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Major Mergers as Possible Drivers of the Galaxy Mass-Assembly in the Early Universe: New Insights from ALMA Observations †

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Abstract: Galaxies are thought to grow both through star formation or by interacting with each other. To understand which process dominates over the other, we investigated the contribution of major mergers to the galaxy mass-assembly across cosmic time. We made use of recent observations from the ALPINE survey to analyze the morphology and kinematic information provided by the [CII] 158 μm line observed in $z \sim 5$ star-forming galaxies. We found that 40% of galaxies at that epoch was undergoing a merging. By combining our results with studies at lower redshift, we computed the cosmic evolution of the merger fraction, estimating that major mergers could contribute up to 30% to the cosmic star-formation rate density at $z > 4$.

Keywords: Galaxies: evolution; Galaxies: formation; Galaxies: high-redshift; Early Universe

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1. Introduction

When the Universe was only $\sim$ 1 Gyr old, galaxies began to experience a rapid evolution with an increase of their size, stellar mass, and metal content, and by forming the first ordered structures that turned into the spiral, elliptical, or irregular sources we observe today. The growth of these galaxies can be explained through several processes, such as internal star formation or the refueling of new fresh gas that can be accreted both from the surrounding intergalactic medium or via major mergers (i.e., two or more interacting sources with a stellar mass ratio typically lower than 4). Although in-situ star formation and gas accretion seem to be the ruling path for galaxy assembly at lower redshift (e.g., [1]), evidence for an increasing role of mergers at earlier epochs has been found (e.g., [2,3]).

An estimate of the number of major mergers at different cosmic times is not trivial. On-going or post-mergers are typically characterized by morphological or kinematic disturbances, while galaxies that are going to interact between each other are seen as close pairs in the sky. However, these methods require respectively high resolutions and spectroscopic observations in order to provide a robust estimate of the merger fraction, which are mostly missing at very high redshifts. Moreover, rest-frame UV/optical surveys (usually explored to spot interacting galaxies at a given cosmic time) could be biased against very dust-obscured merging components, underestimating the real merger rate (e.g., [4]).

In this work, we exploit the data obtained by the ALMA Large Program to INvestigate [CII] at Early times (*ALPINE*; [5–7]) to compute the first statistically significant estimate of the merger fraction in a sample of *normal*[1] star-forming galaxies (SFGs) at the end of the Reionization epoch (i.e., at $z \sim 5$). ALPINE collected $\sim$ 70 hours of ALMA observations of

[1] **With the term *normal*, we refer to galaxies lying along the star-forming main-sequence of galaxies (e.g., [8–10]).**

the [CII] 158 μm line and the surrounding continuum in a sample of 118 primordial sources, previously selected in the rest-frame UV to be along the *main-sequence* (e.g., [10]) of SFGs at $4 < z < 6$, thus being representative of the average galaxy population at that epoch. Furthermore, all targets benefit from a wide multi-wavelength coverage and spectroscopic redshifts from previous observational campaigns, making ALPINE a golden sample for the study of the processes involved in the first stages of galaxy formation in the high-redshift Universe and, particularly, for the computation of the major merger fraction. Indeed, the rest-frame far-infrared [CII] line is poorly affected by dust extinction with respect to optical tracers, providing morphological and kinematic information of dust-obscured merger components that could be partially or completely missed by the UV/optical surveys.

This paper is structured as follows: in Section 2 we describe the data, methods and criteria used to estimate the merger fraction. The results and discussion on the merger fraction, its evolution with the cosmic time, and the merger contribution to the galaxy mass-assembly are reported in Section 3. Summary and conclusions are provided in Section 4. Throughout this work, we adopt a $\Lambda-$CDM cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2. Methods

