Cosmology with objects from the Hamburg Quasar Surveys

© D. Reimers [1,2]

[1] Universitдt Hamburg, Hamburger Sternwarte, Gojenbergsweg 112, D-21029 Hamburg
[2] Email: dreimers@hs.uni-hamburg.de

Abstract: The highlights of the Hamburg Quasar Surveys (HS and HE) for questions of cosmological relevance are briefly reviewed:

- The discovery of the delayed HeII reionization of the Universe at z = 3 with HE 2347-4342
- The most accurate measurement of the primordial Deuterium abundance D/H in HS 0105+1619
- The discovery of up to now 10 new gravitationally lensed multiple QSOs
- The discovery of several transparent lines of sight to high redshift QSOs and the first observation of the rich EUV QSO absorption line spectra with HST, e.g., in HS 1700+6416
- The discovery of the most metal deficient known stars (HE 0107-5240, HE 1327-2326, HE 0557-4840) with Fe abundances of 10 (-5) solar and below
- The discovery of the bright PopII Uranium star HE 1523-0901 with the most accurate age determination from U/Th, Th/Eur, U/Ir, and Th/Os as 13.2. Gyrs.

1. Introduction:

High-redshift quasars brighter than B = 16.5 are extremely rare objects (~ 10^2 with z > 2.2 on the whole sky) but important targets for a variety of cosmological questions. The only way to discover these objects is an All-Sky-Survey. When we started in ~ 1983 the Hamburg bright QSO survey, the only existing wide-angle QSO survey was the Palomar-Green (PG) survey (Green et al., 1986), a UV excess survey based on photographic Schmidt plates. However, due to the entrance of the Ly б emission line into the B band, the broad-band UV excess method is unable to detect QSOs with z ≥ 2.2. Our intention was therefore from the beginning to use our own Schmidt-telescope on Calar Alto for an objective prism survey primarily for bright QSOs in the redshift range 2.2 ≤ z ≤ 3.2. From 1990 on we extended the prism survey to the south using the ESO Schmidt. The northern Hamburg Survey (HS) with a spectral resolution of about 50 E FWHM at Hг covers 567 Schmidt fields on 13600 deg^2, the southern Hamburg/ESO Survey (HE) with a corresponding resolution of 15 E covers ~ 9000 deg^2 on 380 Schmidt fields. Due to the high spectral resolution the Hamburg/ESO Survey could be used in addition to the QSO search for surveys of specific types of stars like WDs, horizontal branch stars, carbon stars, and in particular extremely metal deficient stars relevant for cosmology. All plates were digitised with the Hamburg PDS 1010 G microdensitometer. Details can be found in Hagen et al. (1995), Wisotzki et al. (1996) and Reimers & Wisotzki (2002).

2. Quasars and Cosmology

Bright, high-redshift QSOs are ideal sources for the investigation of intervening matter on the line of sight, be it diffuse for absorption lines studies or compact in form of gravitational lenses. In the following, the highlights from the HS and HE Surveys are presented which have contributed to observational cosmology.

2.1 The discovery of HeII reionization of the universe at z = 3 in HE 2347-4342

Intergalactic HeII Ly б absorption at л = 303.78 E can be observed with HST in the far UV of z ≥ 2.8 QSOs. However, due to intervening HI Lyman limit systems (LLS) most of the lines of sight to z = 3 are heavily attenuated. As shown by Мшller & Jakobsen (1990) and Picard & Jakobsen (1993) only ~ 5 % of the lines of sight to z = 3 are clear. Combined with the small number of bright QSOs (≤ 100) the expectation was that just a handful of bright QSO suitable for HeII absorptions studies exist. When we embarqued in 1990 on the Hamburg/ESO Survey, one of the explicit aims was to detect one bright QSO suitable for HeII observations with HST. A survey of bright promising HE QSOs with IUE finally in 1995 lead to the discovery of the "clear" line of sight towards HE 2347-4342. Subsequent observations with the GHRS onboard HST showed that HE 2347-4342 displays patchy HeII absorption at z = 2.8 – 2.9 (Reimers et al., 1997). The obvious explanation is that HE 2347-4342 marks the transition between optically thick HeII absorption for z > 3 as observed earlier in Q 0302-003 (Jakobsen et al., 1994) and a finite HeII opacity ф = 1 seen in HS

