The Puzzle of the Lyα Galaxies: New Results from the VLT

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Observations of high-redshift galaxies show that at early cosmic epochs the cosmic UV radiation field appears to be dominated by small galaxies with strong Ly-alpha emission. Although usually small and of relatively low luminosity, these galaxies are easily identified from their line emission. Observations with the VLT resulted in significant progress in the understanding of the nature of these distant galaxies and of their role in the early Universe.

The pioneers: R. B. Partridge and P. J. E. Peebles

The history of the Lyα galaxies began in 1967 with a pioneering paper by R. B. Partridge and P. J. E. Peebles. In this article, published in the Astrophysical Journal, the two Princeton University astrophysicists discussed the formation of the first galaxies in the Universe. They concluded that the first galaxies probably began their lives with strong initial bursts of star formation at cosmic epochs corresponding to redshifts between 10 and 30. Because of the presence of many massive, hot, and luminous stars in these starbursts, Partridge and Peebles predicted very high ultra-violet (UV) luminosities of the newly formed galaxies, and they estimated that the light emitted by such objects during the first few hundred million years should actually be observable. Because of the large distance, the light emitted by the young galaxies as far-UV radiation is redshifted to the red and near-infrared spectral range. Hence, the detection of such objects requires observations at these wavelengths.

As the most promising way to find these objects, Partridge and Peebles proposed to search for their Lyman-α (Lyα) line emission. This spectral line, due to transitions from the first excited energy level to the ground state of hydrogen atoms, is important in many astrophysical processes. In normal galaxies Lyα emission is produced during the recombination of interstellar hydrogen gas, which has been ionised by hot stars. Simple estimates show that up to about 2/3 of the Lyman continuum photons (and up to about 6 % of the total luminosity) of hot stars can be converted into Lyα photons. This also means that, in principle, Lyα emission equivalent widths of the order 100 to 200 Å can be expected in the spectra of such galaxies.

Of course 6 % is still only a minor fraction of the total emitted luminosity. However, as noted by Partridge and Peebles, in the small wavelength range covered by the Lyα line, the expected spectral flux density is much higher than in the adjacent continuum. Therefore, detecting the line emission against the strong sky background in the red spectral range appeared much easier than looking for the continuum emission.

In 1967 sensitive astronomical detectors were limited to wavelengths ≤ 1 µm. Thus, observations of the redshifted Lyα line appeared feasible only up to redshifts where the observed wavelength of Lyα does not exceed 1µm, which means redshifts $z = \Delta\lambda/\lambda \leq 7$. In view of this limitation, Partridge and Peebles calculated the emitted luminosity and the expected observed Lyα flux emitted at an epoch corresponding to $z \approx 7$.

To appreciate the courage and foresight of taking up this topic in 1966, when the paper was submitted, we have to recall that the Cosmic Microwave Background, confirming the present cosmological concepts, had been discovered just one year before, that the most distant galaxy known at that time had a redshift of about 0.5, that neither galaxy formation nor star formation was well understood, that the most advanced astronomical detectors were image tubes followed by photographic plates, and that there existed only two astronomical telescopes with apertures exceeding 2.5 m. Since in 1966 getting time at the largest existing telescopes was probably as difficult as today, Partridge and Peebles assumed for their feasibility estimates a more modest (and more typical) 90-cm telescope, equipped with an image tube with an S1 cathode. With these assumptions Partridge and Peebles predicted that the Lyα emission of very young galaxies at $z \approx 7$ should be detectable with an exposure time as short as five minutes(!).

The search for the Lyα emitting galaxies

Prompted by the 1967 paper, many different groups started searching for redshifted Lyα (and UV continuum) emission of high-redshift galaxies. However, although a large amount of observing time was invested, and although the surveys soon reached much fainter magnitudes than those predicted by Partridge and Peebles, for many years no redshifted Lyα emitting galaxy was found. Some Lyα emission was detected from distant radio galaxies and from some galaxies associated with distant QSOs. However, it was not clear whether starbursts or non-thermal ionising sources were responsible for the Lyα emission from these objects.

