SCIENCE WITH THE VLT/VLTI

The Early Universe with the VLT

HIGHLIGHTS OF THE ESO WORKSHOP, APRIL 1–4, 1996

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Progress in science is not a steady process. Occasionally, when a fundamental breakthrough takes place, the frontier of our knowledge of Nature moves suddenly ahead more than it had in years before. Those who last April attended in Garching the workshop "The Early Universe with the VLT" were left with the feeling that one of these *quantum jumps* is indeed taking place right now in observational cosmology. The main breakthrough is probably represented by the success of a simple but robust photometric criterion for the identification of high-redshift galaxies, that has allowed to find star-forming galaxies all the way to $z = 3.5$, and that may well work also beyond (cf. Steidel *et al.*, 1995, *AJ*, 110, 2519; see also Macchetto and Giavalisco, 1995, *The Messenger*, 81, 14). M. Giavalisco showed a series of impressive Keck telescope spectra of these galaxies, selected in both the generic field and the *Hubble Deep Field* (HDF), and together with D. Macchetto argued for these objects being the precursors of present-day spheroidals caught in the act of their formation. Figure 1 (also shown by Giavalisco, from Madau *et al.*, 1996, preprint) gives an idea of the kind of high-level information on the evolution of the universe that we can now grasp from these data. The global star-formation rate (SFR) per unit comoving volume appears to climb a factor ~ 10 from $z = 0$ to $z \simeq 1$, a result that comes from the Canada-France Redshift Survey that was presented by F. Hammer. Beyond $z = 1$, one now has a set of lower limits established by HDF and Keck spectroscopic data. These limits are likely to move up somewhat as new data will soon become available, with the expectation that in a few years the whole diagram will be filled all the way to $z \simeq 5$ with determinations as accurate as those now available for $z \lesssim 1$. The product will be the accurate reconstruction of the whole global star-formation history of the universe. Theoretical work on the *chemical evolution of the universe* (hopefully a closed box indeed) that parallel these observations was presented at the meeting by M. Fall, while complementary constraints on the early SFR that can be obtained from far-infrared observations by FIRAS/COBE and ISO, were discussed by J.L. Puget, M. Rowan-Robinson, and A. Franceschini.

Searching for very high redshift galaxies, either by Lyα imaging or photometrically locating breaks in the spectral energy distribution, was further discussed by K. Meisenheimer, E. Thommes, and E. Giallongo, the latter reporting the discovery of the so far most distant star-forming galaxy at $z = 4.7$, about 2″ away from a quasar with the same redshift (see Fig. 2). 3D spectroscopic observations of this object were also presented by G. Adam, and the merits for high-redshift studies of a 3D, adaptive optics fed spectrograph on the VLT were further illustrated by G. Comte. Yet another way of finding high-redshift galaxies was illustrated by Y. Mellier, who advocated strong gravitational lensing by massive clusters offering the advantage of amplifying the light of distant galaxies, thus helping their detailed study.

While the very high redshift galaxies played the *primadonna* role at the meeting, very impressive was also the progress of systematic studies of the redshift and morphology of galaxies at more moderately high redshifts (R. Ellis, M. Colless, and W. Couch). The HDF images have now allowed to morphologically classify galaxies as faint as $I = 24.5$, and have shown once more that the well-known excess in faint galaxy counts is mainly due to blue, irregular, star-forming galaxies. So, the ratio of blue to red galaxies appears to increase with redshift, both in the field as well as in clusters (the latter being the Butchler-Oemler effect), and it remains to be quantitatively established what difference exists (if any) between field and clusters as far as the evolution with z of the B/R ratio is concerned.

Intriguingly, Figure 1 suggests that the global SFR may peak somewhere around $z = 2$, tantalisingly close to the well-known peak in the QSO redshift distribution that was reviewed by S. Cristiani. However, the distribution itself remains somewhat uncertain beyond $z = 2$, and various speakers (R. McMahon, R. Webster, A. Omont, and P. Shaver) reported on current efforts to put it on firmer grounds, with special emphasis on prospects to detect QSOs beyond the $z = 5$ *wall*. What relation is there between the peak in the QSO activity and the expected peak in the global SFR? Hence, what relation is there between the formation of galactic spheroids, and that of massive central black holes, the likely powerhouse of QSO emission? These questions did not receive answers at the meeting, but several speakers (H. Röttgering, A. Cimatti, and S. di Serego Alighieri) discussed the latest results – especially from HST – concerning high-redshift radio galaxies, and the perspectives to understand the connection between galaxy formation and nuclear activity. The relative contribution of QSO's and primeval galaxies in reionising the universe was then explored by A. Blanchard.

