The Formation of Intermediate-Mass Galaxies over the Last 8 Gyrs

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The physical processes driving the growth of galaxies can be robustly investigated all the way to $z = 1$, i.e. when the Universe was only about 40 % of its current age. The advantage of restricting ourselves to this redshift range is that the total stellar mass, extinction, star-formation rate, gas-phase metal abundance, and galaxy kinematics can be recovered with reasonable accuracy. Moreover, half of the stars in spirals were formed less than 8 Gyrs ago. More practically, as we shall show, the current generation of instruments at the ESO VLT allows us to study galaxies up to $z = 1$ at approximately the same level of detail as what has been done for nearby galaxies. Here we present the first results of the properties of galaxies out to this redshift based on a moderately large sample of $0.4 < z < 1$ galaxies using VLT/FORS, ISAAC and GIRAFFE. This study has allowed us to investigate the important physical processes that shaped galaxies including merging, gas accretion, and feedback from intense star formation.

Measuring stellar masses, star-formation rates and oxygen abundances: the importance of extinction

To investigate the physical processes shaping galaxies at 40 % of the age of the Universe, we have gathered a sample of 200 galaxies selected from the Canada France Redshift Survey ($I_{AB} < 22.5$, $0.4 < z < 1$). These galaxies have stellar masses ranging from 3×10^{10} to $3 \times 10^{11}\,M_\odot$, i.e., dominated by intermediate-mass galaxies. Almost all of them have been imaged by the Hubble Space Telescope and several have been observed using the combination of FORS2 and ISAAC in order to recover their physical characteristics and to compare them to local galaxies in the same mass range.

But before reviewing our findings, we believe it necessary to be precise in the definition of the words 'massive' and 'dwarfs' when these terms are applied to galaxies. The physical characteristics of local galaxies seem to suggest that massive galaxies have $M_{star} > 3 \times 10^{11}\,M_\odot$ (i.e., approximately the Milky Way and more massive), and that dwarfs are defined by $M_{star} < 3 \times 10^{10}\,M_\odot$. At this dividing point, the massive galaxies are dominated by older populations, high surface mass densities, and are dominated by the morphological type, E/S0. Spiral and irregular galaxies with lower surface densities and younger populations dominate the intermediate and dwarf mass regime respectively (Kauffman et al. 2003).

Studies of the 'star-formation history' of the Universe suggest that the star-formation rate density has declined significantly from $z \approx 1$ to the current epoch. Massive E/S0s and dwarfs are apparently not the main contributors to this decline, because the early-type galaxies were mostly in place at $z = 1$, and dwarf galaxies contribute marginally to the global stellar mass or metal content. Therefore to understand how galaxies grew, we focus, in the following, on the population of intermediate-mass galaxies. Intermediate-mass galaxies populate the 'knee' of the luminosity function and comprise at least 2/3 of the current stellar mass density (Brinchman and Ellis 2000; Heavens et al. 2004). Locally, according to the morphological classified luminosity function from the Sloan Survey (see Nakamura et al. 2004), 53 % of galaxies are early-type spirals (earlier than Sbc), 27 % are E/S0, 17 % are late-type spirals, and only few (3 %) are classified as irregulars.

The near-IR luminosity of galaxies seems to correlate well with their stellar masses. This is intriguing because most of the near-IR light is not coming from the main-sequence stars that make up most of the galaxy mass. One may justifiably suspect that mass estimates based on near-infrared photometry must have large uncertainties and whether this method can apply equally to starbursts and early-type evolved galaxies. Bell et al. (2003) have ingeniously circumvented these difficulties, by applying an empirical correction depending on the *B–V* colour of the galaxies (the bluer galaxies have lower stellar masses at a given *K* luminosity which is contaminated by red supergiant stars). Nevertheless the systematic uncertainty related to stellar-mass estimates could be as high as a factor of 2–3, by, for example, ignoring the effects or range of possible choices for the stellar initial mass function (IMF). Since dynamical mass estimates are sensitive to different systematic effects, only through the comparison of dynamical and photometric mass estimates can we overcome problems related to, e.g., the choice of plausible IMFs, the amount and distribution of the extinction, and our ignorance of the star-formation history of individual galaxies.

