Evolution in the Lyman-α forest

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received; accepted

Abstract. We reanalyse the spectra used by D.-E. Liebscher et al. (1992) with the same goal – determining the cosmological parameters – and basically the same assumptions but with a different statistical method, which does not rely on binning the data. Also, we correct for selection effects. We basically confirm their result, with somewhat larger but still very small (formal) errors. However, all world models within the 99% confidence region are ruled out because a firm lower limit on Ω_0 is significantly larger. This directly demonstrates for the first time the existence of intrinsic evolution in the Lyman-α forest.

Key words: cosmology: theory – quasars: absorption lines – cosmology: observations – large-scale structure of Universe

1. Introduction

A method of determining the cosmological parameters λ_0 and Ω_0 has recently been suggested by D.-E. Liebscher et al. (1992 – hereafter LPH). They use the redshift distribution of Lyman-α forest lines, with the assumption that the Lyman-α forest absorbers have a constant comoving density. This basically determines the volume element as a function of redshift, which depends on the cosmological model and is especially sensitive to a positive value of the cosmological constant λ_0. (See, e.g., Feige (1992) for an explanation of this effect.) Under this assumption, which means no intrinsic evolution – we henceforth use ‘evolution’ to mean intrinsic physical evolution and not in the more general and somewhat misleading sense of ‘dependence on z’ – they find an acceptable fit only in a small area of the λ_0-Ω_0-plane. It is important to realise that, if evolution is present in the absorbers, one would not necessarily expect to find any (then necessarily wrong) cosmological model (not even an extreme one perhaps excluded by other arguments) which would be compatible with the observations without requiring evolution; i.e., evolutionary effects and the influence of the cosmological model are not necessarily degenerate, especially when, as is here the case, one has a large data set extending to high redshifts. Of course, the fact that LPH find an acceptable fit does not prove the assumption of no evolution, but it does mean that one cannot say that ‘evidence of evolution is directly seen in the spectra’; the fact that an acceptable fit is found demonstrates that a cosmological model exists in which no evolution is required to explain the observed spectra.

The paper by LPH was subjected to much criticism, but our investigation shows that most of this is unfounded. We have confirmed their results with a better statistical method (and have reproduced their results with their method as a check at the outset of our investigation); the result is perfectly consistent with the assumptions and gives an acceptable fit.

This was admittedly somewhat surprising, since we have a number of points of criticism of LPH. First, the distribution of spectral lines was not used directly, but rather the lines were counted in redshift bins. Binning introduces free parameters and throws away information (cf., e.g., Press et al. (1992)) and should be avoided if possible. Also on the mathematical side, a fit to their Z^2 instead of Z was done. In addition, since the smallest equivalent width capable of being registered by all detectors used in the inhomogeneous sample of Lyman-α forest lines is 0.2 Å, this implies, because the lowest redshift in their sample is z = 0.003, that the intrinsic equivalent width W_{intr} to which the sample is complete must also be ≈ 0.2 Å. Of the 1297 lines used by LPH only 832 have a W_{intr} larger than this minimum. Furthermore, since the physical distance between two absorbers is a function of their redshifts and the cosmological parameters λ_0 and Ω_0, their sample is only complete to distances greater than that corresponding to the minimum observable distance in the given world model. To avoid biasing, we must for each world model exclude a certain number of lines from the statistical analysis. (See the discussion for ‘resolution bias’ in Kayser (1995).)
2. Basic theory

2.1. Cosmology

We make the ‘standard assumption’ that the Universe can be described by the Robertson-Walker metric. With the assumption of no evolution, the absorbers have a constant comoving density. The proper distance (this is the distance \( D^p \) in Kayser et al. [1995], hereafter KHS) in a given world model between two absorbers with redshifts \( z_x \) and \( z_y \) is given by \( D^p(z_y) - D^p(z_x) \). This is simply

\[
D^p_{xy} = \frac{c}{H_0} \int_{z_x}^{z_y} \frac{dz}{\sqrt{Q(z)}} \quad (1)
\]

where

\[
Q(z) = \Omega_0 (1 + z)^3 - (\Omega_0 + \lambda_0 - 1)(1 + z)^2 + \lambda_0. \quad (2)
\]

The idea is to find the cosmological parameters for which \( D^p_{xy} \) corresponds most closely to what is observed in the spectra; if there is no evolution, then this must be the correct world model, if the fit is acceptable. We use the distance between adjacent absorbers \( \Delta z \) as the observational quantity. This is of course equivalent to the number of lines per redshift interval except for the loss of precision due to binning in the latter case.

