HIGHLIGHTS FROM THE KEY PROGRAMME
'A WIDE-ANGLE OBJECTIVE PRISM SURVEY FOR BRIGHT QUASARS'

The Hamburg / ESO Survey

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The Hamburg/ESO Survey is one of the important observational projects currently being carried out at La Silla whose objective is, among other things, to provide targets for the VLT (and HST).

1. Introduction

Bright quasars, in particular at high redshift, are an important tool of extragalactic astronomy and cosmology. Quasars can be used as light sources which probe intervening matter at cosmological distances and offer thereby a means to study the physical properties of distant gas clouds (abundances, ionising radiation) by high-resolution spectroscopy of absorption-line systems and of the Lyα forest. Notice that even with UVES at the VLT, a high-resolution spectrum of a 16th-magnitude QSO will require 10 hours integration time to reach a signal-to-noise ratio of 100. Such bright QSOs are also required for studies of absorption lines at $z > 2$ in the UV with the Hubble Space Telescope. Here we have to meet the additional

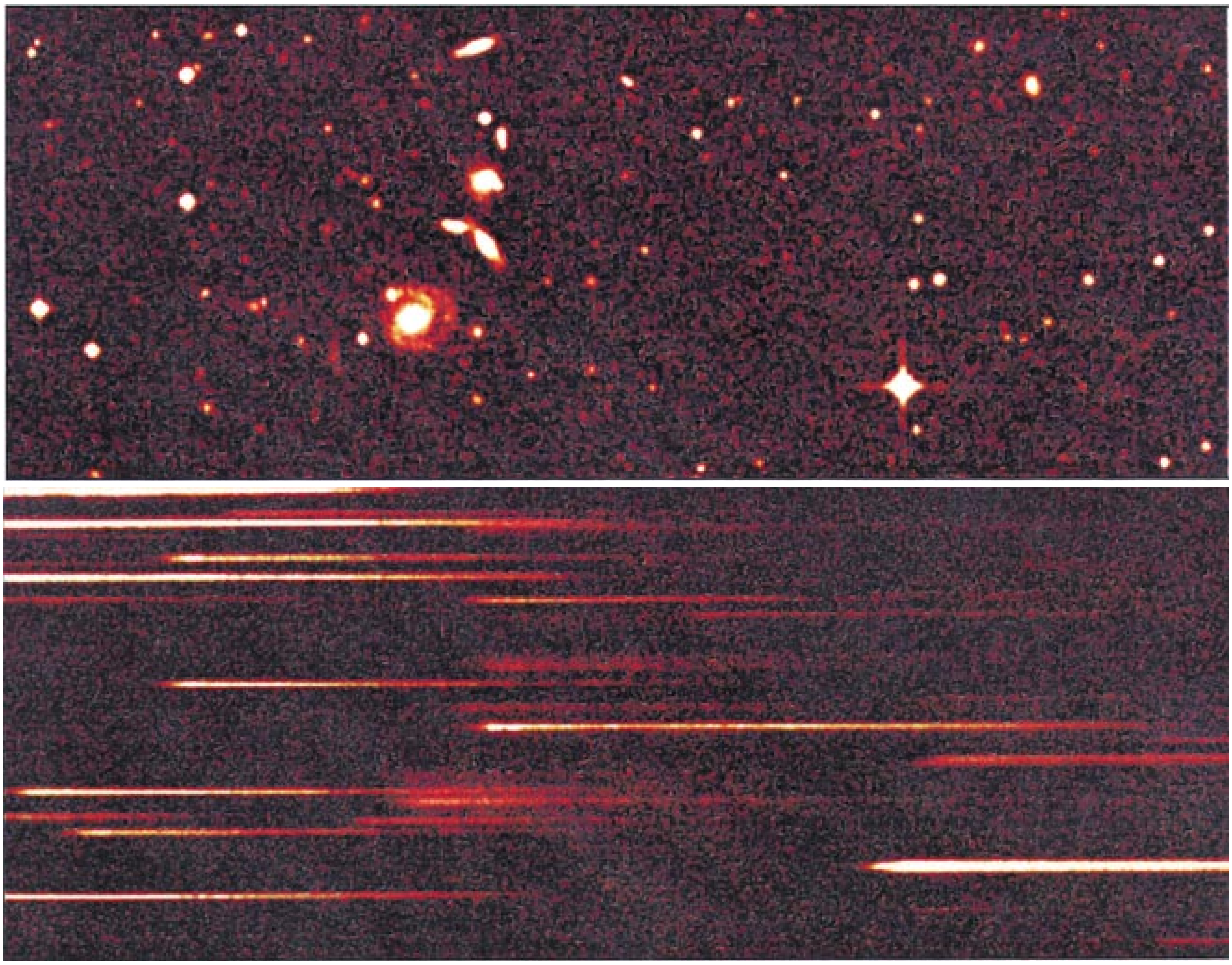

Figure 1: The area around the Seyfert 1 galaxy HE 0323–4204 (= ESO 301–G13; z = 0.058). In the upper panel, the direct image from The Digitized Sky Survey *shows* a *small group of interacting galaxies. The lower image is the corresponding section from the scanned objective-prism plate, with the same image scale: In the centre, the Seyfert galaxy is conspicuous because of its long, blue spectrum (note that it is much sharper than the fuzzy spectra of the other galaxies, indicating its point source active nucleus); there are also some emission lines. The other objects are normal foreground stars.*

complication that for $z > 2$ due to absorption by optically thick Lyman limit systems of intergalactic matter, at most 20% of the lines of sight are transparent down to the shortest wavelengths observable with HST (1150 Å). This leaves us with the rather pessimistic (realistic) prediction that the whole sky may contain only 20 QSOs with $z > 2$ observable spectroscopically at resolution > 10^3 with HST in the UV (Jakobsen, 1995).

