The Galaxy Disk in Cosmological Context
Proceedings IAU Symposium No. 254, 2008
J. Andersen, J. Bland-Hawthorn & B. Nordström, eds.

doi:10.1017/S1743921308027373

Reconciling the Metallicity Distributions of Gamma-ray Burst, Damped Lyman-α, and Lyman-break Galaxies at $z \approx 3$

Johan P. U. Fynbo[1], **J. Xavier Prochaska**[2], **Jesper Sommer-Larsen**[3], **Miroslava Dessauges-Zavadsky**[4], **and Palle Møller**[5]

[1]Dark Cosmology Centre, Niels Bohr Institute, Copenhagen University, Juliane Maries Vej 30, 2100 Copenhagen O, Denmark
email: jfynbo@dark-cosmology.dk

[2]Department of Astronomy and Astrophysics, UCO/Lick Observatory, University of California, 1156 High Street, Santa Cruz, CA 95064, US

[3]Excellence Cluster Universe, Technische Universität München; Boltz-manstr. 2, D-85748 Garching, Germany

[4]Observatoire de Genève, 51 Ch. des Maillettes, 1290 Sauverny, Switzerland

[5]European Southern Observatory, Karl-Scharschild-strasse 2, D-85748 Garching bei München, Germany

Abstract. We test the hypothesis that the host galaxies of long-duration gamma-ray bursts (GRBs) as well as quasar-selected damped Lyman-α (DLA) systems are drawn from the population of UV-selected star-forming, high z galaxies (generally referred to as Lyman-break galaxies). Specifically, we compare the metallicity distributions of the GRB and DLA populations against simple disk models where these galaxies are drawn randomly from the distribution of star-forming galaxies according to their star-formation rate and HI cross-section respectively. We find that it is possible to match both observational distributions assuming very simple and constrained relations between luminosity, metallicity, metallicity gradients and HI sizes. The simple model can be tested by observing the luminosity distribution of GRB host galaxies and by measuring the luminosity and impact parameters of DLA selected galaxies as a function of metallicity. Our results support the expectation that GRB and DLA samples, in contrast with magnitude limited surveys, provide an almost complete census of star-forming galaxies at $z \approx 3$.

Keywords. gamma-rays: bursts – interstellar medium

1. Introduction

The past 10 years has marked the emergence of extensive observational analysis of high redshift ($z > 2$) galaxies. This remarkable and rapid advance was inspired by new technologies in space and ground-base facilities for deep imaging, clever approaches to target selection, and the arrival of 10 m class ground-based telescopes for spectroscopic confirmation. A plethora of classes are now surveyed, each named for the observational technique that selects the galaxies: the Lyα emitters (Hu *et al.* 1998), the Lyman break galaxies (LBGs, Steidel *et al.* 2003), sub-mm galaxies (e.g., Chapman *et al.* 2005), distant red galaxies (van Dokkum *et al.* 2006), damped Lyα (DLA) systems (Wolfe *et al.* 2005), extremely red objects (Cimatti *et al.* 2003), long-duration γ-ray burst (GRB) host galaxies (e.g., Fruchter *et al.* 2006), MgII absorbers, radio galaxies (Miley & De Breuck 2008), quasar (QSO) host galaxies, etc. Large, dedicated surveys have identified in some cases thousands of these galaxies providing a direct view into the processes of galaxy formation in the young universe.

Because of the significant differences in the sample selection of high z galaxies, there has been a tendency by observers to treat each population separately and/or contrast the populations. However, the various populations will overlap to some extent and it is important to understand how (see also Adelberger *et al.* 2000; Møller *et al.* 2002; Fynbo *et al.* 2003; Reddy *et al.* 2005).

Of the various galactic populations discovered at $z > 2$ to date, only two offer the opportunity to study the interstellar medium at a precision comparable to the Galaxy and its nearest neighbors: the damped Lyα systems intervening quasar sightlines (QSO-DLA) and the host galaxies of GRBs which exhibit bright afterglows (GRB-DLA). These galaxies are characterized by a bright background source which probes the gas along the sightline to Earth. In the case of QSO-DLA it is the background QSO while for GRB-DLA it is the afterglow of the GRB located within the host galaxy. Hence, the GRB-DLA will not probe the full line-of-sight through the host. The gas in the ISM imprints signatures of the total HI column density, the metal content, the ionization state, the velocity fields, and the molecular fraction along the line-of-sight. Because the galaxies are identified in absorption, there is no formal magnitude limit for the associated stellar populations. In this respect, they may trace a large dynamic range in stellar mass, morphology, star formation rate, etc.

