than 1 Gyr from the Big Bang, in clear disagreement with the semi-analytic models for galaxy formation. It is clear that work needs to be done in order to bridge the gap between the large scale predictions of the standard models, which are supported by observation, and the predictions on the scale of individual galaxies, their formation and evolution. In particular the role of mergers as derived from these models is very probably exaggerated in importance as a driving element in the production of Milky Way sized galaxies in general.

References

Carretero C., 2007, PhD. Thesis, University of La Laguna, Spain
Carretero C., Vazdekis A., Beckman J. E., 2007, MNRAS, 375, 1025
Donahue M., Gaskin J., Patel S. K., Joy M., Clowe D., Hughes J. P., 2003, ApJ, 598, 190
Elmegreen D. M., Elmegreen B. G., Kaufman M. et al., 2006, ApJ, 642, 158
Ettori S., De Grandi S., Moendi S., 2002, A&A, 391 841
Navarro J. F., Frenk C. S., White S. D. M., 1995, MNRAS, 275, 56
Read A. M., Ponman T. J., 1998, MNRAS, 297, 143
Shimizu M., Kitayama T., Sasaki S., Suto Y., 2003, ApJ, 590, 197
Whitmore B. et al., 2006, Astronomy Picture of the Day, *http://antwrp.gsfc.nasa.gov/apod/ap061024.html*