Highlights of Spanish Astrophysics VI, Proceedings of the IX Scientific Meeting of the Spanish Astronomical Society held on September 13 - 17, 2010, in Madrid, Spain. M. R. Zapatero Osorio et al. (eds.)

The VVDS-Deep Survey: the growth of bright galaxies by minor mergers since $z \sim 1$

C. López-Sanjuan[1], O. Le Fèvre[1], L. de Ravel[2], O. Cucciati[1], O. Ilbert[1], L. Tresse[1], S. Bardelli[3], M. Bolzonella[3], T. Contini[4], B. Garilli[5], L. Guzzo[6], D. Maccagni[5], H. J. McCracken[7,8], Y. Mellier[7,8], A. Pollo[9,10], D. Vergani[5], and E. Zucca[3]

[1] Laboratoire d'Astrophysique de Marseille, Pôle de l'Etoile Site de Château-Gombert 38, rue Frédéric Joliot-Curie, F-13388 Marseille, France
[2] Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK
[3] INAF-Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127, Bologna, Italy
[4] Laboratoire d'Astrophysique de Toulouse-Tarbes, Université de Toulouse, CNRS, 14 av. E. Belin, F-31400 France
[5] IASF-INAF, Via Bassini 15, I-20133, Milano, Italy
[6] INAF-Osservatorio Astronomico di Brera, Via Brera 28, I-20021, Milan, Italy
[7] Institut d'Astrophysique de Paris, UMR 7095, 98 bis Bvd Arago, F-75014, Paris, France
[8] Observatoire de Paris, LERMA, 61 Avenue de l'Observatoire, F-75014, Paris, France
[9] The Andrzej Soltan Institute for Nuclear Studies, ul. Hoza 69, 00-681 Warszawa, Poland
[10] Astronomical Observatory of the Jagiellonian University, ul Orla 171, PL-30-244, Kraków, Poland

Abstract

In this work we measure the merger fraction, $f_{\rm m}$, of $L_B \geq L_B^*$ galaxies in the VVDS-Deep spectroscopic Survey. We define kinematical close pairs as those galaxies with a separation in the sky plane $5h^{-1}$ kpc $< r_{\rm p} \leq 100h^{-1}$ kpc and a relative velocity $\Delta v \leq 500$ km s^{-1} in redshift space. We study $f_{\rm m}$ in two redshift intervals and for several values of μ, the B-band luminosity ratio of the galaxies in the pair, from 1/2 to 1/10. We take $\mu \geq 1/4$ and $1/10 \leq \mu < 1/4$ as major and minor mergers. The fraction of minor mergers for bright galaxies evolves with redshift as a power-law $(1+z)^m$ with index $m = -0.4 \pm 0.6$ for the merger fraction and $m = -0.8 \pm 0.9$ for the merger rate. We split our principal galaxies in red and blue by their rest-frame $NUV - r$ colour, finding that i) $f_{\rm m}$ is higher for red galaxies, ii) $f_{\rm m}^{\rm red}$ does not evolve with z, and iii) $f_{\rm m}^{\rm blue}$ evolves dramatically. Our results show that the mass of normal $L_B \geq L_B^*$ galaxies has grown $\sim 25\%$ since $z \sim 1$ because of minor and major mergers. The relative contribution of the mass growth by merging is $\sim 25\%$ due to minor mergers and $\sim 75\%$ due to major ones. The relative effect of merging is more important for red galaxies, with those subject to 0.6 minor and 0.7 major mergers since $z \sim 1$, which leads to a mass growth of $\sim 40\%$ and a size increase by a factor of 2. These results show that minor merging is a significant but not dominant mechanism driving the mass growth of galaxies in the last ~ 8 Gyr.

1 Introduction

Major mergers, the encounter of two galaxies of comparable masses leading to a fusion, have now been well documented in the nearby as well as in the distant universe. While the fraction of major mergers in the nearby Universe is about 2% [15, 2], it has now been convincingly shown that major mergers were more numerous at redshifts up to $z \sim 1$ [6, 3, 9, 10]. Major mergers have been shown to contribute a significant part, but not a dominant one, of the mass growth of galaxies above the characteristic luminosity L^*, with major mergers responsible for about 20% of the stellar mass growth [18, 3, 11].