A complementary approach to gather insight into the formation of galactic spheroids (i.e., ellipticals and the bulge

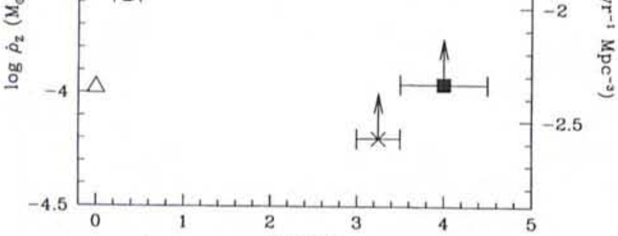

*Figure 1: The global star formation and metal production rates per unit comoving volume (right scale and left scale, respectively) as a function of redshift (from Madau et al. 1996, preprint). The open triangle gives the local value (from Gallego et al. 1995, ApJ, **455**, L1); filled circles are from the Canada-France Redshift Survey (Lilly et al., 1996, ApJ, **460**, L1); the cross is from Steidel et al. (1996, ApJ, in press); and the filled squares are for galaxies in the Hubble Deep Field. The horizontal line is the cosmic-time average rate as derived from the local abundance of heavy elements (assuming $q_0 = 0.5$ and $H_0 = 50$ (paper presented by M. Giavalisco).*

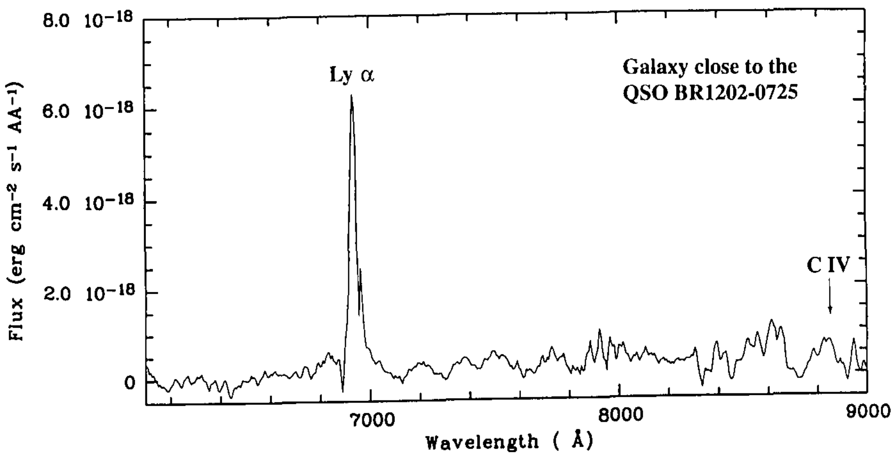

*Figure 2: A 3.5-hour integration on the galaxy ~ 2″ from the z = 4.7 QSO BR1202-0725 obtained with the EMMI spectrograph at the ESO 3.5-m NTT (courtesy of S. D'Odorico). The spectrum shows a strong emission line identified as Lyα at z = 4.702, and a continuum level in agreement with the integrated magnitude of this object (I = 24.1, Fontana et al., 1996, MNRAS **279**, L27). This level of the rest frame ultraviolet continuum indicates a star-formation rate of ~ 30 $M_\odot$ yr^{-1}. The C IV emission doublet is not detected, which sets an upper limit to its intensity of ~ 1/10 that of Lyα. The object is one of the-high redshift candidates from a deep, four-colour study of the galaxies in the field of the QSO (paper presented by E. Giallongo).*

of spirals) is to follow their evolution with redshift. R. Bender and M. Franx reported about the construction of the fundamental plane relation for cluster ellipticals up to $z \simeq 0.4$, thus setting a tight lower limit ($z \gtrsim 2$) for the formation epoch of the bulk of the present-day stellar content in these galaxies. Combining HST imaging (giving accurate effective radii and surface brightness distributions) with 8–10-m-telescope spectroscopy (giving velocity dispersions and metallicity indices) is the winning strategy in this field, and D. Koo reported recent Keck observations of high-z ellipticals as well as spirals and faint blue galaxies. The evolution of the fundamental plane and Tully-Fisher relations involve both dynamical and stellar population properties of galaxies. As such, they can constrain the formation epoch of the stars in these galaxies, but still allow a variety of galaxy-build-up scenarios. For example, in some CDM simulations of galaxy formation and evolution (reported by G. Kauffmann and M. Steinmetz) the bulk of stars may well form at very high z, but their assembly to build up the big galaxies of today does not complete the process before $z \lesssim 1$. Thus, even more fundamental than the fundamental plane itself may eventually be the empirical construction of the *distribution functions* of the velocity widths and velocity dispersions at various redshifts. Velocities – better than luminosities – indeed represent a rather direct measure of the depth of galaxy potential wells, and their distribution traces the assembly of dark matter halos on galaxy scales, the firmer result of CDM simulations.

Next to galaxies on the mass scale, galaxy clusters at high redshift also received wide coverage at the meeting, including X-ray searches (H. Böhringer) and their optical counterparts (G. Chincarini), group and cluster detection from QSO absorption line systems (P. Petitjean and M. Haehnelt) and from gravitational shear (P. Schneider and B. Fort). While systematic studies of moderate redshift clusters (unfortunately mostly limited to the northern hemisphere) are now well under way (R. Carlberg), successful detections of clusters around powerful AGNs were reported. These included a cluster at $z = 1.2$, that combined HST and Keck data show to contain already red (i.e. old) ellipticals (M. Dickinson), and the detection of clustering at a redshift as high as ~ 2.4 (P. Francis). Tracing the evolution of large-scale structure (LSS) at high redshift was then illustrated both by present and planned galaxy redshift surveys (V. De Lapparent and G. Vettolani), and by gravitational shear (P. Schneider and B. Fort).