1700+6416, the first exceptionally UV bright QSO from the HS (Reimers et al. 1989, 1992), observed with HUT for z < 2.7 (Davidsen et al., 1996). The patches of low HeII opacity below z = 2.9 can be interpreted on the first bubbles of HeIII which finally overlap for z < 2.8 leading to a 'normal' HeII Lyman б 303.78 E forest at lower redshifts. This picture has been confirmed finally by high resolution FUSE observations of the HeII 303.78 E forest in HE 2347-4342 (Kriss et al., 2001) and HS 1700+6416 (Fechner et al., 2007a) – the only two QSOs bright enough for FUSE. A detailed comparison of the HI and HeII forest has shown that the ratio з = N(HeII/N(HI) – which can be shown to depend only on the steepness of the ionizing spectrum (Jakobsen, 1994) – has a mean value of ~ 80 but varies considerably on length scales of 10 – 15 Mpc (comoving), i.e. the ionizing UV background fluctuates considerably (Fechner & Reimers, 2007a, 2007b).

The final breakthrough of HeII reionization of the universe at z = 3 has two directly observed consequences: (1) the IG medium is abruptly reheated which leads to a relatively sudden increase of the mean kinetic temperature of the IG medium (Schaye et al., 1999; Ricotti et al., 2000; Theuns et al., 2002) and (2) due to the sudden change in the HeII opacity from z > 3 (optically thick) to z < 3 (optically thin), photoionization of metals in the truly diffuse IGM changes rather abruptly as seen in the evolution of the SiIV/CIV ratio with redshift (Songaila, 1998). The delayed reionization of HeII at z = 3 compared to HI at z > 6 is due to the fact that HeII (in contrast to HI) can only be ionized by the hard nonthermal continuum of AGN which form largely later than stars as we observe in the evolution of the QSO luminosity function.

2.2 The primordial Deuterium abundance D/H from HS 0105+1619

The theory of big bang nucleosynthesis predicts that the primordial D/H ratio depends sensitively on the cosmological baryon to photon ratio n_b/n_r (e.g. Kolb & Turner, 1990; Schramm & Turner, 1998). A precise measurement of the primordial deuterium abundance therefore gives the cosmic baryon density Щ$_b$. A natural place to look for primordial abundances is in high-redshift, low metal abundance intergalactic clouds where there is little contamination with processed matter ejected by stars where D is destroyed. However, it has turned out that for several reasons this is an extremely difficult measurement, and one of our HS quasars has met the necessary conditions. Because of the expected low D/H ratio of a few times 10^{-5}, the H column density has to be at least 10^{17} cm^{-2} which is a Lyman limit system. In such Lyman limit systems the Ly б line itself is often multiple and complex, and in the wing of such a strong line the weak D Ly б line shifted only by ~ 80 km/s to the blue has to be measured. This has turned out to be feasible only with high-resolution spectrographs on 10m class telescopes. David Tytler and coworkers have conducted a survey for suitable systems using among others all the bright QSOs from our northern HS Survey. It has turned out that the success rate in finding suitable clouds with measurable D and H is less than 1 % among high redshift quasars.

The z = 2.536 Lyman limit system in HS 0105+1619 (z = 2.6, B = 16.9 Hagen et al., 1999) is favourable for a precise measurement for two reasons. At first, with a hydrogen column density $logN_H$ = 19.42 the D satellite line is seen in several Lyman lines (Ly в, г, 5, 6, 7) which eliminates the blending problem with the normal Ly б forest in case that only D$_б$ is seen. Secondly, the z = 2.536 LLS has a metallicity of 0.01 solar which means that the observed D/H abundance ratio is primordial within the measurement errors. Thirdly, the measurement of the intrinsic velocity widths of D and H shows that the width is mainly thermal $V(D)/V(H) = 1/\sqrt{2}$ and that the D lines come from the same gas as the HI line. The final result was D/H = $2.54 \pm 0.23 \cdot 10^{-5}$ which leads to Щ$_b h^2 = 0.0205 \pm 0.0018$ (O'Meara et al., 2001).

2.3 Multiple QSOs and Ho from time delays

Bright, high z QSO surveys are particularly suited to discover gravitationally lensed QSOs due to the magnification bias. From the start of our bright QSO surveys one focus was the intention to discover further multiple QSOs because the 'founding father' of gravitational lens theory is my Hamburg colleague Sjur Refsdal. S. Refsdal had in a pioneering paper (Refsdal, 1964) shown how Ho can be measured from the light travel time difference (time delay) between two images of a lensed QSO, provided the gravitational potential of the lensing galaxy is sufficiently well known. S. Refsdal also pioneered the theory of microlensing (Chang & Refsdal, 1979), again long before microlensing has been observed unambiguously.