2.2. Statistics

We use a method similar to that described in Kayser [1995]: We calculate the distribution of distances between pairs of adjacent absorbers, divide the sample into \( N \) subsamples based on redshift (with the same number of objects in each subsample) and compare \( m = N/2 \) independent pairs of samples with \( m \) Kolmogorov-Smirnov (K-S) tests (instead of just two samples and one test as in Kayser [1995]). Since the null hypothesis is that the distribution is independent of redshift, the choice of independent pairs is arbitrary.

What is the probability \( P_{\text{min}} \) that the minimum of all \( m \) K-S probabilities \( P_i \) is less than a given \( P_0 \)? Since, if \( \min(P_i) > P_0 \) all values \( P_i \) must be larger than \( P_0 \) we have

\[
P(\min(P_i) > P_0) = (1 - P_0)^m \quad (3)
\]

and thus

\[
P_{\text{min}} = P(\min(P_i) < P_0) = 1 - (1 - P_0)^m. \quad (4)
\]

Solving for \( P_0 \) we obtain

\[
P_0 = 1 - \frac{\sqrt[1/m]{1 - P_{\text{min}}}}{} \quad (5)
\]

It is obvious that using just two subsamples will not allow one to reject the null hypothesis that the distribution is independent of redshift if there is a symmetry with respect to the redshift separating the subsamples, even though the distribution is not independent of redshift.

We can reject the null hypotheses that this distribution is independent of redshift at the 100(1 - \( P_{\text{min}} \))% confidence level in the cases where \( \min(P_i) < P_0 \). Here, we conservatively considered a probability \( P_{\text{min}} \) of 1% or larger to be compatible with the observations and used three pairs of samples, thus ruling out all world models with a value of \( \min(P_i) \) less than \( P_1 = 1 - \sqrt[1/3]{0.99} \approx 0.0033 \) at the 99% confidence level. Of course, as mentioned above, for each world model the actual sample is different in order that it be complete down to a certain distance between pairs of adjacent absorbers. (See Fig. 1)

3. The sample

For purposes of comparison, we used the same sample of spectral lines as in LPH, except that we omitted 7 lines with \( z < 1.65 \) (taken from Bahcall et al. [1991]). This means that the sample is now complete to \( W_{\text{intr}} = 0.2/(1 + 1.65) \approx 0.0755 \text{ Å} \).
Table 1. Spectra used. The redshift $z$ refers to the midpoint of the wavelength interval. References are Atwood et al. [1985], Pettini et al. [1990], Sargent et al. [1988], Steidel [1990], Carswell et al. [1991], and Rauch et al. [1992].

| #  | QSO    | $z$  | $\lambda$ [Å] | $\Delta \lambda$ | reference |
|----|--------|------|---------------|-----------------|-----------|
| 1  | 0420-388 | 2.25 | 3850-4050    | 0.5             | Atwood    |
| 2  | 0420-388 | 2.46 | 4100-4300    | 0.5             | Atwood    |
| 3  | 0420-388 | 2.46 | 4450-4650    | 0.5             | Atwood    |
| 4  | 0420-388 | 2.99 | 4750-4950    | 0.5             | Atwood    |
| 5  | 2206-199N| 2.25 | 3860-4052    | 0.09            | Pettini   |
| 6  | 2206-199N| 2.43 | 4070-4282    | 0.09            | Pettini   |
| 7  | 0114-089 | 3.11 | 4900-5100    | 1.5             | Sargent   |
| 8  | 0013+072 | 2.45 | 3900-4500    | 1.5             | Sargent   |
| 9  | 1159+124 | 3.11 | 4600-5400    | 1.5             | Sargent   |
| 10 | 1247+267 | 1.84 | 3260-3660    | 0.8             | Sargent   |
| 11 | 1511+091 | 2.70 | 4300-4700    | 1.5             | Sargent   |
| 12 | 1623+269 | 2.29 | 3700-4300    | 0.8             | Sargent   |
| 13 | 2126-158 | 3.11 | 4800-5200    | 1.5             | Sargent   |
| 14 | 0142-100 | 2.45 | 3900-4500    | 0.8             | Sargent   |
| 15 | 0237-233 | 2.04 | 3500-3900    | 0.8             | Sargent   |
| 16 | 0424-131 | 2.04 | 3600-3800    | 0.8             | Sargent   |
| 17 | 1017+280 | 1.80 | 3300-3500    | 0.8             | Sargent   |
| 18 | 2000-330 | 3.44 | 5100-5700    | 1.35            | Steidel   |
| 19 | 0055-209 | 3.52 | 5400-5600    | 1.35            | Steidel   |
| 20 | 0000-263 | 3.77 | 5400-6200    | 1.35            | Steidel   |
| 21 | 1208+101 | 3.60 | 5400-5800    | 1.51            | Steidel   |
| 22 | 1100-264 | 1.91 | 3440-3640    | 0.11            | Carswell   |
| 23 | 1100-264 | 2.05 | 3640-3780    | 0.11            | Carswell   |
| 24 | 0014+813 | 2.74 | 4500-4600    | 0.36            | Rauch     |
| 25 | 0014+813 | 2.87 | 4600-4800    | 0.36            | Rauch     |
| 26 | 0014+813 | 3.03 | 4800-5000    | 0.36            | Rauch     |
| 27 | 0014+813 | 3.15 | 5000-5100    | 0.36            | Rauch     |
| 28 | 0014+813 | 3.28 | 5100-5300    | 0.36            | Rauch     |