As major mergers are apparently not the most important contributor to the mass growth since $z \sim 1$, other processes need to have taken place. Secular processes such as steady cold accretion [4] or other mass accretion processes like minor mergers must drive this transformation. In the present work we present the first measurement of the minor merger fraction and rate from kinematically confirmed close pairs. We are able to perform this study using the VVDS-Deep spectroscopic redshift survey which offers a unique combination of deep spectroscopy ($I_{\rm AB} \leq 24$), that enables the study of faint (i.e., minor) companions, and a wide area (0.5 deg^2), that contains enough bright galaxies for a statistically robust analysis.

2 VVDS-Deep sample and methodology

The VVDS-Deep sample [7] is magnitude selected with $17.5 \leq I_{\rm AB} \leq 24$. The spectroscopic survey has been conducted on the 0224-04 field with the VIMOS multi-slit spectrograph on the VLT, with 4h integrations using the LRRED grism at a spectral resolution $R \sim 230$. A total of 8359 galaxies with $0 < z_{\rm spec} \leq 1.2$ and $17.5 \leq I_{\rm AB} \leq 24$ (primary objects with flags = 1, 2, 3, 4, 9; and secondary objects, those that lie by chance in the slits, with flags = 21, 22, 23, 24, 29) from second epoch VVDS-Deep data [8] have been used in this work. We define kinematical close pairs as those galaxies with a separation in the sky plane $5h^{-1}$ kpc $< r_{\rm p} \leq 100h^{-1}$ kpc and a relative velocity $\Delta v \leq 500$ km s^{-1} in redshift space, and impose that the most luminous galaxy in the pair has $M_B \leq -20 - 1.1z$. Further details about how we dealt with selection effects and luminosity completeness are in [13].

3 The minor merger fraction of $L_B \geq L_B^*$ galaxies

In this section we study the merger fraction of bright galaxies as a function of μ, the B-band luminosity ratio of the galaxies in the pair, reaching the minor companion regime ($1/10 \leq \mu < 1/4$) with spectroscopically confirmed close pairs. We show the values of $f_{\rm m}\,(\geq \mu)$ obtained at $z_{\rm r,1} = [0.2, 0.65)$ and $z_{\rm r,2} = [0.65, 0.95)$ in Fig. 1. The observed dependence of $f_{\rm m}$ on μ is parametrized well as

$$f_{\rm m}\,(\geq \mu) = f_{\rm MM} \left(\frac{\mu}{\mu_{\rm MM}}\right)^s, \tag{1}$$

where $f_{\rm MM}$ is the major merger fraction ($\mu \geq \mu_{\rm MM} = 1/4$). This dependence was predicted by the cosmological simulations of [14] and used by [12] in mass-selected spectro-photometric close pairs. The error-weighted least-squared fit to the data yields $s = -0.64 \pm 0.13$ at $z = 0.8$ and $s = -1.11 \pm 0.19$ at $z = 0.5$.

We also study the merger fraction as a function of the blue or red colour of the principal galaxy in the pair. We define red, quiescent galaxies as those with $M_{\rm NUV} - M_r \geq 4.25$, and blue, star-forming galaxies as those with $M_{\rm NUV} - M_r < 4.25$. We find that i) the merger fraction of red galaxies ($f_{\rm m}^{\rm red}$) is higher than the merger fraction of blue galaxies ($f_{\rm m}^{\rm blue}$). ii) $f_{\rm m}^{\rm red}$ evolves little, if any, with cosmic time. We find that the power-law index is $s = -0.90 \pm 0.17$ in the range $0.2 \leq z < 0.95$. This implies that red galaxies have a similar number of minor and major companions, $f_{m/M}^{\rm red} = 1.28 \pm 0.35$. And iii) $f_{\rm m}^{\rm blue}$ is lower at $z = 0.5$ than at $z = 0.8$. The observed evolution is faster for higher values of μ, so we obtain different ($> 2\sigma$) values of power-law index: $s = -0.57 \pm 0.15$ at $z = 0.8$ and $s = -1.25 \pm 0.23$ at $z = 0.5$.

Using the merger time scales from [5], we compute the merger rate $R_{\rm m}$ (number of mergers per galaxy and Gyr, Fig. 1). We find that the minor merger rate ($1/4 \leq \mu \leq 1/10$) decreases with increasing redshift. That is, minor mergers become more numerous with cosmic time for $M_B^{\rm e} \leq -20$ galaxies. This trend is opposite to that for major mergers, which increase with redshift. This is the first quantitative measurement of the minor merger rate using close pair statistics at these redshifts. In addition, the total (major + minor, $\mu \geq 1/10$) merger rate is roughly constant with redshift, $R_{\rm m} = 0.103^{+0.013}_{-0.011}$ Gyr^{-1}.