The ALPINE survey took advantage of ALMA Band 7 (275–373 GHz) observations to detect the [CII] line at 158 μm rest-frame and the surrounding continuum emission from a sample of 118 star-forming galaxies at $4.4 < z < 4.6$ and $5.1 < z < 5.9$. The ALMA data cubes of the ALPINE targets were reduced and calibrated using the Common Astronomy Software Applications (CASA; [11]) pipeline. A line-search algorithm was applied to each continuum-subtracted cube resulting in 75 [CII] detections (with a signal-to-noise ratio $S/N > 3.5$) and 43 **non-detections**. At first, we performed a morphological and kinematic classification of the 75 [CII]-detected galaxies in ALPINE by examining their continuum-subtracted data cubes from the data release 1 [5]. For each target, we inspected the channel maps surrounding the emission line, the intensity and velocity maps, the integrated spectrum, the position-velocity diagrams (PVDs) produced along the major and minor axis of the velocity map, and the multi-wavelength ancillary data at the position of the source. Mergers are typically characterized by the presence of two or more components in the optical images and/or in the ALMA intensity maps and PVDs, as well as by complex behavior in the channel maps and multiple peaks in the [CII] spectra. Following these criteria, we found that 23 out of 75 ALPINE galaxies could be good major merger candidates, and we used them to obtain the first measurement of the merger fraction from [CII] observations at $z \sim 5$.

3. Results and Discussion

3.1. Major merger fraction

As we did not have estimates of the stellar mass for most of our individual merging components, we first defined major mergers candidates based on their K_s-band flux ratio (i.e., $1 < \mu_K < 4$), being the K_s band a good tracer of the stellar mass of galaxies up to high redshift. However, being the K_s-band ratio available for only 9 out of the 23 candidate mergers, we complemented this information with the [CII] flux ratio obtained from the spectral components of each system. We found a good agreement between the [CII] and K_s-band flux ratios for the objects having these two measures in common, with the 12% of this sub-sample having $\mu_K > 4$, suggesting a possible minor merger contamination. Therefore, we defined the major merger fractions in the two ALPINE redshift bins (at mean redshift $z \sim 4.5$ and 5.5, respectively) as:

$$f_{\mathrm{MM}} = 0.88\,\frac{\sum_{j=1}^{\mathrm{N_p}} w^j_{\mathrm{comp}}}{\mathrm{N_g}}, \tag{1}$$

where the factor 0.88 accounts for the uncertainty on the real merger nature (as discussed above), N_p represents the number of all the mergers in our sample, N_g is the number of ALPINE galaxies in the considered redshift bin, and $w^j_{\rm comp}$ is the weight associated to each merger to correct for incompleteness. More specifically, mergers whose major component is close to the threshold of the observable [CII] flux may have a secondary minor component that will be lost because of instrumental limitation. For this reason, we weight each minor component in our sample as follows:

$$w_{\rm comp}(L,z) = \frac{\int_{L_2}^{L_1} \Phi(L,z)\, dL}{\int_{L_{\rm lim}}^{L_1} \Phi(L,z)\, dL}, \tag{2}$$

where $\Phi(L,z)$ is the [CII] luminosity function derived from the UV-selected central ALPINE targets [12], $L_{\rm lim}$ is the luminosity corresponding to the limiting flux of each ALPINE pointing, L_1 is associated to the flux of the primary component $F_{1,[\rm CII]}$, and L_2 corresponds to $F_{2,[\rm CII]} = F_{1,[\rm CII]}/4$, as based on our definition of major merger (see [3] for more information).

We obtained $f_{\rm MM} = 0.44^{+0.11}_{-0.16}$ and $f_{\rm MM} = 0.34^{+0.10}_{-0.13}$, at $z \sim 4.5$ and $z \sim 5.5$, respectively. These results are shown in Figure 1, along with the major merger fractions computed from other works in the literature in samples of galaxies with stellar masses and merger selection criteria similar to ours. In particular, the grey points at $z > 4$ were obtained by [13] through morphological analysis and pair counts for a sample of optically-selected galaxies. Their data points are lower than our results, possibly highlighting an incompleteness of optical surveys due to missing dust-obscured merger components, which are instead bright in the FIR. We also combined data at $z < 4$ with our measurements at $z \sim 5$ to provide the cosmic evolution of the major merger fraction (excluding points by [13] as they do not differentiate between major and minor mergers), finding a rapid increase from $z = 0$ to $z \sim 2$, a peak at $z \sim 2 - 3$, and a possible slow decline for $z > 3$. A similar trend is also predicted by theory, as found by [14] from the Evolution and Assembly of Galaxies and their Environments (EAGLE) hydrodynamical simulation [15].