Among luminous QSOs there is also an enhanced probability to detect gravitational lenses. Surdej et al. (1993) found that among high-luminosity QSOs ($M_V < -29$) there is a chance of the order of 1% to discover a multiple image. Multiple QSOs offer the possibility to measure the Hubble constant H_0 via the time delay between images, to study the distribution of dark matter in the lenses and to measure the transverse sizes of absorbing gas clouds along the two light paths. The number of multiple QSOs truly gravitationally lensed is still small (≤ 20).

Since the rare bright QSOs can be found only by wide-angle surveys which cover basically the whole extragalactic sky, we proposed in 1989 to start such a survey for the largely unexplored southern sky using the ESO 1-m Schmidt Telescope equipped with an objective prism, in extension of an already running similar project in the northern hemisphere, the Hamburg Quasar Survey (Hagen et al., 1995), using the Schmidt telescope on Calar Alto (the former Hamburg Schmidt).

The prime scientific aims of the Hamburg/ESO survey as originally formulated (Reimers, 1990) are:

- to provide a sample of high-redshift QSOs for detailed absorption-line studies with the VLT;
- to search for further gravitational lenses (multiple QSOs);
- to find a few bright unabsorbed QSOs at EUV rest wavelengths suitable for He II 304 Å (the He II Lyα forest and the He II Gunn-Peterson test) and for metal abundance studies using EUV absorption lines;
- to provide a more complete QSO sample at the bright end since there was growing evidence that existing wide-angle QSO surveys like the Palomar-Green survey are rather incomplete.

As a by-product of the survey, we expected to find several interesting species of rare hot stars, e.g., exotic white dwarfs. While we gained experience conducting the survey, it became clear that several more objectives could be added to this list, among others:

- to directly determine the combined *local* ($z \approx 0$) luminosity function of quasars and Seyferts;
- to investigate the evolution of luminous QSOs up to $z = 3$;

We hope to convince the reader in the following that we have indeed reached our aims.

