Transactions IAU, Volume XXVIIIA
Reports on Astronomy 2009–2012
Ian Corbett, ed.

doi:10.1017/S1743921312002931

COMMISSION 28 GALAXIES

GALAXIES

PRESIDENT **Roger L. Davies**
VICE-PRESIDENT **John S. Gallagher III**
PAST PRESIDENT **Françoise Combes**
ORGANIZING COMMITTEE **Stephane J. Courteau, Avishai Dekel, Marijn Franx, Chanda J. Jog, Shardha Jogee, Naomasa Nakai, Monica Rubio, Linda J. Tacconi, Elena Terlevich**

TRIENNIAL REPORT 2009-2012

1. Highlights in extragalactic research 2009-12

The membership of Commission 28 is so large, and the spread of research interests so broad, that the research highlights presented here of necessity represent just a small subset of the work carried out over the past three years. Progress in the area of galaxy evolution continues to be particularly rapid, driven by both the availability of new multi-wavelength survey data and the development of increasingly sophisticated simulations to model the complex behaviour of stars and gas (e.g. Agertz *et al.* 2011; Guo *et al.* 2011; Keres *et al.* 2009; Schaye *et al.* 2010).

1.1. Galaxy Evolution out to z~ 1

The physical nature of early type galaxies (ETG) has been further elucidated by the ATLAS^{3D} survey (Emsellem *et al.* 2011; Cappellari *et al.* 2011), which conclusively showed that in the local Universe the great majority (86%) of ETGs with $M_K > -21.5$ have disks or disk-like kinematics. Low angular momentum systems that might be thought of as *classical* elliptical galaxies are rare, and found predominantly in the highest density region of the survey, the Virgo cluster core, where they comprise 20% of the galaxy population.

The galaxy merger rate over time is one of the fundamental tracers of galaxy evolution. Studies based on large *HST* surveys (e.g., GEMS, GOODS, COSMOS) report a wide range of values for the observed major merger fraction and the inferred merger rate among massive galaxies over the last 7 Gyr. Among massive ($M_\star > 2.5 \times 10^{10}\ M_\odot$) galaxies, the major merger rates typically range from 2% to 10% per Gyr, and the volume-averaged major merger rate from a few $\times 10^{-3}$ to $\times 10^{-4}$ galaxies Gyr^{-1} Mpc^{-3} (e.g., Lotz *et al.* 2008; Jogee *et al.* 2009; Conselice *et al.* 2009; Bundy *et al.* 2009; de Ravel *et al.* 2009; Robaina *et al.* 2010; Lotz *et al.* 2011). The dispersion in published values can be significantly reduced by properly calibrating the visibility timescale using hydrodynamic merger simulations, and taking into account differing parent galaxy selection (Lotz *et al.* 2011). The implied minor merger rate over the last seven Gyr is at least three times the major merger rate (Jogee *et al.* 2009; Lotz *et al.* 2011).

The star formation activity of merging and non-interacting galaxies is of great astrophysical interest, since the cosmic star-formation rate (SFR) density appears to have declined by up to a factor of ten since $z \sim 1$. Recent observational work has shown that out to $z \sim 1$, the average SFR of visibly-merging massive galaxies is only modestly enhanced (by a factor of 0.5–2.0) compared to non-interacting galaxies. This result is in agreement with numerical simulations by Di Matteo *et al.* (2007) and Cox *et al.* (2008), who report a similar modest enhancement in the SFR of major mergers spanning a range of mass ratio, progenitor gas fraction and Hubble types, and orbital geometry. Furthermore, it appears that visibly-merging systems only account for a small fraction (well below 30%) of the total cosmic SFR density over the last seven Gyr (Jogee *et al.* 2009; Robaina *et al.* 2010; Lotz *et al.* 2008; Bell *et al.* 2005), implying that the decline in cosmic SFR density at $z < 1$ is predominantly shaped by changes in the star-formation rate of non-interacting galaxies.