The connection between long-duration GRBs and star-forming galaxies has been empirically established. At large redshift, there is an exclusive coincidence of GRBs with actively star-forming galaxies (e.g., Hogg & Fruchter 1999; Bloom *et al.* 2002; Fruchter *et al.* 2006), the majority of which show elevated specific star-formation rates (Christensen *et al.* 2004). At low z, there is a direct link between GRBs and massive stars via the detection of spatially and temporally coinciding core-collapse supernovae (Hjorth *et al.* 2003; Stanek *et al.* 2003, but see also Fynbo *et al.* 2006). The simplest hypothesis, therefore, is that these galaxies uniformly sample high z galaxies according to star-formation rate, i.e. $f_{GRB} \propto \mathrm{SFR}(L)\phi(L)$, where $\phi(L)$ is the luminosity function.

The link between QSO-DLA and star-forming galaxies is less direct, primarily because the bright background quasar precludes the easy detection of stellar light. Nevertheless, the presence of heavy metals in all QSO-DLAs (and dust in the majority) indicates at least prior star-formation (Prochaska *et al.* 2003). Furthermore, the observation of CII* absorption suggests heating of the ISM by far-UV photons from ongoing star-formation in at least half of the sample (Wolfe *et al.* 2003, 2004. Furthermore, a handful of QSO-DLA have been detected in emission and exhibit properties similar to low luminosity LBGs (Møller *et al.* 2002). In contrast to the GRB-DLA, however, the QSO-DLA are selected according to their covering fraction on the sky, i.e. the probability of detection is the convolution of the HI cross-section with the luminosity function: $f_{DLA} \propto \sigma_{HI}(L)\phi(L)$. While both populations of DLAs may be drawn from the full sample of star-forming galaxies, their distribution functions would only be the same if $\sigma_{HI}(L) \propto SFR(L)$ (see also Chen *et al.* 2000).

In Fynbo *et al.* 2008 (F08) we test these ideas by comparing the observed metallicity distributions of QSO-DLA and GRB-DLA with simple predictions based on empirical measurements of star-forming galaxies at $z = 3$. In this paper we give a brief description of the model – for more details we refer to F08. Our study is similar in spirit to the studies of Fynbo *et al.* (1999) who combined the LBG luminosity function with a Holmberg relation for σ_{HI} to predict the luminosities and impact parameters of QSO-DLA galaxies, Jakobsson *et al.* (2005) who compared the luminosity distribution function of GRB host galaxies with the LBG luminosity function, and Chen *et al.* (2005) and Zwaan *et al.* (2005) who reconciled the properties of local galaxies with the QSO-DLA cross-section and metal abundances.