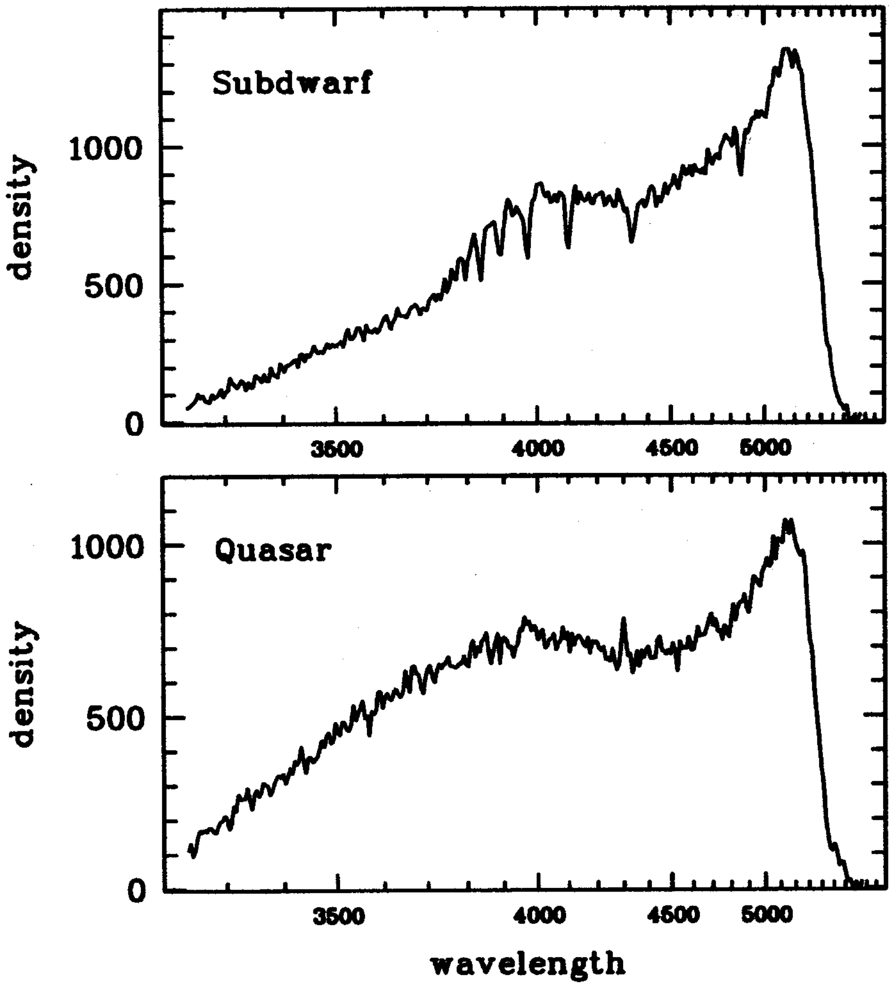

Figure 2: Example Schmidt spectra of two bright colour-selected quasar candidates, illustrating the power of using a high-dispersion objective prism. Note the non-linear wavelength scale. Ordinate is photographic density above diffuse background in arbitrary units. The sharp drop longward of 5400 Å is caused by the photographic emulsion. The narrow Balmer absorption lines clearly identify the upper object as a Galactic star. The lower panel shows a quasar at z = 0.15 (confirmed by slit spectroscopy): no stellar absorption is visible, and the only emission feature is a very weak and narrow [O II] line at a redshifted wavelength of ~ 4300 Å.

2. Survey Procedure

The ESO Schmidt is one of the few large Schmidt telescopes with an objective prism. With 4° prism angle the dispersion is quite high (450 Å/mm at Hγ), and one might think this property makes it useless for extragalactic, especially quasar work where usually faint limiting magnitudes are to be achieved. However, it turned out that in a wide-angle survey for bright ($B < 17...18$) sources this was a lucky combination, as the spectral resolution in the prism spectra is high enough to unambiguously detect many stellar absorption features, and the quasar candidate samples scheduled for follow-up spectroscopy can be kept small (see Fig. 2). Recall that at $B \approx 16$, more than 90% of just the UV excess sources are blue stars rather than quasars. With ~ 5–6 magnitudes of dynamic range on the plates, we furthermore have essentially no *bright* limit: If there should exist a sister object to 3C 273 within the area covered by our plates, we are confident that we would find it (in fact, 3C 273 itself has already been 'rediscovered', see Fig. 4).

Performing an automated wide-angle survey using Schmidt plates requires the ability to digitise, store and process a large number of Schmidt plates on a reasonable time scale, with a minimum of human interaction. After an initial phase where we used an older digitisation and reduction scheme to select our candidates (described in Wisotzki et al., 1996a), we implemented in 1994 a newly-developed software package designed to preserve a maximum of information inherent in the plates while still keeping up with the requirement of high efficiency. In brief, the essential steps of the procedure are:

1. Object detection on digitised plates. Thanks to the availability of *The Digitized Sky Survey,* we have a 100% coverage of our objective-prism plates with a corresponding direct plate. This step yields a catalogue of typically ~ 150,000 sources per Schmidt field. No morphological segregation is im-

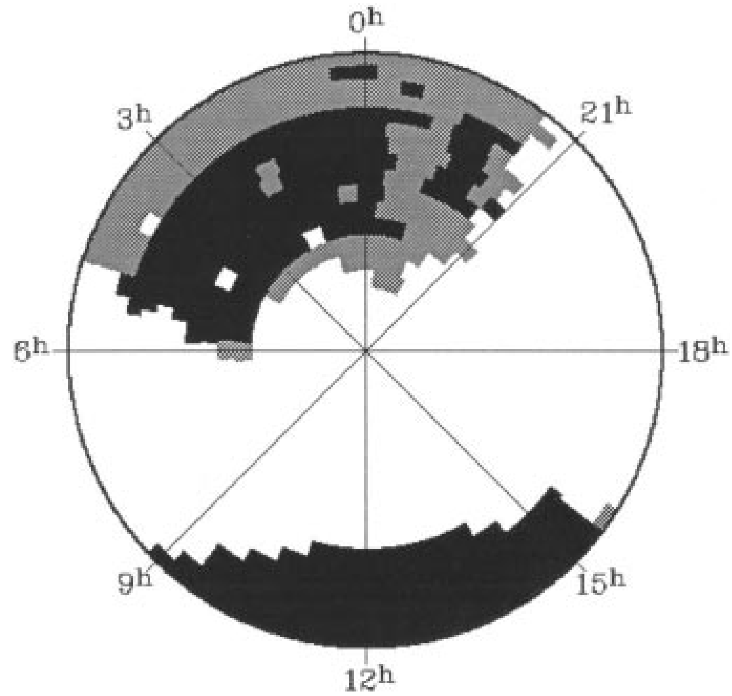

Figure 3: Distribution of available (shaded) and already digitised (black) ESO Schmidt objective-prism plates in the Hamburg/ESO survey, in azimuthal equal-area projection centred on the South Pole. The surrounding circle shows the equator (δ = 0°), and octants are labelled by right ascension. The fields left white are in or too close to the Milky Way, except three plates still missing.

posed: both point and spatially resolved sources remain in the sample. This is important and quite different from most other QSO surveys; we do not wish to introduce biases against gravitationally lensed or low-redshift objects.