Starting about 1995, many galaxies with redshifts of $z \approx 3$ were discovered using the Lyman-break technique. Practically all the distant galaxies found with this technique showed clear spectroscopic signatures of strong starbursts. However, in most cases the Lyα line occurred either in absorption or as a relatively weak emission feature. Similar results were found for samples of high-redshift galaxies selected on the basis of photometric redshifts (see Figure 1).

More detailed models of starburst galaxies soon provided a plausible explanation for the weakness of the Lyα emission of the young $z \approx 3$ galaxies. Partridge and Peebles were certainly correct, noting that in young starbursts copious numbers of Lyα photons are produced. However, because of the high absorption cross-section of hydrogen atoms for Lyα photons, even a small amount of neutral hydrogen can make a galaxy completely opaque for Lyα.

Normally the absorption of Lyα by an interstellar hydrogen atom will be followed by a re-emission at the same frequency. Thus, hydrogen atoms essentially scatter the Lyα photons, which in principle can still escape after some random walk through the neutral hydrogen layer. However, the resonance scattering greatly increases the effective light path of these photons. Therefore, even a small amount of truly absorbing material embedded in the scattering layer will result in the eventual absorption of the Lyα photons. A most efficient UV absorber is interstellar dust, which is normally abundant in star-forming regions. Thus, the combination of resonance scattering by neutral hydrogen and dust absorption provides a highly plausible explanation for the absence of strong Lyα emission in most known young galaxies. It also seemed to explain why more than two decades of searches for high-redshift Lyα galaxies were not successful.

Soon after the above explanation for the absence of strong Lyα emission in distant starburst galaxies, and the reason for the futility of the earlier searches had been more or less accepted, the history of the Lyα galaxies took an unexpected turn in the mid-1990's. The first Lyα galaxies were detected on the basis of their strong emission line. In an ApJ letter of 1998 Ester Hu, Lennox Cowie, and Richard McMahon reported the discovery of the elusive high-redshift Lyα galaxies during observations with the new 10-m Keck II telescope. The objects discovered by these authors had redshifts of $z \approx 3.4$ and $z \approx 4.5$ and Lyα emission equivalent widths > 100 Å. However, their luminosities were only about one hundredth of that predicted by Partridge and Peebles. This obviously explains why it took a telescope of 10 m (instead of 1 m) aperture to find them.

From the large Lyα equivalent widths, it was clear that the faintness of these objects was not due to dust absorption. Obviously, these galaxies were intrinsically faint and small (see Figure 2). On the other hand, the relatively high space density of the distant Lyα galaxies derived by Hu et al. indicated that the Lyα galaxies provided a major contribution to the star formation and to the cosmic radiation field at the corresponding epochs. Nevertheless a reliable assessment of the effects and the importance of the Lyα galaxies required more information on their detailed properties and their density as a function of redshift. Therefore, the first results immediately started a new wave of searches for high redshift Lyα galaxies. In addition, new studies of the physics of these objects were triggered. Some of this new work was carried out at ESO using the VLT. In the following we describe new results on the nature and the space density of these distant galaxies which resulted from these VLT observations.

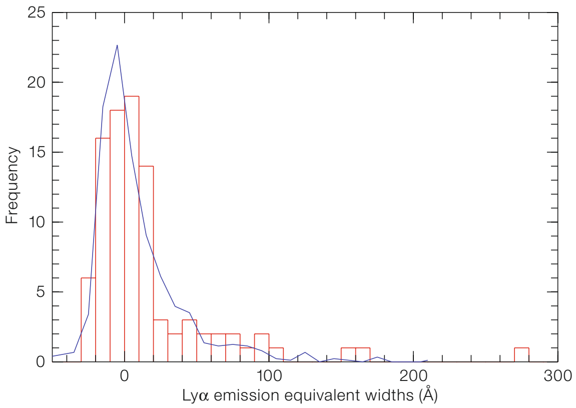


Figure 1: Distribution of the Lyα emission equivalent widths in samples of high-redshift galaxies selected using broadband photometry. The histogram is based on the FDF spectroscopic survey (Noll et al. 2004), selected on the basis of photometric redshifts. The blue line shows the distribution derived by Shapley et al. (2003) for Lyman-break-selected galaxies.