New work using deep spectra taken with DEIMOS on Keck II, together with improved modelling techniques, shows that the stellar mass Tully-Fisher (TF) relation out to $z \sim 1.3$ can be recovered with a scatter, which is 2-3 times smaller than in earlier work and in fact, comparable to the scatter at $z \sim 0$ (Miller *et al.* 2011). This suggests that over the past 8 billion years there is a tight relationship between the mass in stars and the total mass (derived dynamically), and that the baryonic TF relation is firmly established at $z = 1$.

2. Galaxy Evolution at z = 1.5 to 4

The global stellar mass density reaches $\sim 50\%$ of its present-day value by $z \sim 1$, suggesting that galaxies grew much of their stellar mass at redshift $z > 1$. We still do not know, however, whether the star-formation history of galaxies at $z > 1$ is primarily driven by stellar mass, mergers, galaxy environment, or other factors.

Multiple lines of evidence suggest that massive galaxies at $z = 2 - 3$ host significant disk components, with strong implications for the processes by which galaxies grow at high redshift. The SINS survey (Förster Schreiber *et al.* 2009) measured ionized gas kinematics of $z \sim 2$ star-forming galaxies and found examples of clumpy, turbulent, and geometrically thick systems having high velocity dispersions ($\sigma \sim 30 - 120$ km/s). About one-third of such systems show rotating disk kinematics.

Using HST near-infrared imaging from the GOODS-NICMOS survey, Weinzirl *et al.* (2011) analyzed the rest-frame optical structure of one of the largest (166 with $M_\star \geqslant 5 \times 10^{10}\ M_\odot$) samples of massive galaxies at $z = 2 - 3$. They found that 40% of these massive galaxies were ultra-compact and quiescent, compared to less than 1% at $z \sim 0$. Furthermore, the majority ($\sim 65\%$) of these massive galaxies have disky morphologies, with many of these systems being extended and associated with high star formation rates (several tens to hundreds $M_\odot$ yr^{-1}). The presence of disky massive galaxies is also reported from other, smaller samples (van Dokkum *et al.* 2011; Forster Schreiber *et al.* 2011; van der Wel *et al.* 2011). Weinzirl *et al.* (2011) suggest that the large fraction of disky systems in these high mass galaxies implies that *cold mode accretion* (e.g; Dekel & Birnboim 2006; Dekel *et al.* 2009a,b; Kereš *et al.* 2005; Kereš *et al.* 2009; Brooks *et al.* 2009; Ceverino *et al.* 2010) must play an important role in galaxy growth at $z > 2$, in addition to gas-rich major mergers.

Direct unambiguous observational evidence for cold mode accretion is still lacking, but multiple possibilities, both in support of and against this scenario, are under consideration (e.g., Dijkstra & Loeb 2009; Steidel *et al.* 2010; Goerdt *et al.* 2010; Faucher-Giguere &

Keres 2011; Fumagalli *et al.* 2011; Kimm *et al.* 2011; Le Tiran *et al.* 2011; Giavalisco *et al.* 2011)

The cold molecular gas content of galaxies and the star formation law of galaxies at $z = 1 - 3$ are now starting to be measured. Daddi *et al.* (2010a) report gas fractions of 50-65% in massive ($M_\star \sim 4 \times 10^{10} - 1 \times 10^{11}\ M_\odot$) IR-selected BzK galaxies at $z \sim 1.5$. Tacconi *et al.* (2010) have used measurements of CO emission to determine the cold gas fraction in normal star-forming galaxies at $z = 1.1 - 2.4$. For stellar masses spanning $M_\star \sim 3 \times 10^{10} - 3.4 \times 10^{11}\ M_\odot$, they find cold gas masses three to ten times higher than in today's massive spiral galaxies.