Estimates of star-formation rates (SFRs) for individual galaxies are usually believed to be very uncertain. A significant uncertainty is the IMF: most (all?) tracers used to estimate SFRs are proportional to the number of massive (e.g., IR) or very massive, ionising, stars (e.g., Hα). In a critical examination of the literature, Kennicutt (1998) has provided us with some useful tools to derive SFRs based on various indicators and all assuming the same IMF. Similarly, it is also important to be consistent when comparing SFR with stellar mass by using a common IMF. For observational reasons, UV continuum or [O II]λ3727 fluxes have been frequently used to estimate the SFR, since these wavelengths are redshifted into the visible window at moderate or high redshifts. Unfortunately, these estimates are strongly affected by dust, its distribution and amount, and thus underestimate the true SFR of individual galaxies by very large factors (see Figure 1). Indeed, actively star-forming galaxies, starbursts, especially the dust-enshrouded ones, the luminous infrared galaxies with bolometric luminosities about $10^{11}\,L_\odot$, LIRGs, are so numerous at $z > 0.4$, that the only viable tracers of the star-formation rate at those redshifts are only those which account for the light reprocessed by dust (IR), or those that can be properly corrected for extinction (e.g., Hα after using Hα/Hβ to estimate the extinction). For a given

IMF, mid-IR and extinction-corrected Hα fluxes can be used to estimate the SFR with an uncertainty < 0.3 dex (Flores et al. 2004).

The strong evolution of the number density of luminous IR galaxies means that extinction must be properly accounted for when estimating SFRs or metal abundances. A commonly used method to estimate the gas-phase metal abundance of a galaxy is R_{23} = ([O II]λ3727 + [O III] λ4959,5007) / Hβ. R_{23} is sensitive to the extinction through the ratio of [O II]λ3727 to Hβ. Further, one needs a sufficient spectral resolution (R > 1000) and signal-to-noise ratio (S/N > 10) to properly correct the underlying stellar absorption, especially for measurements of Hγ and Hβ lines. Another difficulty is due to the fact that, at z > 0.5, the Hα line is redshifted to the near-IR, and the Hα/Hβ ratio has to be estimated using two different instruments. A way to circumvent the difficulty (and the cost of near-IR spectroscopy), is to use the ratio Hγ/Hβ, although the Hγ line is often faint. The most exhaustive study has been made by Liang et al. (2006), by comparing the extinction from Hγ/Hβ to that from the ratio of IR to Hβ emission (Figure 2). The typical uncertainty in this case is 0.2–0.3 dex when oxygen abundance is derived from R_{23}.

The uncertainties in the estimates of stellar masses, SFR, and oxygen abundance for intermediate-redshift galaxies can appear very high, even if derived with great care. However, what we need is to compare the properties of intermediate-mass galaxies at high and low redshift. By adopting exactly the same method at both redshifts, it is very likely that the residual relative error is much smaller than a few tenths of a dex.

Measuring kinematics of z = 0.6 galaxies: the need for 3D spectroscopy

The Tully-Fisher (T-F) relation is an important correlation linking stellar mass to the maximal rotational velocity in disc galaxies. The evolution of this relation at intermediate redshift is currently a matter of intense debate (e.g., Conselice et al. 2005). Conselice et al. (2005) has obtained the first T-F relation in K-band up to z ~ 1.2, using slit spectroscopy at Keck. Compared to the local relation, the distant relation does not seem to have evolved in slope or zero point but shows a significantly larger scatter. In fact, the scatter is so large, that one can even wonder if the T-F is still a valid relation at all for intermediate-redshift spiral galaxies (see Figure 3).