The mystery of the strong line emission

As described above, for many years astronomers were puzzled by the fact that no Lyα galaxies could be observed. That they were finally discovered in the mid-1990's resulted in a new big mystery. The question now was, why these galaxies could emit such a strong Lyα flux in spite of the expected quenching of the Lyα photons by the combination of resonance scattering and dust absorption. As a possible answer to this question it was suggested in the literature that the Lyα galaxies were too young to have formed heavy chemical elements, which are needed to form dust. This explanation appeared plausible, since the first galaxies are expected to form from primordial matter produced by the Big Bang, which (apart from tiny amounts of deuterium and lithium) is composed of hydrogen and helium. Under astrophysical conditions neither hydrogen nor helium can form solids. Thus, dust particles can form only after heavier chemical elements have been produced by the nuclear processes in stars. A very important first result of the VLT observations was high-quality FORS spectra of Lyα galaxies showing conspicuous lines of heavy elements (Figure 3). In particular, these spectra contained lines of carbon and silicon, which are among the main constituents of interstellar dust particles.

If dust is present in young galaxies, Lyα photons can still escape, if the dust and (or) the neutral hydrogen are distributed inhomogeneously and if, by chance, no such material is present along the line of sight between us and the starburst. That the amount of dust and cool material along the line of sight plays a role for the observed Lyα flux is supported by the finding that the Lyα emission strength of high-redshift galaxies decreases with increasing dust reddening and that the Lyα emission is lower in galaxies with strong interstellar absorption lines, typical for cool interstellar gas (Shapley et al. 2003, Noll et al. 2004). However, for a given reddening, the Lyα emission strength tends to vary considerably and there exist Lyα galaxies with high Lyα equivalent widths and a modest amount of reddening. Thus, missing dust and/or missing neutral hydrogen along the line of sight cannot fully explain the observed strong line emission.

Another mechanism, which can avoid the quenching of the Lyα emission, is the presence of sufficiently large velocity gradients in the neutral gas. If a hydrogen

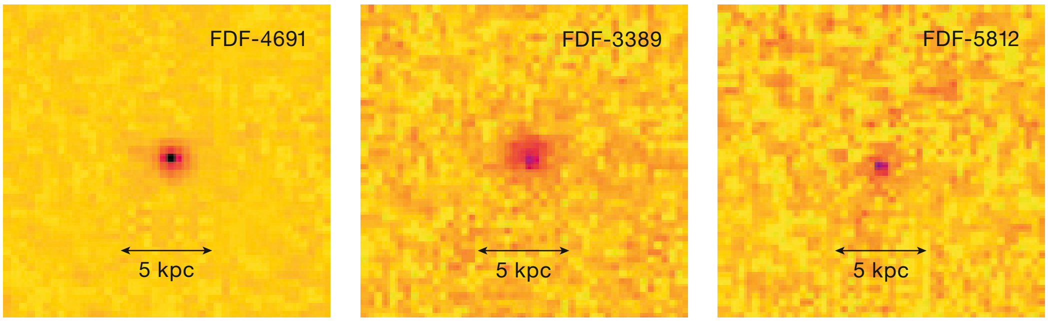


Figure 2: Examples of HST/ACS F814W images of three Lyα galaxies.

