Chapter 1

Introduction

The spectra of quasistellar objects—more commonly called QSOs or quasars—are dominated by conspicuous emission lines, the largest of which is associated with the Lyman alpha transition of neutral hydrogen. On the long-wavelength side of this emission line, almost all of the not very numerous absorption lines can be readily identified as ionic transitions of metals, i.e., elements heavier than helium. Shortward of the Ly α emission line, however, quasar spectra are very densely populated with hundreds of absorption lines, the overwhelming majority of which are now known (after a suggestion from Lynds 1971) to be lines of the Lyman series of neutral hydrogen H I. The strongest and most numerous of these lines are due to the Ly α transition $1s \rightarrow 2p$, which has a large cross section and a rest wavelength of 1215.67 Å. The densely populated section of the spectrum between the Ly α and Ly β emission lines has been dubbed the "Lyman α forest," and its appearance in the spectrum toward quasar HE 0940–1050 will be presented in this work.

The physical picture corresponding to the absorption spectrum is as follows. Once radiation has been emitted by the quasar, its wavelength increases as a result of the cosmological expansion of the universe. If the wavelength reaches 1215.67 Å and the photons are absorbed by a high enough concentration of neutral hydrogen atoms along the line of sight, a Ly α absorption line appears in the observed spectrum with the same redshift z as that of the absorbing material. Since redshift is also a measure of distance according to the Hubble law, absorption spectra yield a picture of gaseous absorbers, or "clouds," scattered along the path from the quasar to Earth.

Traditionally the absorbers with column densities of up to $N_{\rm H\,I} \sim 10^{16}$ atoms per cm^2 along the line of sight have been called Ly α forest clouds. The metal lines present in the systems with the higher column densities become increasingly stronger up to $N_{\rm H\,I} \sim 10^{17}$, where the gas also becomes optically thick to ionizing radiation. The continuous absorption below 912 Å in the rest frame of these so-called Lyman-limit systems produces a characteristic discontinuity at the Lyman limit in the observed spectrum. Finally, the damped Ly α systems with $N_{\rm H\,I} \gtrsim 10^{20}$ produce such heavily saturated Ly α absorption lines that the line profiles are dominated by so-called damping wings.

The Ly α clouds with the lowest column densities arise in the intergalactic medium and were thought to constitute a primordial population because they appeared to

lack metal lines and showed little clustering—as opposed to the systems with higher column densities and strong metal lines which seem to be associated with galaxies. However, as mentioned in chapter 7, recent detection of C IV absorption in clouds with column densities at least as low as $N_{\rm HI} \simeq 10^{14.5}$ has cast some doubt on this picture of different parent populations. From the other side, steadily improving theoretical simulations are blurring the distinction between discrete low-$N_{\rm HI}$ absorbers and other density fluctuations in a more diffuse medium.

Regardless of whether their chemical composition has undergone some metal enrichment, and regardless of whether future approaches will take a more general view of structures in the intergalactic medium, the fact remains that the systems producing Ly α absorption lines in quasar spectra provide an extremely useful probe of baryonic matter in the universe, its distribution over a wide range of densities and temperatures, and its evolution in time. The Ly α clouds appear at all directly observable redshifts and are by far the most numerous population at higher redshifts, where quasar lines of sight cover look-back times representing a significant fraction of the lifetime of the universe.[1]

Observational data provide input and constraints not only for theories of structure formation in the universe, but also for theories of the metagalactic ultraviolet radiation field that is assumed to be responsible for keeping the Ly α forest clouds in a highly ionized state (Haardt and Madau 1996). After it was noticed that the number density of Ly α lines in the vicinity of a quasar does not increase as strongly with redshift as expected, Bajtlik, Duncan and Ostriker (1988) proposed a specific model in which enhanced photoionization of the Ly α clouds by the quasar causes what they dubbed the "proximity effect." The principal parameter in this model is the ratio of the quasar's Lyman-limit flux density to that of the ambient UV background (UVB). Thus, attempts to determine the UVB by integrating over the contributions from all presumed sources could now be complemented with actual indirect measurements of the UVB at the Lyman limit.

The final aim of this work is to see if there is any detectable proximity effect in the Ly α forest toward HE 0940–1050, and if possible to obtain an estimate of the UVB under the assumption that photoionization is indeed responsible for the proximity effect. Before that could be attempted, however, the raw two-dimensional echelle data had to be converted into a one-dimensional normalized spectrum. Since this is a long and involved process for a first-time student, the individual steps will be described in great detail. Chapter 3 explains the preliminary steps required for the actual data reduction in chapter 4. Chapter 5 describes the additional corrections and normalization which produce a spectrum suitable for fitting absorption lines.

[1] The general properties and cosmological significance of quasar absorption systems are also presented in a brief and understandable introduction by Tytler (1997). For these and other topics concerning the Ly α forest, along with the developments in recent years, see the very thorough review by Rauch (1998).

The first part of the actual analysis, covered in chapter 6, begins by fitting Voigt profiles to all of the absorption lines in the Ly α forest in order to obtain the distributions of their redshifts, column densities and Doppler parameters. Chapter 7 describes the expected shapes of these distributions, introduces the theoretical model values chosen to parametrize these distributions, and explains how a preliminary examination of the data was used to define the sample used in the subsequent analysis.

The actual investigation of the proximity effect in the spectrum of HE 0940 is covered in chapter 8. A very brief introduction is followed by a description of the photoionization model in which the necessary formulas are also presented. The relevant quasar flux density is then determined via extrapolation to the Lyman limit.

After explaining the Monte Carlo methods and programs used to simulate the proximity effect, the data are compared to the Monte Carlo results for three different scenarios. The first represents the Ly α forest distributions in the absence of quasar radiation. The second and third include the presence of quasar radiation plus either the UVB model presented by Bajtlik, Duncan and Ostriker (1988) or a UVB with a Lyman-limit intensity that is constant with redshift. Trying different values of this constant leads to a more concrete estimate of the order of magnitude for the UVB and gives an impression of the range of errors involved. More general sources of error and systematic uncertainties are also mentioned.

The discovery of a possible void in the spectrum at $z \approx 2.58$ brings up the closely related topic of a possible two-quasar proximity effect, in which a foreground quasar produces a line-free region in the absorption spectrum of another quasar when it ionizes the Ly α clouds along the line of sight to the latter. After estimating the size of the void candidate in the spectrum of HE 0940, the region is examined more closely for the presence of weak lines, and two estimates of the region's statistical significance are made. Chapter 9 closes by considering a few of the conditions necessary for seeing such a foreground quasar and by providing rough estimates for its possible location and luminosity.