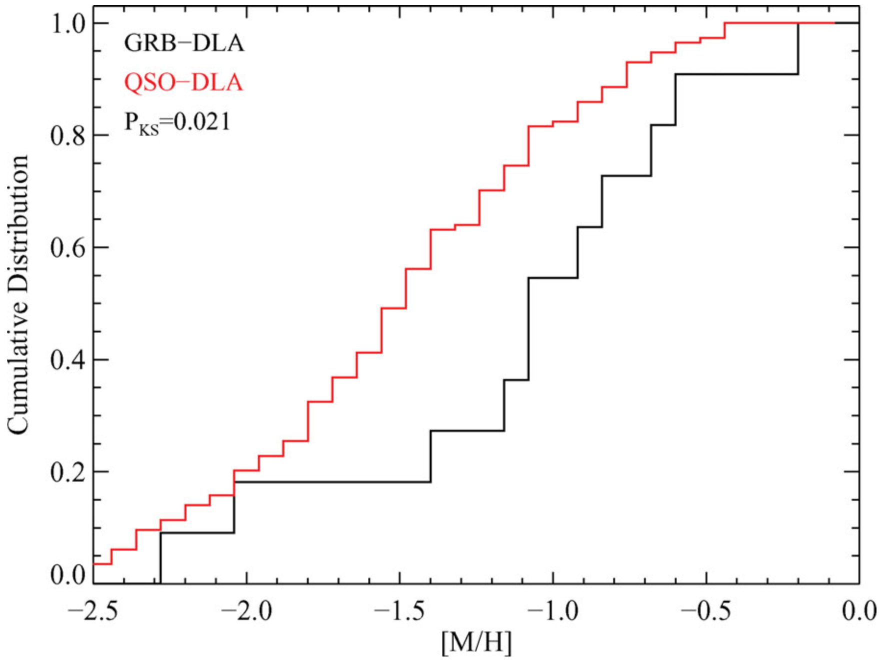

Figure 1. The histograms show the cumulative distribution of QSO-DLA and GRB-DLA metallicities in the statistical samples compiled by Prochaska *et al.* (2003) and Prochaska *et al.* (2007). As seen, the GRB-DLA metallicities are systematically higher than the QSO-DLA metallicities.

2. Analysis and results

Our aim is to model the metallicity distribution function of the GRB-DLA and QSO-DLA shown in Fig. 1. As seen, GRB-DLA systematically have higher metallicities than QSO-DLA (see also Savaglio 2006, Fynbo *et al.* 2006b). Our expectation was that this fact could be due to a combination of two effects: 1) SFR-selection vs. HI cross-section selection causing GRB hosts to on average by brighter and hence more metal rich, and 2) the on average larger impact parameters for QSO-DLA than GRB-DLA, which coupled with metallicity gradients will also shift the GRB-DLA towards lower metallicities. Full details of our model can as mentioned be found in F08. Here we just illustrate the model and repeat the main conclusions. To simulate the distribution of GRB-DLA metallicities we start with the 1700 Åluminosity function for LBGs from Reddy *et al.* 2008. To convert to metallicities we assume a metallicity-luminosity relation with slope 0.2 ($Z \propto (L/L_*)^{0.2}$) as seen locally. We normalise the relation so that it reproduces the metallicities for the LBGs at the bright end of the luminosity function. The simulated distribution based on these few and simple assumptions are in excellent agreement with the observed distribution (see F08). To simulate the distribution of QSO-DLA metallicities we specifically assume that each LBG is embedded in a flat gas disk. Then we assume two further relations: a galaxy luminosity vs. disk size relation and a recipe for assigning metallicity gradients to a galaxy with a given luminosity. Again, the simulated distribution using model parameters that are consistent with observed relations either locally or directly at $z \approx 3$. Fig. 2 and Fig. 3 further illustrate the main elements of our model.

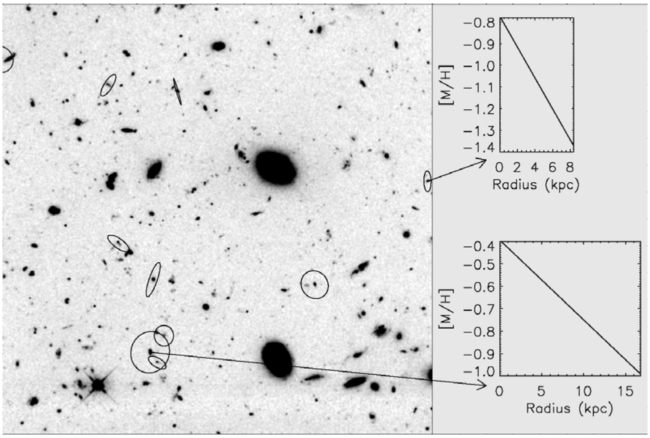

Figure 2. A subfield from the HDF North R-band image. We have selected LBGs with redshift between 2.8 and 3.2 from the catalog of photometric redshifts of Fernández-Soto *et al.* (1999). Over-plotted on each LBGs is the extent of a randomly inclined HI disk with a radius given by our prescription (See F08) Note that the majority of the total QSO-DLA absorption cross-section is caused by fainter galaxies than those shown here. On the right we show the radial metallicity profile from the centre to the largest radius at which the column density is above the definition of a DLA (N(H) $> 2\times10^{20}$ cm^{-2} in our model for two of the galaxies.

3. Shortcomings of the model

Obviously this is a very simple model: $z \approx 3$ galaxies do not all have flat, round gas disks around them, GRBs do not all explode exactly in the centres of their host galaxies, most likely $z \approx 3$ galaxies do not have nice, smooth metallicity gradients, etc. However, these shortcomings are probably of minor importance as long as $z \approx 3$ on average can be described as disks with metallicity gradients and GRBs occur significantly closer to the centres of their hosts than the typical impact parameters for QSO-DLA.