2. Full-plate scan of objective-prism plate in mapping mode with the PDS 1010G in Hamburg, requiring about 16 hours of scanning time. Each plate yields 430 MB of raw pixel data, archived permanently on CD-ROM. A small portion of such a scan, together with the corresponding section of the direct data, is shown in Figure 1.

3. Astrometric transformation from direct to spectral plate, providing an accurate (~ 5 Å rms) wavelength zero point for each spectrum. Spectra locations contaminated by a nearby object are automatically recognised and flagged as 'overlaps'.

4. Optimal extraction of spectra from the digital data, giving ~ 40,000 spectra above a minimum S/N ratio of 2 per plate, corresponding to a detection limit of B ≃ 18 ± 0.5 (depending on plate quality and seeing).

5. Candidate selection using a multitude of selection criteria:

– UV excess spectra;
– objects with 'blue' continuum slopes;
– emission-line objects;
– spectra with continuum breaks;
– dedicated Seyfert criterion.

Note that, contrary to a frequent belief, presence of emission lines is *not* essential for quasar candidate selection on digitised objective-prism plates; the large majority of quasars already satisfies the UV excess condition.

6. Remove 'false candidates', mostly stars and plate artefacts. This is the only partially interactive step in the procedure. At the same time, the remaining candidates are graded for follow-up observations. The 'completeness limit' is fixed one magnitude above the detection limit (i.e., at S/N ≈ 5). Below this limit, only *bona fide* QSO candidates, especially at high *z*, remain in the sample.

7. Snapshot slit spectroscopy of high-grade candidates using mainly the ESO 1.52-m telescope. An exposure time of 5 minutes is usually sufficient, yielding spectra with S/N > 15 for virtually all candidates. A success rate of ~ 60–70% has now been achieved, with most of the non-quasars being peculiar blue stars.

3. Status of the Project

At the time of writing (April 1997), the mapping of the Southern extragalactic hemisphere by ESO Schmidt prism plates is essentially complete. Altogether, more than 460 spectral plates have been taken – just in time before the Schmidt telescope will stop to take IIIa-J glass plates. Plate digitisation, candidate search and follow-up spectroscopy are completed for more than 200 fields. Figure 3 shows the distribution of acquired and processed fields in the sky. About 650 new bright QSOs and Seyfert galaxies have been discovered, together with several hundred QSOs previously known in the fields. A first set of the newly discovered objects has already been published (Reimers et al., 1996a), and more will follow soon.

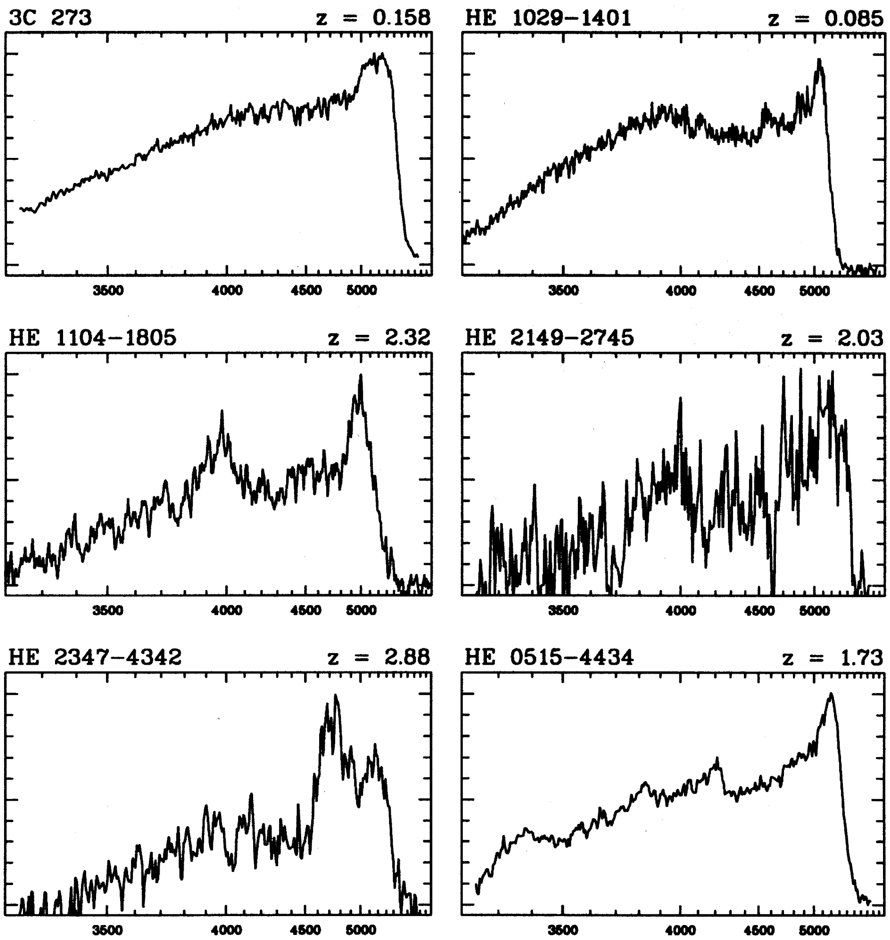

Figure 4: Portrait gallery with prism spectra of highlight objects featured in the text.