The first gravitational lensed QSO which we discovered was HE 1104-1805 (Wisotzki et al., 1993), maybe the most remarkable among the now 10 new discoveries from the HS and HE surveys. The flux ratios of the broad emission lines and of the continuum are different between images A and B, and the continuum flux ratios vary with wavelength, image A being distinctly bluer than A (1992). At that time we could not finally distinguish between the possibilities physical pair versus lensed QSO with microlensing causing the difference between the two images. In the meantime (Poindexter et al., 2007) image A being distinctly bluer than B, the time delay has been determined as T_D = 152 d, and the lens galaxy at z = 0.73 was discovered by Courbin et al. (1998). HE 1104-1805 is a gravitational (macro)lens with strong differential microlensing effects where the small QSO continuum source is strongly affected, while the larger broadline region is not. Morgan et al. (2007) estimate from the variability an accretion disk size (continuum source) of $5 \cdot 10^{15}$ cm.

Among the 10 gravitationally lensed multiple QSOs from our survey (cfa-www.harvard.edu/castles/), 5 are double, 5 are quadruples. Four of them have measured time delays (HE 0435-1223, RXJ 0911+0551, HE 1104-1805, HE 2149-2745) and could be used to determine Ho (Courbin, 2003; Oguri, 2007). At large, Hubble constants derived from the gravitational lens effect agree with the Cepheid/SNIa value of ~ 70 km/s (Mpc) although with a large scatter due to the degeneracies with the shape of the lens potentials. Turning around the argument, the reasonable agreement between the classical and the gravitational lens methods can be used to obtain information on the gravitational potential, in particular on DM in various types of lensing galaxies up to large distances.

HE 1104-1805 with its brightness and its image separation of 3.″1 has also been extremely useful for the measurement of the size of Ly б “clouds” by comparing the Ly б forest in the two lines of sight using high resolution spectroscopy (Smette et al., 1995). In addition, component A has a DLA at z = 1.66 while in the line of sight of B the hydrogen column density is already lower by a factor of ~ 100. The size of the DLA therefore is of the order of $\leq$ 20 kpc, consistent with a normal galactic disk.

In HE 0512-3329, both components have a DLA at z = 0.93, however with distinct differences. At a transverse separation of 5 kpc, the metal abundances are identical within the errors of measurement, but only one line of sight shows severe dust depletion and continuous absorption (dust extinction) in the UV. This is the first time that a single damped Ly б galaxy – probably the lensing galaxy – is probed by two different lines of sight – apparently two opposite sides of a single galaxy (Lopez et al., 2005).
HE 0818+1227 is particularly illustrative for shear effects in the lense. The lensing galaxy at z = 0.39 is the end member of a group of 4 luminous galaxies, and the combined effect of this galaxy chain is that the lensing galaxy is not on the line connecting the two QSO images (cf. CASTLES).

2.4 The EUV spectroscopy of high-redshift quasars

Besides the observation of HeII 303.8 E absorption in the two extremely bright QSOs HE 2347-4342 and HS 1700+6416 we have observed several bright, high-redshift QSOs from the HS and HE Surveys with the Hubble Space Telescope. Such objects are extremely rare due to the combination of a steep decrease of the surface density of quasars with brightness (factor of 6 per mag) with an increase with redshift of the probability to encounter at least one optically thick Lyman limit system (LLS) along the line of sight which leads to a steep dependence of the number of observable objects with limiting UV flux.

The first high-redshift QSO observed spectroscopically with HST was HS 1700+6416 (z = 2.73). It has a rather spectacular UV spectrum with 7 optically thin LLSs with redshifts between 0.86 and 2.44 which shape a "Lyman Valley" in the mean opacity as predicted by Мшller & Jakobsen (1992).

Prominent absorption lines which in HS 1700+6416 have been seen for the first time in a cosmic object except the sun are OV 629 E ; OIV 553/554, 608, 787 E; OIII 702, 833 E; NeIV 543 E; NeV 480, 568 E; SIII 677, 698 E; SIV 657 E; NIII 374, 685, 989 E; CIII 386 E and many others (Reimers et al., 1992; Vogel & Reimers, 1995). Also, the HeI resonance lines 584 E and 537 E could be seen for the first time in LLSs of HS 1700+6416 (Reimers & Vogel, 1993).