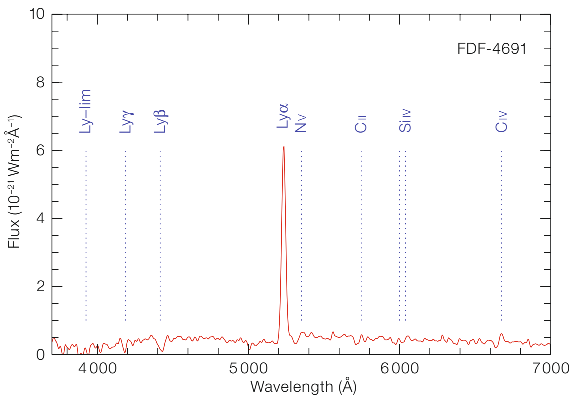


Figure 3: FORS spectrum of the Lyα galaxy FDF-4691 (from Tapken et al. 2004).

atom is moving relative to the volume emitting the Lyα line with a velocity larger than the line widths, the atom cannot absorb or scatter the Lyα photons. In this case the Lyα photons can penetrate the neutral hydrogen layer and escape. Such velocity differences are not unexpected since the velocity of sound is much higher in the hot Lyα emitting gas than in the cool neutral hydrogen layers. Thus, assuming turbulent media with subsonic turbulence, the Lyα lines emitted by the hot ionised gas are expected to have profiles which are significantly broader than the velocity dispersion of the scattering layers. However, because of the very high absorption cross-section of neutral hydrogen, even the outer wings of the absorption profiles can prevent the escape of the Lyα photons. On the other hand, it can be shown that the probability for an escape of the Lyα photons can increase strongly if large-scale velocity fields are present in the scattering layers. Mechanisms producing such large-scale velocity fields can be mass infall, or mass outflows from the galaxies powered by stellar winds or radiation pressure from the central stars. Since such velocity fields also affect the profiles of the Lyα lines, line profile observations provide a critical test of this hypothesis.

We have used the VPH grisms available on the FORS instruments to obtain medium-resolution spectra of a sample of Lyα emitting high-redshift galaxies in the FORS Deep Field (Appenzeller et al. 2004). The observed Lyα profiles were compared to model profiles, which were computed using the radiative transfer code of Meinköhn and Richling (2002), which is particularly well suited for modelling resonance scattering in moving media. Examples of the observed profiles and model fits are presented in Figure 4. For these computations (described in detail in Tapken et al. 2007) we assumed a central volume of turbulent, ionised hydrogen, emitting the Lyα radiation. This region was assumed to be surrounded by a shell of dusty neutral hydrogen.

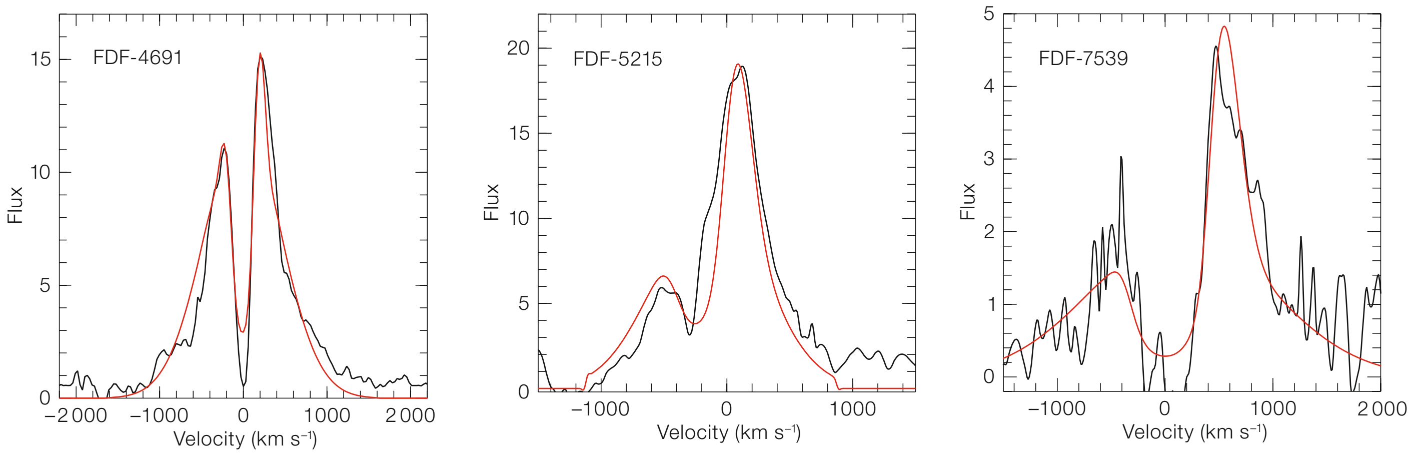
The calculations showed that the observed profiles could be reproduced reasonably well with this model, if a modest (10–200 km s^{-1}) expansion velocity of the neutral hydrogen shell was assumed. From the observed line wings (which are not much affected by the neutral hydrogen shell) high velocities (> 600 km s^{-1}) of the ionised gas could be derived. These high velocities can be explained by supersonic turbulence caused by supernova shocks and strong stellar winds in the compact, strong starbursts. The combination of the relatively broad intrinsic Lyα profiles and the expansion of a neutral hydrogen shell readily explains the fact that a major fraction of the Lyα photons can escape, in spite of the presence of a dusty neutral hydrogen shell in front of the emitting region.