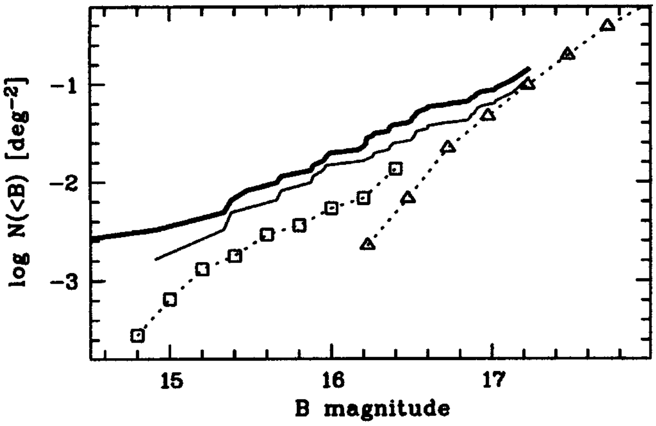

Figure 5: Cumulative surface densities of bright QSOs with z < 2.2. Thick line: Hamburg/ESO survey, z > 0.07, thin line: the same for z < 0.2. Open squares show the z > 0.07 counts from Schmidt & Green (1983), triangles give the LBQS (Hewett et al., 1995) relation, valid for z > 0.2.

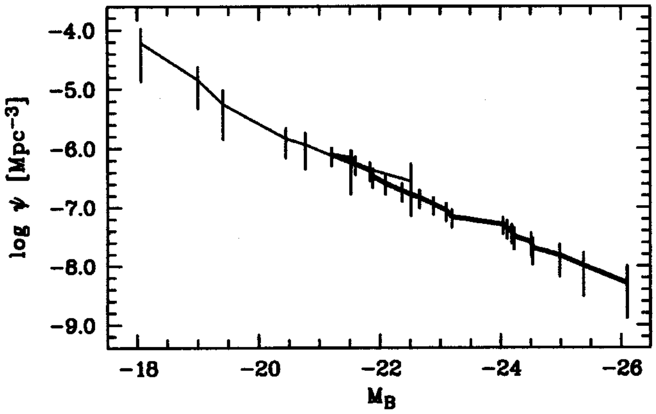

Figure 6: Combined local luminosity function of quasars and Seyfert 1 nuclei with z < 0.3, based on magnitudes corrected for the host galaxies.

In order to allow quantitative estimates of quasar surface densities and luminosity functions, we have launched a photometric calibration project for the Hamburg/ESO survey. Based on short B and V exposures made with the Dutch 90-cm telescope on La Silla, we are now able to give reliable magnitudes down to $B \simeq$ 18–19 in already more than 300 fields; we expect to finish the calibration by the end of 1997 and shall then make the sequences available to the community.

In the following we highlight some of the most important results obtained during the last few years. In Figure 4 we present examples of objects, compiled from the database of digital objective-prism spectra. In this figure we additionally feature our two champions: 3C273 (= HE 1226+0219; B = 13.2, z = 0.158) and HE 1029–1401 (B = 14.1, z = 0.085), the two brightest QSOs in the entire sky.

4. Highlights

4.1 The local luminosity function of QSOs and Seyfert 1 nuclei

It is well known that quasars undergo strong evolution with cosmological epoch with a maximum in number density and/or luminosity at redshifts between $z \simeq$ 2 and 3. Good knowledge of the local quasar luminosity function (QLF) is required for several reasons:

• Quasar evolution can be understood quantitatively only with a reliable zero-point at the present epoch.

• The interpretation of quasar absorption lines requires knowledge of the evolution of the metagalactic UV background radiation field which is itself due to quasars.

• Detailed studies of quasar properties, e.g., host galaxies or distribution of spectral properties, demand a complete local sample from which unbiased sub-samples can be drawn.

In a first analysis, a complete flux-limited subsample has been constructed on a ~ 600 deg^2 subarea of the Hamburg/ESO survey (Köhler et al., 1997). The two main results of this investigation are summarised in Figures 5 and 6. First, we find that the cumulative surface density $N(< B)$ of bright QSOs is much higher than in the Palomar-Green survey (PG; Schmidt & Green, 1983), by a factor ~ 3 at B = 16, and by an even larger factor at B = 15, while it joins smoothly the relation from the LBQS (Hewett et al., 1995) for B > 17 (cf. Fig. 5). Our results confirm the suspicion raised by authors that the PG survey is highly incomplete.

Using this sample we have constructed the combined local (z < 0.3) luminosity function (LF) of QSOs and Seyfert 1 nuclei, the first such construction from a single survey in the literature. The cumulative LFs of luminous quasars and of low-luminosity Seyferts join smoothly (cf. Fig. 6), and both can be represented by the same single power law $\phi(L) \propto L^{\alpha}$ with $\alpha \approx -2.2$, without any indication of a break as demanded by the 'standard picture' of pure luminosity evolution. We find that the space densities of the most luminous QSOs ($M_B < -24$) are much higher in the local universe than hitherto assumed, as the Hamburg/ESO survey contains almost an order of magnitude more low-redshift QSOs per unit volume than the PG survey. The implication is that between z = 2 and z = 0 quasar evolution is much slower than assumed, and that the most luminous sources show the slowest evolution, in clear contradiction to the notion of pure luminosity evolution.