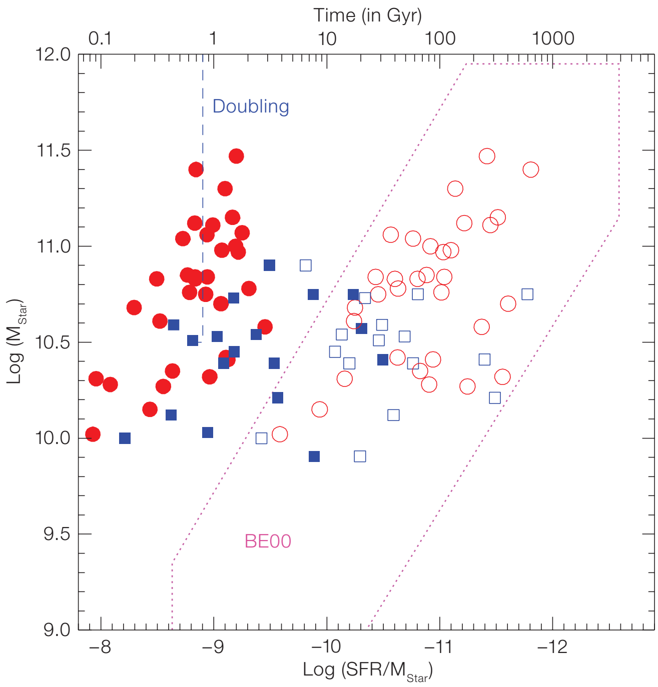


Figure 1: Stellar mass versus specific star-formation rate (red full dots: LIRGs, full blue squares: starbursts). The star-formation rates have been estimated from the IR luminosity or extinction-corrected Hα luminosity. Open symbols represent the same objects, but for which the SFR has been estimated using the [O II]λ3727 luminosity, not corrected for extinction by dust (see Brinchmann and Ellis 2000, BE2000). The difference in the star-formation rates illustrates the danger in making such estimates on the sole basis of UV line or continuum emission. The LIRGs observed at z > 0.4 can easily double their stellar masses if their star formation was sustained at the observed rate for ~ 800 Myrs. This figure is reproduced from Hammer et al. (2005).

We made use of the unique opportunity afforded by the 15 deployable integral field units of the 3D spectrograph GIRAFFE, as part of the FLAMES facility on UT2. With GIRAFFE, in its IFU mode, we are able to recover the kinematics of almost all the emission-line galaxies with I_{AB} < 22.5 (Flores et al. 2006). We obtained, during the GIRAFFE GTO, the kinematics of a sample of 32 galaxies (selected in the CFRS and Hubble Deep Field South) at z ~ 0.6 using the [O II] doublet. At first sight, the T-F relation obtained from GIRAFFE IFU data is very similar to the one obtained by Conselice et al. (2005).

We then constructed a classification scheme that took advantage of both maps of the kinematics of each galaxy (velocity field and velocity dispersion maps) and optical morphologies from high-resolution images taken with the HST. This classification scheme aims to identify rotating discs, relying on the fact that given the spatial resolution of the GIRAFFE IFU (0.52 arcsec $pixel^{-1}$), most of the velocity gradient of the rotation curve in rotating discs falls into only one IFU pixel. The measured dispersion within this pixel is then dominated by large-scale motions (i.e., the rotation) rather than by random motions at smaller scales resulting in a peak in their velocity dispersion map located at their dynamical centre of their large scale kinematics. Using such prescriptions, we find that only 34 % of galaxies in our sample are rotating discs; 22 % were classified as 'perturbed rotation' because a rotation is seen in their velocity field but the peak in their velocity dispersion map is off-centred and thus cannot be attributed to rotation; the remaining 44 % of galaxies have very complex dynamics with quite chaotic velocity fields, and are similar to what is expected for merging or strongly interacting galaxies. A few of the galaxies show a rotation-like pattern in their velocity fields with a dynamical axis significantly rotated from the optical main axis: complex kinematics like this are possibly a sign of strong feedback from the star formation within these galaxies. Translated into the whole intermediate-mass population (including E/S0 and spirals with low star-formation activity), we were led to the astonishing conclusion that only 60 % of these galaxies are in a relaxed dynamical state such as a rotating disc!