A more serious concern is bias in the observed samples of QSO-DLA and GRB-DLA. It has long been discussed to which extent QSO-DLA samples are biased against dusty (and hence likely metal rich and/or large $\log N(\mathrm{HI})$) systems. Studies of radio selected DLAs (free from dust-bias) have found similar column density and metallicity distributions as for optically selected DLA samples (Ellison *et al.* 2001, 2004; Ellison, Hall & Lira 2005; Akerman *et al.* 2005; Jorgenson *et al.* 2006) showing that any dust bias will be so small that it will not fundamentally change the conclusions about cross-section and metallicity distributions inferred from optically selected surveys.

Concerning GRB-DLA there is no dust bias in the detection of the prompt emission itself as γ-rays are unaffected by dust. However, the requirement of an optical afterglow detection from which the redshift the HI column density and metal columns can be measured does potentially exclude very dusty sightlines. Furthermore, there could be an intrinsic (astrophysical) bias against high metallicity in GRB production. In the collapsar model the limit is estimated to be around 0.3 $Z_{\odot}$ (Hirschi *et al.* 2005; Woosley & Heger 2005), but this is very dependent on the as yet poorly understood properties of winds from massive stars (e.g. clumping, Smith 2007). We also note that Wolf & Podsiadlowski (2007) exclude a metallicity cut-off below half the solar value based on statistics of host galaxy luminosities. If true such an intrinsic bias could preferentially exclude massive, dust-obscured starbursts, that typically seem to be enriched above this limit (Swinbank *et al.* 2004), from the GRB samples. Nevertheless, a few extremely red and luminous GRB hosts have been found (Levan *et al.* 2006; Berger *et al.* 2007). So far there are few

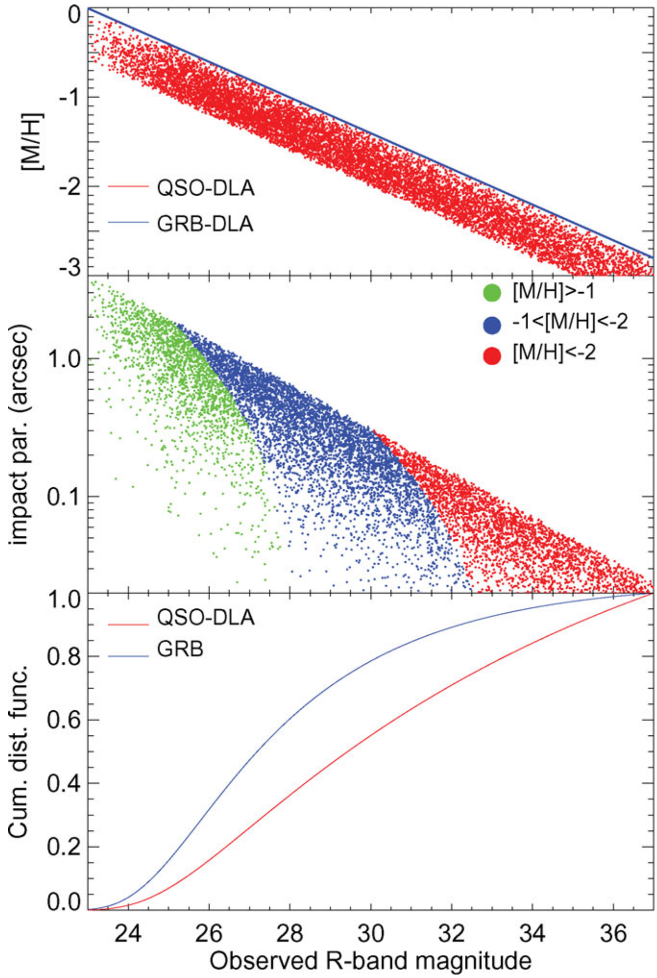

Figure 3. Simulated distributions of luminosity, impact parameter and metallicity (from bottom to top) for QSO-DLA and GRB galaxies at $z = 3$ in our model. In the top panel, QSO-DLA have lower metallicities than GRB hosts at a given R-band magnitude due to the metallicity gradients. In the middle panel impact parameters are lower for fainter QSO-DLA galaxies due to the Holmberg relation and low metallicity QSO-DLA have lower impact parameters due to the luminosity-metallicity relation and the smaller sizes given by the Holmberg relation. In the lower panel QSO-DLA galaxies are fainter than GRB hosts as the selection function for QSO-DLA weights fainter galaxies more than the selection function for GRBs.