From our results, we conclude that, although a relatively small amount of neutral matter along the line of sight certainly plays a role, the high intrinsic velocity dispersion of the emitting ionised gas and large-scale outflows of the neutral hydrogen are the main reasons for the escape of a large fraction of the Lyα photons from the observed galaxies. The small continuum flux (relative to other high-redshift galaxies) indicates a low total mass of the hot stars of Lyα galaxies. If the mass of the hot stars is a measure of the total mass of these objects, Lyα galaxies are probably of lower (and more normal) mass than other known high-redshift galaxies. Therefore, they probably have lower gravitational potentials, which may explain the observed strong outflows.

The space density of Lyα galaxies and their role in cosmic evolution

As noted above, most known Lyα galaxies are small and have intrinsically faint UV continua. However, already Hu et al. (1998) found for the redshift range $3.4 < z < 4.5$ a total star-formation density due to the Lyα galaxies which is comparable to that due to all other known high-redshift galaxies. Since Lyα galaxies tend to be less affected by reddening than other high-redshift galaxies, they are expected to dominate the UV radiation field at these redshifts. Moreover, studies of high-redshift galaxy samples based on photomet-

Figure 4: Examples of observed (black) and computed (red) Lyα emission line profiles of Lyα emitting galaxies.



ric redshifts (and, therefore, relatively free of selection effects) show that the fraction of Lyα emitting galaxies is increasing with redshift (Noll et al. 2004). According to Shimasaku et al. (2006) at $z = 6$ about 80 % of all high-redshift galaxies are Lyα galaxies with intrinsic Lyα emission equivalent widths > 100 Å. Hence, at very high redshifts these objects are expected to strongly dominate the cosmic UV radiation field and the cosmic ionisation.

For a more quantitative assessment of the role of the Lyα galaxies in the early Universe obviously a reliable knowledge of their space density as a function of luminosity and redshift is needed. Therefore, during the past years, various different groups have invested much work to derive this so-called 'luminosity function' of the Lyα galaxies at different redshifts. There were basically two types of such programmes: firstly, large-area surveys were used to improve the number statistics of these objects; secondly, very deep observations in smaller fields were used to reach fainter Lyα galaxies and to derive the faint part of the luminosity function for these objects. This faint part is important, since, within the observational limits, faint galaxies are always more numerous than the bright ones.

Particularly successful among the large-area surveys were studies carried out with the wide-field SUPRIME camera of the Japanese national telescope Subaru (see, e.g., Shimasaku et al. 2006). These surveys resulted in important information on the space density of luminous Lyα galaxies and on the cosmic variance of this quantity. Our contribution to the topic was an extension of the luminosity function to lower luminosities, which was possible as a result of the superior sensitivity of the FORS2 instrument and a specially developed set of narrowband filters (Tapken et al. 2006).