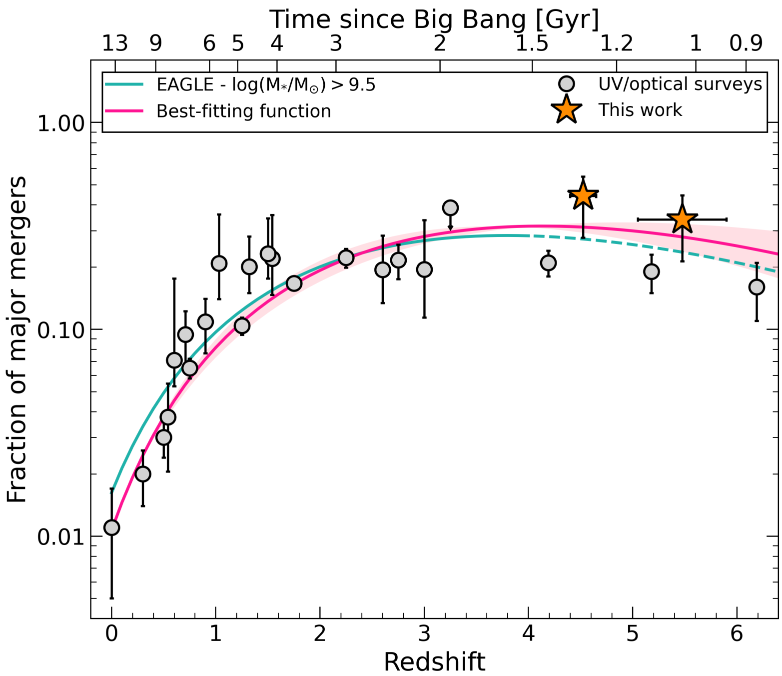

Figure 1. Cosmic evolution of the major merger fraction $f_{\rm MM}$ from the local to the early Universe. Grey circles show the data collected from the literature at different cosmic times through pair counts and/or morphological studies. Orange stars are the $f_{\rm MM}$ estimates from this work. The solid pink line and the shaded region are the best-fit to the data with a combined power-law and exponential function and the associated 1σ error, respectively. The solid blue line represents the redshift evolution (up to $z = 4$) of the major merger fraction from the EAGLE simulation. The dashed line is an extension of that curve to higher redshifts.

3.2. The contribution of major mergers to the galaxy mass-assembly

To quantify the importance of major mergers in the growth of galaxies, we computed the mass accreted via merging per unit time and volume across cosmic time, i.e., the mass accretion rate density $\rho_{\rm MM}(z)$. This quantity can be compared to the other mechanisms of mass accretion, such as the mass gained through the process of star formation, usually represented by the star-formation rate density (SFRD), and is thus of key importance for understanding the role of mergers in the Universe. By assuming that the increase in stellar mass for each merger and at each redshift is given by $\overline{M}_* \, \overline{\mu}^{-1}$, where $\overline{\mu}$ is the average mass ratio of our sample and $\overline{M}_*$ is the average stellar mass obtained by integrating the galaxy stellar-mass function, the mass accretion rate density can be defined as:

$$\rho_{\rm MM}(z) = \overline{\mu}^{-1} \, \overline{M}_* \, \Gamma_{\rm MM}(z). \tag{3}$$

Here, $\Gamma_{\rm MM}(z)$ is the merger rate density, which represents the number of mergers per galaxy and per unit time and volume. The latter depends on the merger timescale $T_{\rm MM}(z)$, the time after which a pair of two galaxies will merge into a single system. This represents the major source of uncertainty in the computation of $\rho_{\rm MM}$, and it is usually obtained through simulations (e.g., [16–18]). We report the cosmic evolution of $\rho_{\rm MM}$ in Figure 2 (on top). The solid lines show the best-fitting curves to the data assuming a combined power-law and exponential function for different merger timescales. To compare the relative contribution of mergers and star formation to the mass-assembly of galaxies through cosmic time, we also show the SFRD from [19], as well as the newest SFRD obtained with the ALPINE data [20] which indicate a possible $z > 4$ evolution of the SFRD that is shallower than previously thought. The bottom panel of the figure shows the ratio between the major merger and star formation contributions to the stellar mass accretion in galaxies at different epochs.