examples of GRB sightlines with very large dust columns (for recent examples see Rol *et al.* 2007; Jaunsen *et al.* 2008; Tanvir *et al.* 2008). The near, mid and far-IR properties of GRB host galaxies have been studied by a number of groups (e.g., Chary *et al.* 2002; Le Floc'h *et al.* 2003, 2006; Berger *et al.* 2003; Tanvir *et al.* 2004; Priddey *et al.* 2006; Castro Cerón *et al.* 2007). A few GRB hosts, all at $z < 2$, have tentatively been detected at sub-mm wavelengths, but their inferred UV/optical (bluer, Gorosabel *et al.* 2003a,b) and dust properties (higher temperatures, Michałowski *et al.* 2008) are different than those of sub-mm selected galaxies. It is a major goal of ongoing GRB follow-up work to try to build a more complete sample less. For now, the incompleteness of the GRB samples remains a fundamental uncertainty on most conclusions drawn on the issue of GRBs as probes of high-z star-formation.

4. Conclusions

We find that with a simple model including the luminosity function for LBGs, a Holmberg relation for gas disk sizes, an L-Z relation and a metallicity gradient it is possible to reconcile the metallicity distributions of QSO-DLA, GRB-DLA and LBGs. In this model the faint end of the luminosity function plays a very important role. As seen in the lower panel in Fig. 3 more than 75% of star-formation selected galaxies are fainter than the flux limit for LBGs, R=25.5. For QSO-DLA galaxies the fraction is even higher. Hence, in this model the GRB and DLA samples, in contrast with magnitude limited surveys, provide an almost complete census of $z \approx 3$ star-forming galaxies that are not heavily obscured.

References

Adelberger, K. L. & Steidel, C. C. 2000, *ApJ*, 544, 218.
Akerman, C. J., Ellison, S. L., Pettini, M., & Steidel, C. C. 2005, *A&A*, 440, 499.
Berger, E., Kulkarni, S. R., Bloom, J. S., *et al.* 2002, *ApJ*, 581, 981.
Berger, E., Cowie, L. L., Kulkarni, S. R., *et al.* 2003, *ApJ*, 588, 99.
Berger, E., Fox, D. B., Kulkarni, S. R., *et al.* 2007, *ApJ*, 660, 504.
Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002, AJ, 123, 1111.
Castro Cerón, J. M., Michałowski, M. J., Hjorth, J., *et al.* 2007, *ApJL*, 653, L85.
Chapman, S. C., Blain, A. W., Smail, I., & Ivison, R. J. 2005, *ApJ*, 622, 772.
Chary, R., Becklin, E. E., & Armus, L. 2002, *ApJ*, 566, 229.
Chen, H.-W., Lanzetta, K. M., & Fernandez-Soto, A. 2000, *ApJ*, 533, 120.
Chen, H.-W., Kennicutt, R. C. Jr., & Rauch, M. 2005, *ApJ*, 620, 703.
Christensen, L., Hjorth, J., Gorosabel, J. 2004, *A&A*, 425, 913.
Cimatti, A., Daddi, E., Cassata, P., *et al.* 2003, *A&A*, 412, L1.
Ellison, S. L., Yan, L., Hook, I. M., *et al.* 2001, *A&A*, 379, 393.
Ellison, S. L. Churchill, C. W., Rix, S. A., & Pettini, M. 2004, *ApJ*, 615, 118.
Ellison, S. L., Hall, P. B., & Lira, P. 2005, *AJ*, 130, 1345.
Fernández-Soto, A., Lanzetta, K. M., & Yahil, A. 1999, *ApJ*, 513, 34.
Fruchter, A. S., Levan, A., Strolger, L., *et al.* 2006, *Nature*, 441, 463.
Fynbo, J. U., Møller, P., & Warren, S. J. 1999, *MNRAS*, 305, 849.
Fynbo, J. P. U., Ledoux, C., Møller, P., *et al.* 2003, *A&A*, 407, 147.
Fynbo, J. P. U., Watson, D., Thöne, C. C., *et al.* 2006a, *Nature*, 444, 1047.
Fynbo, J. P. U., Starling, R. L. C., Ledoux, C., *et al.* 2006b, *A&A*, 451, L47.
Fynbo, J. P. U., Prochaska, J. X., Sommer-Larsen, J., Dessauges-Zavadsky, M., Møller, P. 2008, *ApJ*, in press (F08) (arXiv:0801.3273).
Gorosabel, J., Christensen, L., Hjorth, J. *et al.* 2003a, *A&A*, 400, 127.
Gorosabel, J., Klose, S., Christensen, L., *et al.* 2003b, *A&A*, 409, 123.
Hirschi, R., Meynet, G., & Maeder, A. 2005, *A&A*, 443, 581.
Hjorth, J., Sollerman, J., Møller, P., *et al.* 2003, *Nature*, 423, 847.
Hogg, D. W. & Fruchter, A. S. 1999, *ApJ*, 520, 54.
Hu, E. M., Cowie, L., & McMahon, R. G. 1998, *ApJL*, 502, L99.
Jakobsson, P., Björnsson, G., Fynbo, J. P. U., *et al.* 2005, *MNRAS*, 362, 245.
Jaunsen, A. O., Rol, E., Watson, D. J., *et al.* 2008, *ApJ*, 681, 453
Jorgenson, R. A., Wolfe, A. M., Prochaska, J. X., *et al.* 2006, *ApJ*, 646, 730.
Le Floc'h, E., Duc, P.-A., & Mirabel, I. F. 2003, *A&A*, 400, 499.
Le Floc'h, E., Charmandaris, V., Forrest, W. J., *et al.* 2006, *ApJ*, 642, 636.
Michałlowski, M. J, Hjorth, J., Castro Cerón, J. M., Watson, D. 2008, *ApJ*, 672, 817.
Miley, G. & De Breuck, C. 2008, A&ARv, 15, 67.
Møller, P., Warren, S. J., Fall, S. M., Fynbo, J. U. & Jakobsen, P. 2002, *ApJ*, 574, 51.
Priddey, R. S., Tanvir, N. R., Levan, A. J., *et al.* 2006, *MNRAS*, 369, 1189.
Prochaska, J. X., *et al.* 2003, *ApJL*, 595, L9.