Like all current searches for Lyα galaxies, the survey carried out with the VLT used sky images obtained through a combination of broadband and narrowband filters. Normal galaxies, where the light is dominated by the stellar continua, tend to be visible with a similar brightness in many different filter bands. Emission-line objects are characterised by an excess emission in one or, if the emission line coincides with the overlap region of two filters, in at most two adjacent filter bands (see Figure 5). Filter photometry allows a reliable detection of galaxies which have emission lines in their spectra. More difficult and more complex is the unambiguous identification of the observed emission lines as Lyα. For this purpose one needs reliable photometric redshifts and low-resolution spectra of the candidate galaxies, which rule out other identifications of the observed lines.

In order to reach an optimal signal-to-noise ratio, the passbands of the narrowband filters used for searches of Lyα galaxies are designed to coincide with wavelength regions of particularly low night sky background. Since most of the night sky background in the red and near-infrared is due to airglow produced by OH molecules in the high atmosphere, the spectral regions of low sky background are the gaps or 'windows' in the OH line spectrum. One of these 'OH windows' covers about 20 nm wavelength interval near $\lambda = 815$ nm (corresponding to a Lyα redshift of $z \approx 5.7$). This window is particularly important since, at this wavelength, photometric and spectroscopic follow-up observations are still relatively easy. Therefore, this window was also used for our VLT observations. To reach an optimal sensitivity, the wavelength interval of the 815-nm OH window was covered by a set of three filters (Figure 6). In this way it is possible not only to avoid the strong OH lines outside the window, but also to partially suppress the weaker lines still present inside the 815-nm OH gap. Because of the resulting lower background, the VLT observations allowed us to reach significantly lower Lyα luminosities than had been possible before.

Figure 7 shows the results together with luminosity function data from another recent survey. The new data confirm the high space density of faint Lyα galaxies at high redshift. In particular up to $z \approx 6$ the space density seems not to decrease with redshift. On the other hand, the observed luminosity range and the number of observed objects are still too small, to constrain the luminosity function well. Although much progress has been made, obviously more work is needed to derive the radiation field produced by the Lyα galaxies with an adequate accuracy.

Future work and outlook

Several ambitious large-area searches for Lyα galaxies are underway which will further improve the statistics of these objects. Of particular interest will be the results of the DAzLE survey, which, using infrared imaging, aims at finding Lyα galaxies at redshifts $z > 7$. Hence, during the next few years we will certainly see much more and better statistical data on the bright part of the luminosity function of the Lyα galaxies. Less clear is the outlook for more information on the important faint part of the luminosity function of these objects. Reaching significantly fainter galaxies with normal deep-field observations would require very long exposures times, which appear not realistic for such programmes. More promising may be the 'gravitational telescope' technique, i.e., making use of the flux amplification of distant objects by strong gravitational lensing. Because of their relatively high surface density, Lyα galaxies are well suited for such programmes. Estimates have shown that, with presently available instruments, observations of lensed Lyα galaxies in the field of a single galaxy cluster with a high lensing strength (such as the ROSAT source RX J1347-1145) could provide a significant sample of Lyα galaxies with intrinsic luminosities one to several magnitudes fainter than those known at present. These data could be obtained with a rather modest amount of observing time. Thus, progress concerning the luminosity functions also seems to be possible, provided observing time for such programmes can be obtained.