In HS 1700+6416 it could be shown for the first time that the oxygen to carbon abundance ratio O/C is enhanced by a factor of ~ 3 at low metal-abundances (1/100 solar) and high redshift, in accordance with expactations that nucleosynthesis in early massive-star SNII produce an enhanced oxygen abundance. Future high-resolution spectra, e.g. with COS on HST, will allow to reconstruct the shape of the metagalactic radiation field, which governs the photoionization of metals in the IGM, from line strength ratios OII/OIII/OIV/OV, NeII/NeIII/NeIV/NeV etc. with high accuracy. For methods and first results cf. Agafonova et al. (2007), Reimers et al. (2006) and Levshakov et al. (2008). The detailed reconstruction of the shape of the metagalactic UV background between 1 and 10 Ryd is a precondition for measurements of the metallicity and its evolution with redshift of the diffuse IGM where most baryons (and metals) reside. Up to now the metallicity evolution of the diffuse has been followed with CIV, SiIV, CII and OVI lines from which accurate abundances can be obtained only with knowledge of the spectral energy distribution (SED) of the ionizing background. Consequently, one has to admit that the metallicity of the largest part of the baryons is at present not known.

The direct measurement of the SED is possible only in absorption line systems where a sufficient number of ionization stages can be observed simultaneously. And even in such a favourable case it is always possible that a neighbouring galaxy or AGN is dominant. Therefore in practice the SED and intensity of the ionizing UV background has been reconstructed by integrating at any redshift z over all preceding ionizing sources and taking into account radiative transfer effects in the IGM itself (Haardt & Madau, 1996). A problem is that SED of AGN at energies above 2 Ryd is poorly known. The only 4 objects with measured flux distribution between 2 and 4 Ryd are from the Hamburg Survey. They show that the assumption of a power law distribution of the form $F_н \sim н^б$ with б = -2 for energies above 1 Ryd (Zheng et al., 1997) is unrealistic since the four well observed luminous QSOs HS 1700+6416 (z = 2.73), HS 1307+4617 (z = 2.19), HS 1103+6416 (z = 2.13) and HE 2347-4342 (z = 2.89) are all individuals with distinct differences between each other (cf. Fig. 2 in Reimers et al.,. 1998). Only HS 1103+6416 resembles the mean spectrum of Zheng et al. (1997). HE 2347-4342, one of the most luminous QSOs in the Universe, is also the most extreme in that the turnover of the big blue bump is not seen at all for energies below 4 Ryd. The spectrum follows roughly $F_н \sim н^{-0.6}$ over the whole range between 1 and 4 Ryd. This is the hardest EUV spectrum known so far among QSOs. The spectrum of HS 1700+6416 on the other hand, with a similar optical luminosity, does not follow a power law at all.

2.5 Variability of fundamental constants with cosmic time

HE 0515-4417 (Reimers et al., 1998) is for two reasons up to now the best source for measuring variations of the fine-structure constant:
- it is with V = 14.9 the brightest high redshift (z = 1.72) quasar in the sky which allows high S/N spectra with UVES/VLT
- it has a complex sub-DLA system at z = 1.15 with more than 30 components seen in FeII, which means that 2 dozen simultaneous measurements of Дб/б are possible in one spectrum.

The measurements have up to now yielded a null result (Quast et al., 2005; Levshakov et al., 2006; Chand et al., 2006). For details I refer to Sergei Levshakov's presentation at this conference.

HE 0515-4417 might be interesting in the future also for measurements of the electron to proton mass ratio, since the z = 1.15 sub-DLA system shows a rich H_2 spectrum in its central component (Reimers et al., 2003) which is much less blended with the Ly б forest compared to known systems at higher redshift.

3. Stellar archeology and near-field cosmology with metal-poor stars
The oldest and most metal deficient stars

While the Hamburg/ESO Survey was originally designed as a wide-angle survey for the brightest quasars in the southern hemisphere, it was realized right from the start that the 3 times higher resolution of the HE objective prism plates compared to the HQS would enable an efficient search for various types of stars. As a first step (Christlieb et al., 2002a), techniques have been developed for automatic spectral classification and applied to the entire HES digital data base. In the following years Norbert Christlieb from Hamburg Observatory embarqued on a gigantic project to search for the oldest and most metal-poor stars (PopIII ?). On the entire survey area of 379 plates (8853 deg^2) a total of 20271 candidates in the brightness range $10 \leq B \leq 18$ have been selected. For these candidates spectroscopic follow-up observations were necessary, and up to March 2008 ~ 6840 have been observed with 1 – 6.5m telescopes in Australia, Chile and the USA. In the end this sample contains 528 newly discovered extremely metal deficient stars with less than 1/1000 solar metallicity (less than 100 were known before). The most interesting extremely metal-deficient stars have finally been observed with telescopes of the 8m class (VLT/UVES, Keck/HIRES, Subaru/HD, SMagellan/MIKE), altogether 206 stars with high quality spectra, further 369 stars with “snapshot” quality spectra.