4.2 Gravitational lenses

HE 1104–1805: This new pair at z = 2.32 with 3″.1 separation (see also the

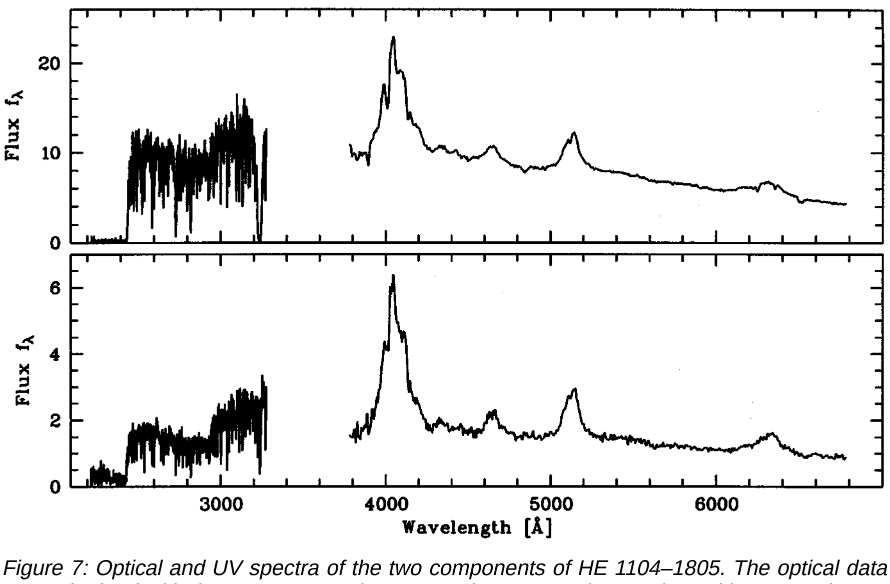

Figure 7: Optical and UV spectra of the two components of HE 1104–1805. The optical data were obtained with the ESO 3.6-m telescope and EFOSC1, the UV data with HST and FOS. Fluxes are given here, and in the following figures, in units of 10^{-16} erg s^{-1} cm^{-2} Å^{-1}.

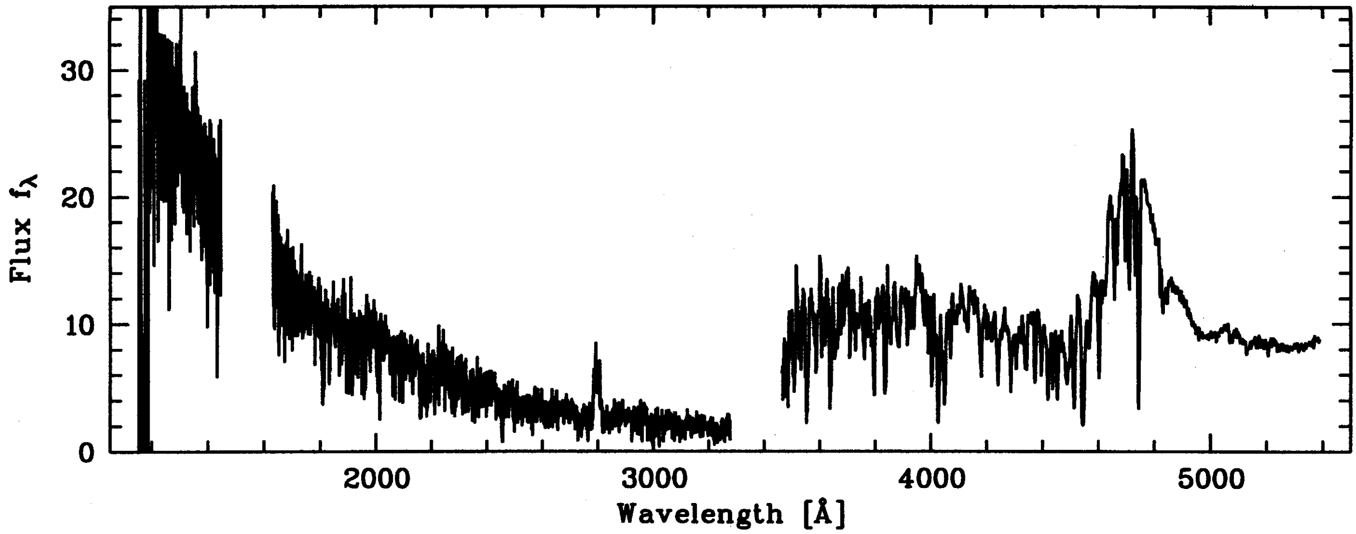

Figure 8: Combined optical/UV spectrum of HE 2347–4342, obtained with the ESO/MPI 2.2-m telescope and EFOSC2, and with HST plus FOS (longer wavelengths) and GHRS (short wavelengths).