Depending on the assumed merger timescale, the contribution of major mergers to the SFRD at $z \sim 5$ varies from less than 5% (assuming [16]) to nearly 30% (assuming [18]).

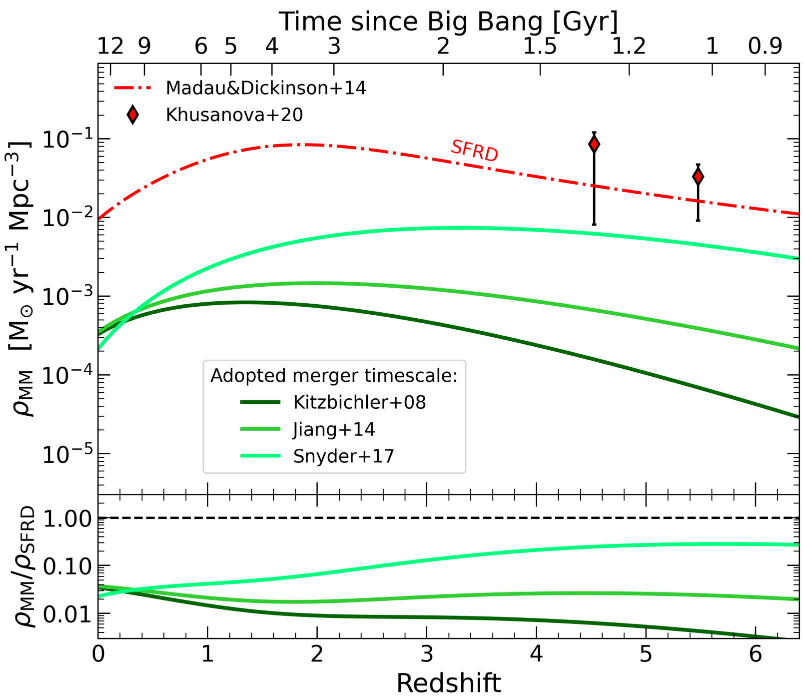

Figure 2. Stellar mass accretion rate density (ρ_{MM}) as a function of redshift (top panel). Solid lines represent the best-fits to the data assuming combined power-law and exponential functions. The colors correspond to different merger timescales. The dot-dashed red line shows the SFRD by [19]. The red diamonds are the total SFRD values obtained from the ALPINE survey [20]. The bottom panel reports the ratio between ρ_{MM} and the SFRD as a function of cosmic time. The dashed horizontal line marks a ratio equal to 1.

4. Conclusions

In this work, we explored the role of major mergers in the stellar mass-assembly of galaxies at $z \sim 5$ by taking advantage of [CII] observations from the ALPINE survey for a significant statistical sample of star-forming galaxies. In particular:

- We identified 23 mergers out of 75 [CII]-detected galaxies, corresponding to $\sim 31\%$ of the sample. By using Equation 1, we put the first constraint from [CII] observations on the fraction of major mergers shortly after the end of the Reionization epoch, which amounts to $f_{MM} = 0.44^{+0.11}_{-0.16}$ and $f_{MM} = 0.34^{+0.10}_{-0.13}$, at $z \sim 4.5$ and $z \sim 5.5$, respectively. By combining these measurements with previous works at lower redshifts, we obtained the cosmic evolution of the merger fraction which highlights a larger presence of interacting galaxies at early times than in the local Universe, as also predicted by simulations (see Figure 1).
- We estimated the stellar mass accretion rate density (ρ_{MM}) due to major mergers, comparing it with the SFRD cosmic evolution (see Figure 2). Depending on the choice of the merger timescale, we found that the contribution of major mergers to the global star-formation rate ranges between 5% to 30% at $z \sim 5$.

These results suggest that major mergers could have played a significant role in the galaxy mass-assembly during the first phases of galaxy formation. However, further investigation is needed in order to firmly establish the relevance of this mass-growth channel in the picture of the galaxy evolution. More sophisticated simulations will put better constraints on the merger timescale which represents by far the largest uncertainty on this kind of analysis. Furthermore, larger statistical samples and deeper resolution will allow us to identify different merger stages and confirm the large fraction of interacting galaxies at early times.

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