which gives us a sample consisting of 1108 of the 1297 LPH lines; including these 7 low-redshift lines would decrease the complete sample, as explained in Sect. 3, to 832 lines. Although the low-redshift lines have a significant impact on the $\chi^2$ method used by LPH, leaving out this few lines makes practically no difference in the analysis. Which are not excluded by the redshift of the lines used in this study. We use, so we choose to leave them out in order to be able to work with a larger complete sample. Since we wanted to use the actual redshifts of the lines and not simply the number of lines per redshift interval, the wavelengths of the lines were determined from scans of the literature spectra and the redshifts ($W_{\text{int}}$) were then calculated. See Table 1 for more details. Our measured wavelengths of all the lines are available from the following URLs:

1. http://www.hs.uni-hamburg.de/english/persons/helbig/Research/Publications/info/lyman-alpha.html
2. ftp://ftp.uni-hamburg.de/pub/misc/astonomy/lyman-alpha.tar.gz

Fig. 2. The probability as a function of the cosmological parameters. The (thick) contour line is at 1%. Only world models within this area are compatible with the data. Note the extremely small area of the $\lambda_0$-$\Omega_0$-plane in this plot – outside this area, no areas with an acceptable probability exist. The lower left corner of the plot corresponds to the de Sitter model. For comparison, the LPH 1 $\sigma$ and 3 $\sigma$ error ellipsoids are included.

4. Calculations, results and discussion

First, for a general overview, we calculated the probability for cosmological models in the area given by $-10 < \lambda_0 < 7$ and $0 < \Omega_0 < 7$, with a resolution of 0.06 ($\approx 33,000$ different models). Almost the entire area of this plane is rejected. Then, in a series of steps, the area containing a probability $P_{\text{min}} > 1\%$ was examined in progressively higher resolution. Only a small region, shown in Fig. 2, was found to be compatible with the observational data.

Thus, we find in agreement with LPH that – with the assumption of no evolution – cosmological models exist which provide an acceptable fit to the data. The fact that the area in the $\lambda_0$-$\Omega_0$-plane in which this is the case is so small means that, if the method is correct, it offers by far...
the best known method of determining the cosmological parameters. The fact that the allowed area is somewhat outside the (present) canonical range of cosmological models is probably one reason for some of the criticism of the work of LPH. Mostly, this has concentrated on the fact that this cosmological model is dominated by the cosmological constant. We hasten to point out that it has not yet been shown that there is a way of excluding this large value of \( \lambda_0 \) in spatially closed \((k = +1)\) world models.\footnote{All cosmological models in Fig. 3 have \( k = +1 \) and \( \lambda_0 > 1 \) and thus are spatially closed and will expand forever. See KHS.} It is generally recognised that gravitational lensing statistics can provide the tightest constraints on a positive cosmological constant. However, at present such constraints have only been derived for flat \((k = 0)\) models. (See, e.g., Kochanek (1996) and references therein.) Basically, large \( \lambda_0 \) values predict too many lenses, primarily because of the relatively large volume element \( dV/dz \) in these models. For \( k = +1 \) models, this effect is not as pronounced, since \( dV/dz \) is generally smaller in a \( k = +1 \) model than in a flat model with the same value of \( \lambda_0 \). Thus, a given upper limit on \( \lambda_0 \) for a flat model corresponds to a weaker limit for a \( k = +1 \) model. Nevertheless, it is conceivable that lensing statistics could rule out the LPH model and other \( k = +1 \) models with a large cosmological constant; this is currently under investigation.

LPH point out ‘advantages’ of their model, such as the fact that a relatively old universe and a relatively large Hubble constant can both be accommodated. In fact, better values for the world age and \( H_0 \) will probably rule out some standard cosmological models in the near future. The point is that such indirect tests don’t rule out the LPH model; if anything, they point in the direction of this or a similar cosmological model.

There is not necessarily any non-baryonic matter in the LPH model, since their value of \( \Omega_0 \), coupled with plausible values for \( H_0 \), gives a density comparable to the baryonic density predicted by nucleosynthesis.\footnote{In the following, the term ‘LPH model’ should be understood to mean the range of cosmological models within the errors of the LPH best fit model as well as our results since, for the purposes of the following discussion, the cosmological models are identical.} (See, e.g., Krauss (1993) and references therein.) This could also be seen as a point in favour of this cosmological model.