Highlights are the three most metal deficient stars known (HE 0107-5240, HE 1327-2326, and HE 0557-4840), the bright, extreme r-process star HE 1523-0901 in which for the first time the abundance ratios of U, Th, Os, and Ir could be applied for the best available age determination.

3.1 The most metal deficient stars

The most metal deficient stars, believed to have been formed at high redshift (z > 5 ?), are archeological relicts with detailed information about the nucleosynthesis processes operating at a time from which we yet have barely any information.

The three record holders in low metallicity from this epoch have been discovered by the Hamburg/ESO Survey: The first was HE 0107-5240 (Christlieb et al., 2002b) with [Fe/H] = -5.2, the second HE 1327-2326 with [Fe/H] = -5.4 (Frebel et al., 2005), and recently HE 0557-4840 (Norris et al., 2007) with [Fe/H] = -4.75. Quite unexpectedly, the first two stars show extreme overabundances, relative to Fe, of carbon [C/Fe] ~ 4, nitrogen [N/Fe] ~ 2-4 and oxygen [O/Fe] ~ 2-3. HE 0557-4840 is a transition type star between the more normal metal deficient star with [Fe/H] > -4 and the two extreme examples both in [Fe/H] and in more moderate CNO overabundances. Concerning the question whether the high CNO abundances are due to self-enrichment in these stars, e.g., by binary evolution or from the preceding (first) generation of stars, Umeda and Nomoto (2003, 2005) have shown that in a Population III star with 25 M_o which explodes with low explosion energy, a large part of the envelope can fall back onto the black hole and as a result high C/Fe, N/Fe, and O/Fe are ejected.

3.2 The Uranium star HE 1523-0901

One important test of cosmological models is the comparison of expansion ages as determined e.g. from the WMAP data (t_{exp} = 13.7 Gyr) with directly determined lower limits for the age of the universe as determined from the age of stars. Well known methods are age determinations of globular clusters by comparison of theoretical isochrones with their MS turnoff for the age of the galactic Halo or WD cooling ages for the galactic disk. While the most metal deficient globular clusters in our Galaxy have [Fe/H] = -2, the question is whether the most metal deficient stars are older and yield a larger value for the lower limit to the age of the universe.

With the discovery of U and Th in the r-process enhanced metal deficient ([Fe/H] = -2.9) star CS 31082-001 by Cayret et al. (2001), the U/Th abundance ratio could be used to infer an age of the heavy elements due to their different half life times (^{232}Th: 14Gyr versus ^{238}U: 4.5 Gyr). The techniques yielded an age of 14 ± 3 Gyr (Hill et al., 2002) where the relatively large uncertainty is due to both the observations (the weak Uranium line 3859.6 E is always on the wing of a strong FeI line) and the assumed production rates of the elements.

In this context, a spectacular success of the HE survey was the discovery of the bright (v = 11.1) giant HE 1523-0901 (Frebel et al., 2007). At [Fe/H] = -2.95 the star has high overabundances of the r-process elements [r/Fe] = +1.8. The combination of high r-process abundances and extreme brightness of the star made possible – through UVES spectra with R = 75 000 and an S/N = 350 at 3900 E – the detection of ~ 16 different neutron-capture elements, besides U and Th also Os and Ir. For the first time it has been possible to use several chronometers, such as the U/Th, Th/Eu, U/Ir, and Th/Os ratios. The resulting age is 13.2. Gyr, in good agreement with the WMAP result of 13.7 Gyr for the age of the universe.

3.3 Nucleosynthesis in the first stars

Two further stars discovered by the HE survey pose new – not yet answered – questions to nucleosynthesis in the first stars. Examples are HE 1424-0241 and HE 1327-2326.

HE 1424-0241 is a star on the lower giant branch with [Fe/H] = -4 which has a strong deficiency of Si relative to Mg (1/25 solar) and deficiencies in Ca and Ti. Nomoto et al. (2008) have suggested that these abundances can be reproduced by the angular dependence of the yield in aspheric explosion models.

Another peculiarity is the presence of SrII (with simultaneous absence of BaII) in HE 1327-2326 for which there is no standard explanation like the weak s-process or the r-process.

Apparently, at the lowest abundances of [Fe/H] ≤ -4 we begin to see the products of individual SN progenitors from the first generation of stars. Larger samples of such stars will finally help us to understand the formation and evolution of the first generation of massive stars in the universe.

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