In terms of star formation laws, studies based on direct CO observations suggest that over the redshift range $z = 1 - 3$, different star formation laws may apply to starbursts and mergers than to normal non-merging systems (Daddi *et al.* 2010b; Genzel *et al.* 2010). While normal non-merging galaxies appear to follow similar molecular gas-star formation relations over three orders of magnitude in gas mass or surface density, gas-rich major mergers produce on average four to 10 times more far-infrared luminosity per unit gas mass. (Genzel *et al.* 2010). A universal SF law can however be obtained when the dynamical timescale is explicitly taken into account (Daddi *et al.* 2010b; Genzel *et al.* 2010).

3. Galaxy Evolution at $z > 5$

The luminosity functions and star-formation rates of galaxies within the reionization epoch at redshift $z > 6$ are now starting to be mapped out for the first time. Using data from the Hubble Space Telescope (HST), Bouwens *et al.* (2011a) identified 73 candidate galaxies at $z \sim 7$ and a further 59 at $z \sim 8$. They use these to derive luminosity functions at $z \sim 7$ and $z \sim 8$ for which the faint-end slope, though somewhat uncertain, is significantly steeper than seen in the local universe, implying that lower-luminosity galaxies dominate the galaxy luminosity density during the epoch of reionization.

Long-duration gamma-ray bursts (GRBs) provide a powerful alternative tool for identifying galaxies at very high redshift. Tanvir *et al.* (2009) found that the host galaxy of GRB090423 lies at a redshift of $z \sim 8.2$, implying that massive stars were being produced and dying as GRBs only ~630 million years after the Big Bang. The stellar populations and star-formation histories of $z > 6$ galaxies are also starting to be studied (e.g. Finkelstein *et al.* 2010, 2011; Bouwens *et al.* 2011b; Finlator *et al.* 2011). The chemical enrichment of the high-redshift interstellar medium has been studied by Ryan-Weber *et al.* (2009), who find evidence for a very rapid build-up of intergalactic CIV over a period of only $\sim 300\,\mathrm{Myr}$ at $z > 5$. This could reflect the accumulation of metals associated with the rising levels of star formation activity from after $z \sim 9$ as indicated by galaxy counts, and/or an increasing degree of ionization of the intergalactic medium (IGM) over this redshift range.

Observations of quasars are pushing further into the reionization epoch, with Mortlock *et al.* (2011) reporting the discovery of a quasar at redshift $z = 7.085$, only 0.77 billion years after the Big Bang, with an estimated black hole mass of 2×10^9 solar masses. They find that the neutral gas fraction in the interstellar medium at this epoch may be as high as 10%, consistent with the results of Stark *et al.* (2010) and Schenker *et al.* (2012) which also suggest that at redshift $z \sim 7 - 8$ we are entering the era where the intergalactic medium is partially neutral. The next three years are likely to see rapid advances in the study of both galaxies and the interstellar medium at $z > 6$.

4. Closing remarks

Key developments over the past three years include the first studies of galaxies and stellar populations at $z > 7$ and the increasing recognition that 'cold-flow' accretion of gas from the cosmic web is likely to play an important role in the evolution of normal galaxies. The next three years should be an exciting time. The commissioning of KMOS and MUSE on the VLT will facilitate a huge increase in the application of integral-field techniques to the study of ever more distant galaxies. At the same time, ALMA will provide new insights into the molecular gas content and star-formation rates of distant star-forming galaxies, and the first results should start to flow from a new generation of SKA precursor and pathfinder telescopes working in HI and radio continuum. Together, these and other new facilities will enable further progress in the study of galaxies at all epochs of cosmic time.