However, the \( \approx 3 \sigma \) upper limit for the total density \( \Omega_0 \) (\( \approx 0.035 \)) is significantly less than the extremely conservative lower limit (\( \approx 0.05 \)) advocated by Peebles (1993, Chapter 20). Since this conservative lower limit on \( \Omega_0 \), based on well-understood physics, is considerably less than lower limits advocated by other researchers, this means that the LPH model is definitively ruled out and that it is not possible to determine the cosmological parameters by this method.

5. Evolution

The conclusion in the last paragraph means that there must be evolution in the Lyman-\( \alpha \) forest, because without evolution, the only cosmological model compatible with the observations is definitively ruled out on other grounds. \textit{This conclusion does not assume any a priori values for the cosmological parameters.}

For a given cosmological model, the comoving distances between adjacent Lyman-\( \alpha \) forest absorbers can be calculated, as shown above. A plot of the average distance per redshift bin should be almost flat if the cosmological model used for the calculation is correct and if there is no evolution. Previously, we assumed no evolution to so determine the cosmological model. However, since we now know that there must be evolution in the Lyman-\( \alpha \) forest, we now, for a few representative cosmological models, calculate what evolution is necessary to explain the observations. Several different binning schemes were used to isolate real effects from noise. (See Fig. 3). The resulting calculated evolution is relatively independent of the world model (except near the LPH model, where of course the calculated evolution is almost flat). This means that Fig. 3 is approximately correct for almost any world

Fig. 3. Evolution in the Lyman-\( \alpha \) forest for the Einstein-de Sitter model \((\lambda_0 = 0, \Omega_0 = 1)\). Higher values mean greater distances between absorbers and thus fewer absorbers per comoving volume. (Values are normalised with respect to the mean.) Different curves correspond to different binning schemes.
model (cf. Fig. 3). This is the first calculation of the evolution of the Lyman-α forest based on observational data which makes no assumptions (other than basic cosmological ones). The general trend is an increase in the comoving density of Lyman-α forest absorbers with $z$ and thus a decrease with time.

The form of the curves in Fig. 3 make it possible to understand why the LPH model is compatible with the observations without requiring any evolution. The basic feature in the curves in Fig. 3 is the fact that the comoving distance between adjacent absorbers decreases with increasing redshift. If there were no evolution, then the comoving distance should be independent of redshift. Thus, a decrease in the comoving distance between adjacent absorbers with increasing redshift can be compensated in a world model in which the comoving distance for a fixed $\Delta z$ is comparatively larger at larger redshifts. This is only the case in a small part of the $\lambda_0-\Omega_0$-plane.

For a given $\Omega_0$ value there is a value of $\lambda_0$ above which no big bang is possible; rather, the universe contracts from $\infty$ to a finite $R_{\text{min}}$ before expanding again. Near this curve separating world models with and without a big bang, which for brevity we refer to in the following as the $A_2$ curve (following Stabell &Refsdal (1966)) are the so-called plateau models, where the universe has a quasi-static phase. (See, e.g. Feige (1992), for a discussion of this phase.) Near the redshift of the plateau, the comoving distance for a fixed $\Delta z$ can become very large. The redshift of the plateau depends sensitively on the value of the cosmological parameters, ranging from $\infty$ near the de Sitter model ($\lambda_0 = 1$, $\Omega_0 = 0$) to values $< 1$ for relatively small values of $\Omega_0$ and $\lambda_0$. Figure 3 shows the comoving distances between adjacent absorbers becoming smaller with increasing redshift, here assumed to be due to intrinsic evolution. It is easy to see that a cosmological model – such as the ones near the LPH model – in which the distance is relatively larger at larger redshift will counteract this effect, producing a flatter distribution which, in such a cosmological model, would imply a lack of intrinsic evolution. Since the redshift of the plateau and hence of the large volume element can be adjusted by moving along the $A_2$ curve, and its width by moving perpendicular to it, it is easy to find a cosmological model which, with no evolution, will be compatible with observational data from a ‘normal’ cosmological model in which the comoving distance between absorbers for a fixed $\Delta z$ decreases with increasing redshift due to evolutionary effects. Due to the sensitivity mentioned above, this will only be possible in a very small area of the parameter space. Since the width of the plateau is even more sensitive to the distance from the $A_2$ curve than is its redshift to the position along the curve, the allowed area in Fig. 3 has an elongated shape.

6 This is WTYPE 17 as given by the INICOS routine mentioned in KHS.
parameter space which is not excluded on other grounds, it is almost independent of the cosmological model.

Acknowledgements. It is a pleasure to thank S. Refsdal for helpful discussions.

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