While the emphasis of the meeting was obviously on high-redshift objects, D. Tytler in his comprehensive general introduction emphasized that a great deal about the early universe can be understood by looking at nearby objects. For example, dating the oldest stars and mapping the age, chemical and kinematic structure in our own Galaxy and in nearby galaxies, getting stellar abundances for residues of the Big Bang nucleosynthesis, etc. One crucial aspect of the local universe still worth investigating concerns *normalisations*. While getting rich samples of galaxies at high redshifts, one would like to compare them to fair samples at $z \simeq 0$, so as to gauge the change that has intervened in between. This includes e.g. the local luminosity function for morphologically typed galaxies (G. Vettolani reported on the ESO redshift survey results), supernovae of Type Ia, where observation of high-z counterparts can help determine q_0 (B. Leibundgut), and of course the local LSS with its walls, filaments, and voids that may or may not persist to high redshifts depending on the cosmological model.

Altogether, this wealth of data needs to be framed in a world model to make sense to us. As S. White pointed out, the current (standard) world model is based on a fairly limited set of basic assumptions, namely: (1) most matter is in some "dark" nonbaryonic form, (2) ordinary baryons are present in the amount predicted by Big Bang nucleosynthesis, (3) primordial density fluctuation are gaussian and were generated by quantum effects during inflation, (4) structures grow solely through the effect of gravity, and (5) galaxies form by dissipative collapse within massive halos made of dark matter. Within this frame the observations should allow us to unambiguously determine a consistent set of the main model parameters: H_0 Ω_0) Ω_b, Ω_{CDM}, Λ, and n, the spectral index of the primordial fluctuations. As S. White emphasised, should this effort fail, we will have to give up some of the five basic assumptions.

The role that the VLT will be able to play in observational cosmology will ultimately depend (besides the commitment of the ESO community) on its complement of focal instruments and on their efficiency. For this reason VLT instruments were on stage both at the beginning and at the closure of the meeting, with the PI's of the first-generation instruments and of those under consideration illustrating their scientific drivers and their technical performances. Thus, I. Appenzeller, S. D'Odorico, P. Felenbok, O. LeFèvre, R. Lenzen, A. Moorwood, and K. Taylor presented respectively FORS, UVES, FUEGOS, VIRMOS, CONICA, ISAAC, AUSTRALIS, and SINFONI, all acronyms that will become familiar to us like today are SUSI and EMMI and TIMMI, etc. Some limitations of the first-generation instruments emerged clearly at the meeting, especially concerning the multiobject and area spectroscopy, and G. Monnet in its closure talk illustrated how ESO is going to cope with this in selecting the next-generation instruments.

In the end, what lessons did we learn from this most exciting meeting, that may be relevant for planning the future science at the VLT? The first lesson was that VLT-grade projects need extensive preparation, both in terms of finding and selecting the appropriate targets, and in terms of dedicated scientific software to handle enormous data cubes. The second lesson comes from the tremendous success of a combined HST and Keck approach to so many astrophysical problems, with HST providing high-resolution imaging on fairly wide fields and/or UV spectroscopy, and the 10-m telescope providing spectra of sufficient resolution of the same objects. By the year 2000 about a dozen 8-m-class telescopes will be in operation world-wide, and European astronomers will held about a 50% share of the whole stack. Maintaining adequate access to HST, and especially to the Next-Generation Space Telescope now under study, is vital for European astronomy to get full profit from its investments on ground-based as well as space-borne telescopes (e.g. VLT, GEMINI, LBT, COBRAS/SAMBA, ISO, XMM, etc.). Only if such access will be secured (and expanded) will European astronomy remain fully competitive. The third lesson also comes from the HST experience. With the HDF, for the first time a huge amount of high-quality, frontier-science data are made public just days after having been obtained. This example is likely to be contagious, and a growing fraction of astronomical data is likely to be distributed in a similar way in the future. We should prepare and be prepared for that, and anticipate the sociological changes that such a new operation mode will bring along. The fourth lesson, perhaps a hardly new one, was that a large variety of observational capabilities is required to make progress in observational cosmology, and it is somewhat reassuring to appreciate once more that the current VLT instrumentation plan offers in fact the needed diversification. However, and this was the fifth lesson, the explosion we are now witnessing thanks primarily to HST and Keck can only accelerate further as more 8–10-m-class telescopes come into line. Hence, timing becomes essential. With progress being so fast, maintaining the schedule and deploying focal instruments in the shortest possible time is a top priority for the VLT project.

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Aerial view of Paranal taken by H. Zodet in May 1996.