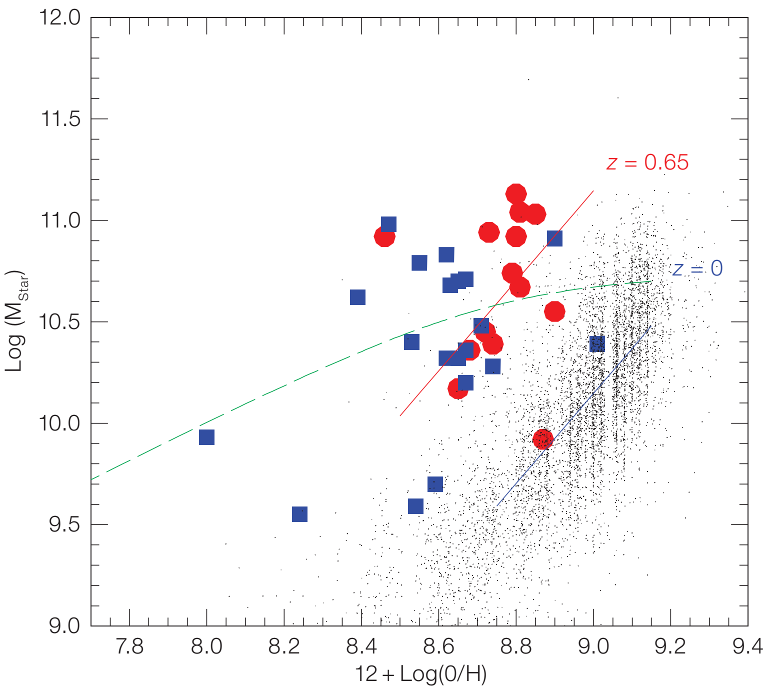
Given these results, a more critical examination of the GIRAFFE T-F relation (Figure 3) and its scatter is very instructive: most (all?) of the scatter of the T-F relation is related to galaxies whose kinematics were classified as perturbed rotations or complex, i.e., precisely those that likely have not yet reached dynamical equilibrium. This illustrates that only 3D spectroscopy can be used to study the evolution of the T-F relation, because slit spectroscopy does not sample the whole kinematics of the galaxies, and it is simply unable to correctly identify galaxies with complex, not yet relaxed dynamics. Keeping only those galaxies with securely identified rotating discs, the distant T-F relation becomes very similar to the local one, even with similar scatter.

Growth of spirals: secular or driven by mergers?

Intermediate mass galaxies in the local Universe are predominantly spirals (70 %) and E/S0 (27 %). They show small or negligible specific star-formation rates, the star-formation rate per unit stellar mass, SFR/M_{stars} (e.g., 10^{-11} yr^{-1} for the Milky Way) and very few are LIRGs (0.5 %). Local intermediate-mass galaxies form a well-defined mass-metallicity sequence with O/H abundance increasing with stellar mass. Six to seven billion year ago, intermediate-mass galaxies showed very different properties (Figures 1, 2 and 3). A significantly higher fraction of galaxies in this mass range are LIRGs (15 %), and, at their observed instantaneous star-formation rates, they can easily double their stellar mass within ~ 800 Myrs. On average their O/H abundances are half the local value at a given stellar mass. One fourth of them show complex kinematics implying that they are neither rotating discs nor ellipsoids supported by dispersion. This fraction is similar to that of galaxies with peculiar morphologies seen in deep HST surveys.

The integrated star formation related to the numerous LIRGs at $z < 1$ suffices by itself to account for the formation of about 40 % of the stellar mass in present-day intermediate-mass galaxies. The

Figure 2: Evolution of the mass-metallicity relation at $z = 0.6$ (red dots: LIRGs, blue points: starbursts; small black dots: local galaxies selected from the Sloan Digital Sky Survey). At $z = 0.65$, the gas phase metal abundance of oxygen is about half that of present-day galaxies. Assuming a 'close-box model' of chemical evolution, meaning that we do not account for in-falling or out-flowing gas, this increase in metallicity can be related to a decrease in the gas content of 30 % to 10 % from $z = 0.6$ to 0 (green dashed line). This figure is reproduced from Liang et al. (2006).