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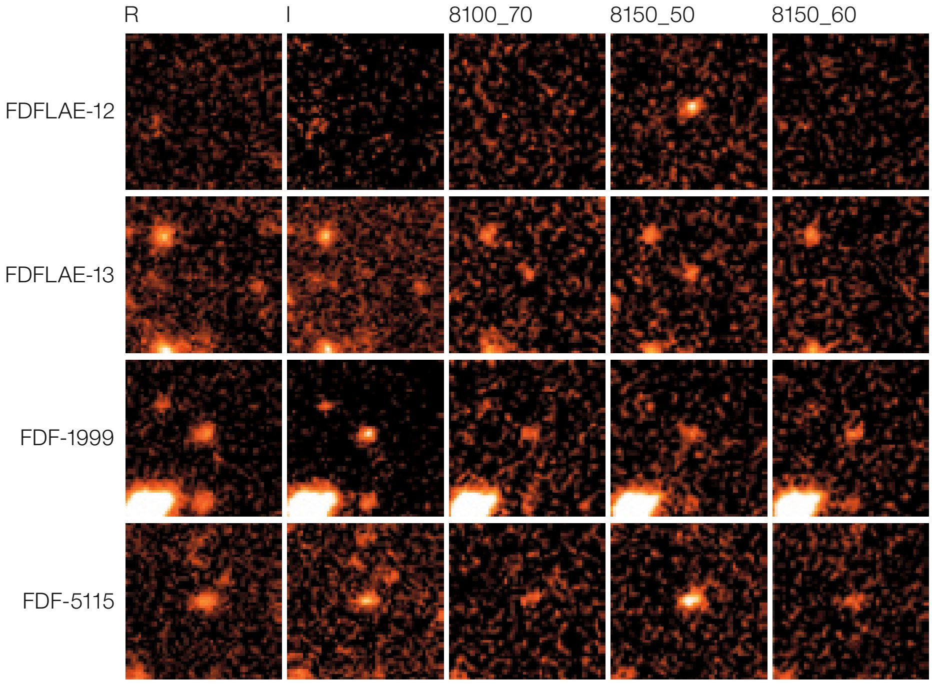
Figure 5: Bessell-R and broadband images and narrowband images of four galaxies in the FORS Deep Field. The upper two panels show $z \approx 5.7$ Lyα galaxies. The lower two panels show, for comparison, corresponding data for a normal $z \approx 3.2$ starburst galaxy and for a $z \approx 1.2$ [O II] emitter.



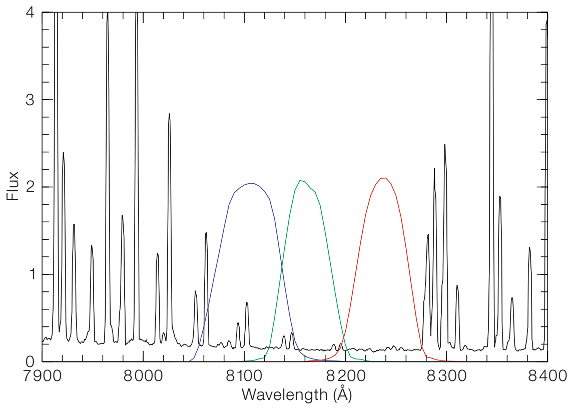


Figure 6: Spectrum of the OH airglow near the 815 nm window. Overplotted are the transmission curves of the special FORS2 narrowband filter set for detecting Lyα galaxies at redshifts ≈ 5.7.

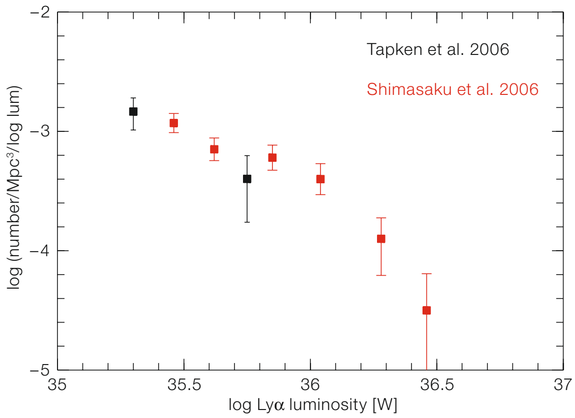


Figure 7: The luminosity function of Lyα galaxies at $z = 5.7$.

Atacama landscape view near the ALMA Site Museum at 3200 m.

Photo: H. H. Heyer, ESO