Roger L. Davies
President of the Commission

References

Agertz, O., Teyssier, R., & Moore, B. 2011, *MNRAS*, 384, 386
Bell, E. F., *et al.* 2005, *ApJ*, 625, 23
Bouwens, R. J. *et al.* 2011a, *ApJ*, 737, 90
Bouwens, R. J. *et al.* 2011b, *ApJ*, submitted, arXiv:1109.0994
Brooks, A. M., Governato, F., Quinn, T., Brook, C. B., & Wadsley, J. 2009, *ApJ*, 694, 396
Bundy, K., *et al.* 2009, *ApJ*, 697, 1369
Cappellari *et al.* 2011, *MNRAS*, 416, 1680.
Ceverino, D., Dekel, A., & Bournaud, F. 2010, *MNRAS*, 404, 2151
Conselice, C. J. 2009, *MNRAS*, 399, L16
Cox, T. J., Jonsson, P., Somerville, R. S., Primack, J. R., & Dekel, A. 2008, *MNRAS*, 384, 386
Daddi, E., *et al.* 2010a, *ApJ*, 713, 686
Daddi, E., *et al.* 2010b, *ApJ*, 714, L118
Dekel, A. & Birnboim, Y. 2006, *MNRAS*, 368, 2
Dekel, A., Sari, R., & Ceverino, D. 2009a, *ApJ*, 703, 785
Dekel, A., *et al.* 2009b, *Nature*, 457, 451
de Ravel, L. *et al.* 2009, *A&A*, 498, 379
Dijkstra, M. & Loeb, A. 2009, *MNRAS*, 400, 1109
Di Matteo, P., Combes, F., Melchior, A.-L., & Semelin, B. 2007, *A&A*, 468, 61
Emsellem *et al.* 2011, *MNRAS*, 414, 888
Faucher-Giguère, C.-A. & Kereš, D. 2011, *MNRAS*, 412, L118
Finkelstein, S. L. *et al.* 2010, *ApJ*, 719, 1250
Finkelstein, S. L. *et al.* 2011, *ApJ*, submitted, arXiv:1110.3785
Finlator, K., Oppenheimer, B. D., & Davé, R. 2011, *MNRAS*, 410, 1703
Förster Schreiber, N. M., *et al.* 2009, *ApJ*, 706, 1364
Förster Schreiber, N. M., *et al.* 2011, *ApJ*, 731, 65
Fumagalli, M., *et al.* 2011, *MNRAS*, 418, 1796
Genzel, R., *et al.* 2010, *MNRAS*, 407, 2091
Giavalisco, M., *et al.* 2011, *ApJ*, 743, 95
Goerdt, T., *et al.* 2010, *MNRAS*, 407, 613
Guo, Q., *et al.* 2011, *MNRAS*, 413, 101
Jogee, S., *et al.* 2009, *ApJ*, 697, 1971
Kereš, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, *MNRAS*, 363, 2
Kereš, D., Katz, N., Davé, R., Fardal, M., & Weinberg, D. H. 2009, *MNRAS*, 396, 2332
Kimm, T., Slyz, A., Devriendt, J., & Pichon, C. 2011, *MNRAS*, 413, L51

Le Tiran, L., Lehnert, M. D., Di Matteo, P., Nesvadba, N. P. H., & van Driel, W. 2011, *A&A*, 530, L6

Lotz, J. M., *et al.* 2008, *ApJ*, 672, 177

Lotz, J. M., *et al.* 2011, *ApJ*, 742, 103

Miller, S. H., Bundy, K., Sullivan, M., Ellis, R. S., & Treu, T. 2011, *ApJ*, 741, 115

Mortlock, D. J., *et al.*, 2011, *Nature*, 474, 616

Robaina, A. R., *et al.* 2010, *ApJ*, 719, 844

Ryan-Weber, E. V., Pettini, M., Madau, P., & Zych, B. J. 2009, *MNRAS*, 395, 1476

Schaye, J., *et al.* 2010, *MNRAS*, 402, 1536

Schenker, M. A., *et al.* 2012, *ApJ*, 744, 179

Stark, D. P., Ellis, R. S., Chiu, K., Ouchi, M., & Bunker, A. 2010, *MNRAS*, 408, 1728

Steidel, C. C., *et al.* 2010, *ApJ*, 717, 289

anvir, N. R. *et al.* 2009, *Nature*, 461, 1254

van Dokkum, P. G., *et al.* 2011, *ApJ*, 743, L15

van der Wel, A., *et al.* 2011, *ApJ*, 730, 38

Weinzirl, T., *et al.* 2011, *ApJ*, 743, 87