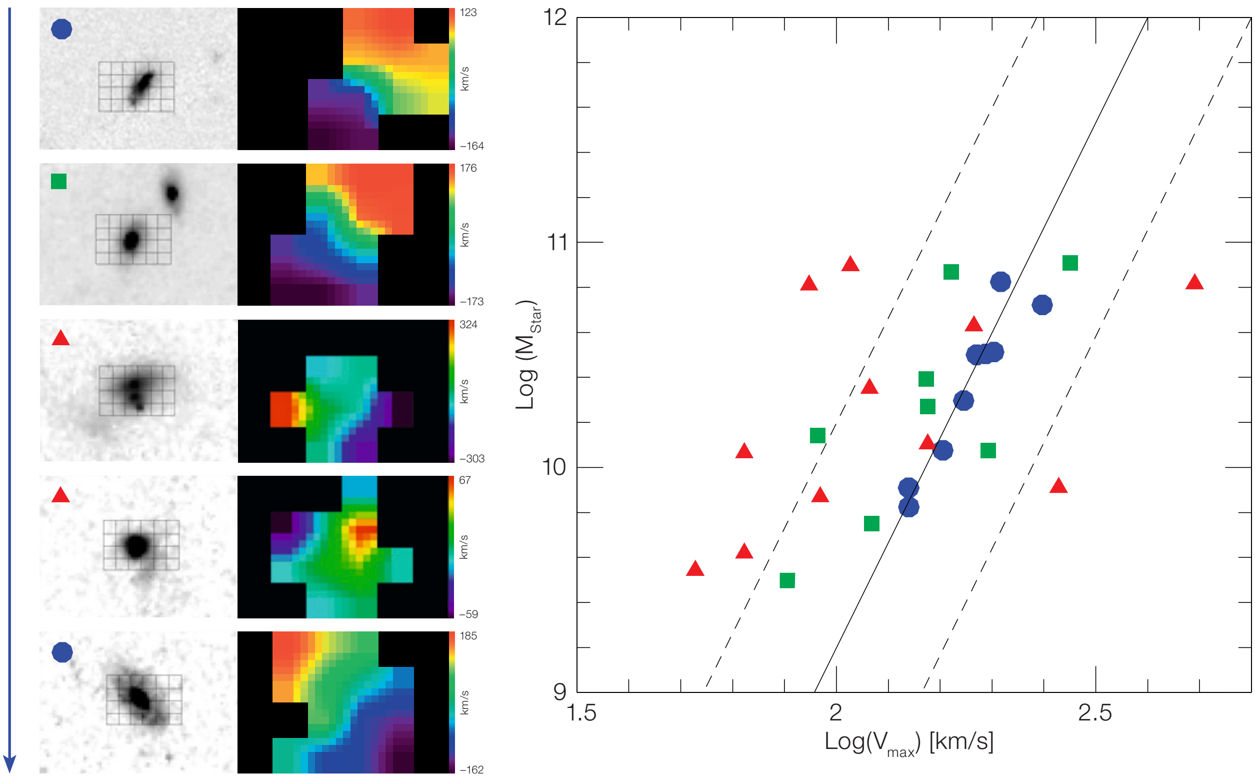
evolution of stellar mass since $z = 1$ independently confirms this. The luminous IR galaxies show a large variety of morphologies and kinematics, including those of rotating discs, mergers, compact galaxies or merger remnants. Which present-day galaxies have experienced such strong star-formation events less than eight billion years ago? Which galaxies in the local Universe had peculiar morphologies or complex kinematics several billion years ago? What physical mechanism is responsible for the strong decline in the star-formation density since $z = 1$? The complexity and the variety of the physical phenomena do not demand a unique scenario for every galaxy. Let us however investigate if one scenario is able to explain most of the observations (see Figure 3). One could be tempted to associate complex kinematics with an early collapse of what will become a normal centrifugally supported disc. This is, however, very unlikely since a significant fraction of stars in all $z = 0.5$–1 galaxies have ages larger than several billion years. So mechanisms which are related to galaxy environment or internal characteristics must be investigated.