Prochaska, J. X., Chen, H.-W., Dessauges-Zavadsky, M., & Bloom, J. S. 2007, *ApJ*, 666, 267.
Reddy, N. A., Erb, D. K., Steidel, C. C., *et al.* 2005, *ApJ*, 633, 748.
Reddy, N. A., Steidel, C. C., Pettini, M., *et al.* 2008, *ApJS*, 175, 48.
Savaglio, S., NJPh, 8, 195.
Stanek, K. Z., Matheson, T., Garnavich, P. M., *et al.* 2003, *ApJL*, 591, L17.
Steidel, C. C., Adelberger, K. L., Shaplet, A. E., *et al.* 2003, *ApJ*, 592, 728.
Tanvir, N. R., Barnard, V. E., Blain, A. W., *et al.* 2004, *MNRAS*, 352, 1073.
Tanvir, N. R., Levan, A. J., Rol, E., *et al.* 2008, *MNRAS*, in press (arXiv:0803.4100).
van Dokkum, P. G., Quadri, R., Marchesini, D., *et al.* 2006, *ApJL*, 638, L59.
Williams, R. E., Blacker, B., Dickinson, M., *et al.* 1996, *AJ*, 112, 1335.
Wolf, C. & Podsiadlowski, P. 2007, *MNRAS*, 375, 1049.
Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2003, *ApJ*, 593, 235.
Wolfe, A. M., Owk, J. C., Gawiser, E., Prochaska, J. X., & Lopez, S. 2004, *ApJ*, 615, 625.
Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2005, *ARA&A*, 43, 861.
Woosley, S. E. & Heger, A. 2006, *ApJ*, 637, 914.
Zwaan, M., van der Hulst, J. M., Briggs, F. H., *et al.* 2005, *MNRAS*, 364, 1467.

Johan Fynbo and Lisbeth Fogh Grove relaxing after Johan's talk.

Birgitta Nordström, Jens Viggo Clausen and John Renner Hansen enjoying a light moment during the Town Hall reception. In the background, Torgny Karlsson (left) and Linus Riel Petersen (center).

Anja Andersen, Ole Strömgren and Bengt Gustafsson at the Town Hall.