discovery report in *The Messenger* 72, 1993) is an exciting object for two different areas of research. Both components are bright enough for high-resolution spectroscopy (component A has B = 16.7, component B has B = 18.6) with the aim to determine the transverse sizes of absorbing clouds in the line of sight. Smette et al. (1995) have shown that the sizes of the Lyα clouds (about 100 such absorber systems have been detected) in the range $1.7 \leq z \leq 2.3$ must be larger than ≥ 200 kpc. Most interesting is a strong metal-line system at z = 1.66 which in A is a damped Lyα system with log $N_H \simeq 20.8$. Our HST spectroscopy with the FOS at $\lambda/\Delta\lambda$ = 1300 of both components shows that the same z = 1.66 system is a Lyman limit system in the line of sight of B with a non zero flux below the LL which allows to determine the hydrogen column density at log $N_H \simeq 17.6$ (Fig. 7). This is the first direct determination of the size of a damped Lyα system: the column density decreases by a factor of 10^3 over 20 kpc. This finding confirms the current picture of damped Lyα systems being 'galactic disks'.

HE 1104–1805 is also a remarkable gravitational lens system, not just a binary QSO. Our spectra taken in 1993 (Wisotzki et al., 1993) showed the two components with very similar spectral properties: identical emission line fluxes except a constant factor 2.8 between components A and B; however, the difference spectrum $f_A - 2.8 \times f_B$ reveals a hard and featureless excess continuum in A that could be due to selective amplification by microlensing by stars in the lensing galaxy. Spectra taken 1.5 years later confirm the gravitational-lens picture: Both components became fainter in the continuum with no changes in the emission-line fluxes (Wisotzki et al., 1995). It appears rather contrived to assume that two physically distinct sources show the same specific spectral variations, while the observed similarity of variations is a natural consequence of the gravitational-lens picture. The observed continuum excess in component A must be largely due to microlensing. Since 1995, we perform a regular spectrophotometric monitoring of this pair at ESO.

HE 2149–2745: This is a pair of redshift z = 2.03 BAL quasars separated by 1.″7 (Wisotzki et al., 1996b). The two spectra, with their highly specific broad P Cyg profiles and detached absorption troughs, appear identical except for a constant factor of 4.3, provide convincing evidence for the gravitational-lens hypothesis. The system is furthermore very interesting as the lensing galaxy has possibly been detected.

4.3 UV bright objects for spectroscopy with HST

Observing high-redshift quasars in the far UV is of key importance for the study of QSO absorption-line studies since the dominant ionisation stages of abundant ions (O III–O IV, NIII–N IV, Ne III–Ne VII, etc.), and the He I 584 and He II 304 resonance lines are in the intrinsic EUV part of the spectrum shifted to the HST range only in high redshift QSOs. However, a serious obstacle is posed by the cumulative free-bound absorption of hydrogen due to the numerous Lyα forest clouds and in particular the optically thick Lyman limit systems (see above).

All bright high-redshift unabsorbed QSOs known today (7 with z > 2) are from the Hamburg Quasar Surveys,

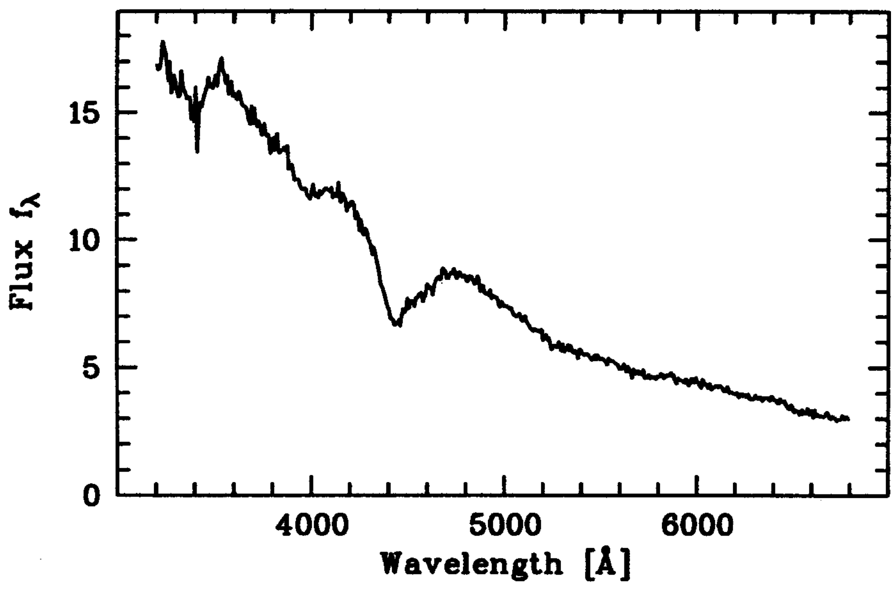

Figure 9: Low-resolution optical spectrum of the enigmatic object HE 1043–0502, taken with the ESO 1.52-m telescope.