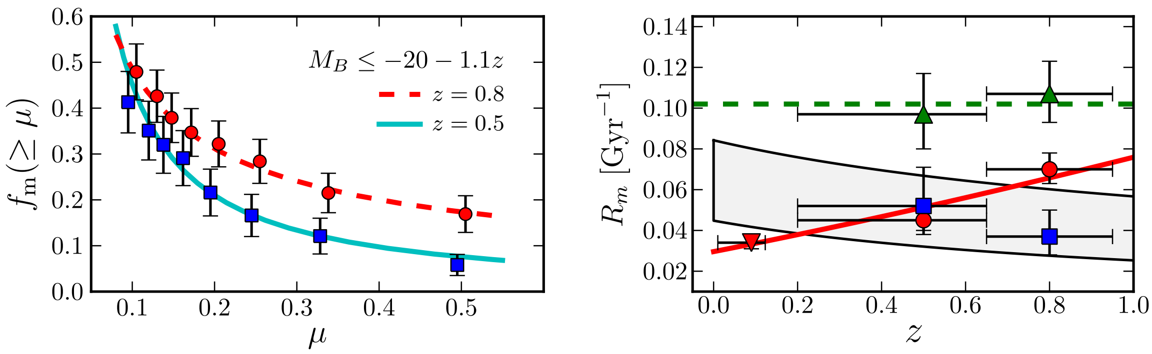

Figure 1: *Left panel*: merger fraction versus luminosity ratio in $B-$band, μ, for close pairs with $r_p^{\rm min} = 5h^{-1}$ kpc and $r_p^{\rm max} = 100h^{-1}$ kpc. Circles are the merger fractions at $z = 0.8$, and squares at $z = 0.5$. The lines are the error-weighted best fits of a power-law, $f_{\rm m}(\geq \mu) \propto \mu^s$, to the $z = 0.8$ ($s = -0.64$; dashed) and $z = 0.5$ data ($s = -1.11$; solid). *Right panel*: merger rate of $M_B^{\rm e} \leq -20$ galaxies versus redshift. Circles are the major merger rate ($\mu \geq 1/4$), squares are the minor merger rate ($1/10 \leq \mu < 1/4$), and green triangles are the total (major + minor, $\mu \geq 1/10$) merger rate. The inverted triangle is the major merger rate of $M_B^{\rm e} \leq -20$ galaxies from Millennium Galaxy Catalogue. The grey area marks the most probable minor merger rate values in the range $0 < z < 1$. The solid line is the least-squares fit of a power-law function to the major merger rate data. The dashed line is the major + minor merger rate if it is assumed constant.

The evolution of the merger rate with redshift up to $z \sim 1.5$ is parametrized well by a power-law function, $R_{\rm m}(z) = R_{\rm m,0}\,(1+z)^n$. The power law-index from the minor merger rate is $n = -0.8 \pm 0.9$, that is negative because the minor merger fraction decreases with redshift. We note that our results are compatible with a constant $f_{\rm mm}$ since $z = 1$ (i.e., $n = 0$). Even in that case, the minor merger fraction does not evolve in the same way that the major one, that increases with redshift with $n = 1.3 \pm 0.3$.

4 The role of minor mergers in the mass assembly of luminous galaxies

We can obtain the average number of mergers per galaxy between z_2 and $z_1 < z_2$ as

$$N_{\rm m} = \int_{z_1}^{z_2} R_{\rm m} \frac{{\rm d}z}{(1+z)H_0 E(z)}, \qquad (2)$$

where $E(z) = \sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}$ in a flat universe. The definitions of $N_{\rm MM}$ and $N_{\rm mm}$ are analogous. Using results from the previous section, we obtain $N_{\rm m} = 0.77 \pm 0.14$, with $N_{\rm MM} = 0.37 \pm 0.08$ and $N_{\rm mm} = 0.40 \pm 0.11$ from $z = 1$ to $z = 0$, indicating that the number of minor mergers per bright galaxy since $z = 1$ is similar to the number of major ones. We also estimate that mergers of companions with $\mu \geq 1/10$ increase the mass of bright galaxies since $z = 1$ by $23 \pm 6\%$. We further infer that the relative contribution of major and minor mergers to this mass assembly is 75% and 25%, respectively.