Six to seven billion years ago, galaxies themselves and their environments were much more gas-rich than today. This is expected from both the star-formation history of the Universe and the metal abundance evolution of galaxies (Figure 2). Even if the gas density on large scales was twice what it is today, accretion of gas in the intergalactic medium gas cannot account for the high frequency of LIRGs. For example the Milky Way is located in a filament, is near a super-cluster, and forms stars at about 1 $M_\odot$ yr^{-1}. This is compared to more than 20 $M_\odot$ yr^{-1} for a LIRG. The complex kinematics and peculiar morphologies of a third of distant galaxies also belies such 'secular evolution'. Merging is broadly recognised both observationally and theoretically to be the most efficient way to produce intense and rapid star formation. Accretion of satellites is widely believed to explain most evolutionary features of galaxies and has strong support in the observations of the halo of the Milky Way and other nearby galaxies. It is unclear from modelling if the accretion of gas from the IGM and small satellites is enough to explain the high specific star-formation rates of LIRGs, and most models of this type indeed fail to explain the dramatic evolution in the number of strong infrared emitters. Moreover these models cannot explain the complex kinematics observed with GIRAFFE (Figure 3).

Major mergers, however, are extremely efficient at producing stars, at maintain-

Figure 3: (right) Tully-Fisher relation for 32 intermediate-mass galaxies at $z \sim 0.6$, as produced using data taken with the GIRAFFE IFUs (Flores et al. 2006). The full line represents the $z = 0$ Tully-Fisher relation (and the dotted lines its 3-sigma scatter). Blue dots represent rotating discs, green squares represent perturbed rotating discs (as by a minor merger or by a galaxy-galaxy interaction) and red triangles represent galaxies with complex kinematics (expected from major mergers). This is illustrated on the left by a few inserts which include HST images and velocity fields (increasing velocity from blue to red). These have been organised to follow a major merger event which can produce either an elliptical, an S0, or a new spiral (see text).

Major merger evolution



ing or even increasing the high values of specific angular momentum observed in local spiral galaxies, and at generating the complex kinematics and morphologies often observed in these galaxies. A scenario whereby major mergers destroy and rebuild discs, the so-called 'spiral rebuilding scenario', is indeed able to account for all the evolutionary trends discussed above (see Hammer et al. 2005). This is not however a proof of the validity of this idea: it is generally believed that the end product of a major merger is an ellipsoidal galaxy, not a disc galaxy. Only complex mechanisms related to strong feedback such as that associated with supermassive black holes would be enough to efficiently expel sufficient amounts of gas, a fraction of which with high angular momentum being available to collapse to form a new disc. It could be also argued that the spiral rebuilding scenario is not necessary. For example, one can imagine that all galaxies with complex kinematics (or peculiar morphologies) are progenitors of early-type galaxies, E/S0. However at $z \sim 0.6$ peculiar/complex galaxies are as numerous as E/S0, and early-type galaxies seem to be largely in place at $z \approx 1$, so it is difficult to believe that this hypothesis could be a realistic alternative.

We have presented here preliminary results showing the evolution of star-formation rate, specific star-formation rate, O/H gas-phase abundance, and circular velocity, all as a function of stellar mass. The fact that rotating discs defined a tight sequence relating their stellar mass and rotation velocity (Tully-Fisher relation) supports the robustness of our estimates based on the dynamics of galaxies at intermediate redshifts. We obviously need better statistics, over a broader range of galaxy types and masses. More robust answers to the questions we have raised here are likely to come from the ESO VLT Large Programme, IMAGES, the 'Intermediate Mass Galaxies Evolution Sequence'. This study, with GIRAFFE IFU and FORS2 MXU mode, will yield the spatially-resolved dynamics and velocity dispersions of ~ 400 disc/early-type, mass-selected galaxies from redshifts of $z = 0.4$–1. Only GIRAFFE with its multi-IFU mode is able to recover properly the Tully-Fisher relation at moderate redshifts.

Equally important are the studies of nearby galaxies such as M31, which may be an example of a disc rebuilt after a major merger at $z \sim 0.6$. Beyond more observations, comparisons with simulations including all of the complex physics associated with gas in-fall, gas out-flow, feedback and formation of supermassive black holes, major and minor merging, etc. will be important for understanding and interpreting the dynamics and properties of high-redshift galaxies, especially those numerous galaxies at intermediate/high redshifts without relaxed kinematics.

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