and 5 of these have been observed in the meantime with HST. Besides HS 1700+6416 (z = 2.72) with its spectacular 'Lyman Valley' spectrum (Reimers et al., 1992) in which altogether about 40 new quasar absorption lines from the EUV have been discovered, allowing abundance studies in high-ionisation systems at high redshift, the most important object is **HE 2347–4342** (V = 16.1, z = 2.87). This bright QSO was discovered on La Silla in a follow-up run in October 1995 and observed with IUE to be unabsorbed down to at least 1200 Å in November 1995. With a flux of 3×10^{-15} erg cm^{-2} Å^{-1} s^{-1} near 1200 Å, HE 2347–4342 is a factor > 10 brighter than the two known z > 3 QSOs in which redshifted He II 304 Å absorption had been observed (Jakobsen, 1995). What had been seen so far was an absorption trough shortward of 304 Å in the QSO rest frame with the open question whether the detected He II opacity is solely due to unresolved He II forest line absorption, or contains a contribution from a diffuse IGM (the so-called Gunn-Peterson effect). Our June 1996 observations of HE 2347–4342 with the GHRS of the Hubble Space Telescope in its low-resolution mode ($\lambda/\Delta\lambda \simeq 2000$) for the first time partly resolve the He II absorption (Fig. 8).

The rather spectacular He II absorption spectrum shortward of 1186 Å shows a succession of broad blacked-out "troughs" with no detectable remnant flux and "voids" with less than 50 per cent flux depression. Detailed modelling of the He II 304 Å forest using a high-resolution spectrum of the Lyα forest taken by Susanne Koehler in a 9-hour exposure with CASPEC at the 3.6-m telescope shows that while the "voids" can be explained by a combination of Lyα forest clouds with an additional small diffuse component (Ω_{diff} < 0.02 $h_{50}^{-1.5}$ as a strict upper limit), the "troughs" can only be explained with the assumption of incomplete He II ionisation (Reimers et al., 1997). Apparently, He II reionisation is delayed compared to H ionisation and the expanding He III regions do not yet overlap at z = 2.9. In HE 2347–4342 we see for the first time the epoch of reionisation of the universe near z = 2.9.

A further highlight is the 1995 discovery of **HE 0515–4434**. With V = 15.1 and z = 1.73 it is the brightest known z > 1.5 QSO in the sky and among the most luminous objects in the universe. From IUE observations we know that between 2000 and 3000 Å it is also the UV brightest high-redshift QSO known and thus the best target for medium-resolution observations with STIS onboard HST of the Lyα forest in the largely unexplored redshift range $1 \lesssim z \lesssim 1.6$.

4.4 Rare stellar objects

The combination of the relatively high spectral resolution of (depending on seeing) 10–20 Å FWHM of the ESO Schmidt objective-prism spectra with a limiting magnitude of $\sim$ 17 for visibility of stellar absorption features applied in a wide-angle survey offers the unique chance to detect stars with unusual spectra, in particular hitherto unknown types of stars. Since both AGN and stars with known absorption features (Balmer and Helium lines, Ca II H+K, ...) can be selected quite effectively, the not classifiable remaining objects have either no lines at all, or absorption spectra with very unusual wavelength patterns.

Among the latter we have found four magnetic white dwarfs with field strengths of several hundred Mgauss (Reimers et al., 1996b), and at least 3 further magnetic WDs with Zeeman triplets. Even more exotic is **HE 1043–0502**: Similar to GD 229 which probably has a He-rich atmosphere with fields above 1000 MG, it has broad, strong absorption features, none of which could be identified yet. We show the discovery slit spectrum in Figure 9, inviting the readers to guess about the physical nature of this object.

Another highlight has been the discovery of a new type of stars, with **HE 0504–2408** as one of their prototypes, namely DO white dwarfs with absorption lines of ultrahigh ionisation states like O VIII, Ne IX, etc. (Werner et al., 1995). According to their line profiles these lines must be found in expanding coronae of hot WDs.

5. Future Prospects

We expect to finish candidate selection and spectroscopic confirmation of candidates in about three years from now, where the time-limiting factor is mainly the digitisation of plates. More than 500 further new bright QSOs will be found, well timed to provide the community with a rich selection of objects for spectroscopy with UVES at UT2 of the VLT.

While the most interesting targets for VLT spectroscopy are presumably the high-z QSOs, the majority of quasars detected in the Hamburg/ESO survey will be at rather low redshifts, about 50% having z < 0.5. This will be an extraordinary pool to construct large and well-defined samples of highly luminous low-redshift QSOs, to study the relationship between QSOs, their environments, and their evolution in detail.

We have recently started developing a software package to classify stellar objective-prism spectra from their absorption lines, with the main intention to enable an efficient search for rare stellar types, irrespective of colour criteria. When applied to the final database of several million spectra, we will be able to construct complete samples of carbon stars, hot and cool white dwarfs of various subtypes, horizontal branch stars, etc.

Among the objects with no detectable stellar features we expect Halo stars with extremely low metal abundances ([Fe/H] < –3). Tests have shown already that we are indeed able to select such objects with good efficiency. It will be possible soon to provide larger candidate samples, in particular of the fainter unevolved objects, which can be observed with UVES with the purpose to study the chemical evolution of the first generation of stars in our galaxy.

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