Applying Eq. (2) to $R^{\rm red}_{\rm mm}$ and $R^{\rm red}_{\rm MM}$, we obtain that the average number of mergers per red galaxy since $z = 1$ is $N^{\rm red}_{\rm m} = 1.3 \pm 0.3$, with $N^{\rm red}_{\rm MM} = 0.7 \pm 0.1$ and $N^{\rm red}_{\rm mm} = 0.6 \pm 0.2$. These values are higher than those from the global population, reflecting the higher merger rate of red galaxies. Weighting the number of mergers with their corresponding mean merger ratio, we find that mergers can increase $42 \pm 8\%$ the mass of red galaxies since $z = 1$. The relative contribution of major/minor mergers to this mass assembly is 80%/20%, indicating that the mass of red galaxies increases by $\sim 10\%$ since $z = 1$ due to minor mergers. If we assume that mergers increase the size of galaxies as $r_{\rm e} \propto M_\star^2$ [1], the mass increase of $\sim 40\%$ since $z \sim 1$ corresponds to a size increase by a factor of ~ 2, which is similar to the growth derived by size studies [16] Our results therefore suggest that un-equal mass mergers ($\mu < 1$) could be the dominant process in the size growth of massive galaxies since $z \sim 1$.

5 Summary and conclusions

We have estimated, for the first time in the literature, the minor merger fraction and rate of $L_B \geq L_B^*$ galaxies from kinematically confirmed close pairs, reaching the minor companion regime, $1/10 \leq \mu < 1/4$ ($\Delta M_B = 1.5 - 2.5$) thanks to the deep spectroscopy in VVDS-Deep ($I_{\rm AB} \leq 24$), and robust statistics in a wide 0.5 deg^2 area.

We find that minor mergers for bright galaxies evolves with redshift as a power-law $(1+z)^n$ with index $n = -0.8 \pm 0.9$ for the merger rate, in contrast with the increase in the major merger rate ($n = 1.3 \pm 0.3$) for the same galaxies. The dependence of the merger fraction on μ is described well by a power-law function, $f_m\,(\geq \mu) \propto \mu^s$. The value of s for the complete magnitude-limited sample, $M_B^{\rm e} \leq -20$, evolves from $s = -0.64 \pm 0.13$ at $z = 0.8$ to $s = -1.11 \pm 0.19$ at $z = 0.5$. When we split our bright galaxies in red and blue following the rest-colour bimodality, we find that in the redshift range explored i) $f_{\rm m}$ is higher for red galaxies, ii) $f^{\rm red}_{\rm m}$ does not evolve with z, with $s = -0.90 \pm 0.17$, and iii) $f^{\rm blue}_{\rm m}$ evolves dramatically: we infer that the major merger fraction decreases by a factor of three from $z \sim 0.8$ to $z \sim 0.5$, while the minor merger fraction is roughly constant.

Our results show that normal $L_B \geq L_B^*$ galaxies have undergone 0.4 minor and 0.4 major mergers since $z \sim 1$, which implies a total mass growth from major and minor mergers with $\mu \geq 1/10$ by about 25%. The relative contribution of the mass growth by merging is $\sim 25\%$ due to minor mergers with $1/10 \leq \mu < 1/4$ and $\sim$75% due to major mergers with $\mu \geq 1/4$. The relative effect of merging is more important for red than for blue galaxies, with red galaxies subject to 0.6 minor and 0.7 major mergers since $z \sim 1$. This leads to a mass growth of $\sim 40\%$ and a size increase by a factor of 2 of red galaxies, in agreement with the evolution of massive galaxies as reported by previous works [16, 17].

To expand on our observational results, the study of the minor merger fraction in other fields will be needed to minimize cosmic variance effect, on larger samples and in the local universe to better constrain the evolution of $R_{\rm mm}$ with redshift.

Acknowledgments

We dedicate this paper to the memory of our six IAC colleagues and friends who met with a fatal accident in Piedra de los Cochinos, Tenerife, in February 2007, with a special thanks to Maurizio Panniello, whose teachings of `python` were so important for this paper. C. L. S. acknowledge the organizers for an enriching meeting, and the funding support of ANR-07-BLAN-0228. Based on data obtained with the European Southern Observatory Very Large Telescope, Paranal, Chile, under Large Programs 070.A-9007 and 177.A-0837. Based on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This work is based in part on data products produced at TERAPIX and the Canadian Astronomy Data Centre as part of the Canada-France-Hawaii Telescope Legacy Survey, a collaborative project of NRC and CNRS.

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