Detection methods

Looking back so far in the history of the universe presents some observational challenges. There are, however, a few observational methods for studying reionization.

[[edit](http://en.wikipedia.org/w/index.php?title=Reionization&action=edit&section=3)]**Quasars and the Gunn-Peterson trough**

One means of studying reionization uses the [spectra](http://en.wikipedia.org/wiki/Spectrum) of distant [quasars](http://en.wikipedia.org/wiki/Quasar). Quasars release an extraordinary amount of energy, meaning they are among the brightest objects in the universe. Some quasars are even detectable as far back as the epoch of reionization. Quasars also happen to have relatively uniform spectral features, regardless of position in sky or distance from [Earth](http://en.wikipedia.org/wiki/Earth). Thus it can be inferred that any major differences between quasar spectra will be caused by interaction with[atoms](http://en.wikipedia.org/wiki/Atom) along the line of sight. For [wavelengths](http://en.wikipedia.org/wiki/Wavelength) of light at the energies of one of the [Lyman transitions](http://en.wikipedia.org/wiki/Lyman_series)in hydrogen, the [scattering cross-section](http://en.wikipedia.org/wiki/Scattering_cross-section) is large, meaning that even for low levels of neutral hydrogen in the [intergalactic medium](http://en.wikipedia.org/wiki/Intergalactic_medium) (IGM), [absorption](http://en.wikipedia.org/wiki/Absorption_(electromagnetic_radiation)) at those wavelengths is highly likely.

For nearby objects in the universe, spectral absorption lines are very sharp, as only photons with energies just sufficient to cause an atomic transition can cause the transition. However, the distances between quasars and the telescopes which detect them are large, which means that the [expansion of the universe](http://en.wikipedia.org/wiki/Metric_expansion_of_space) causes light to undergo noticeable redshifting. This means that as light from the quasar travels through the IGM and is redshifted, wavelengths which had been above the Lyman Alpha limit are stretched, and will at some point be just equal to the wavelength needed for the Lyman Alpha transition. This means that instead of showing sharp spectral lines, a quasar's light which has traveled through a large, spread out region of neutral hydrogen will show a [Gunn-Peterson trough](http://en.wikipedia.org/wiki/Gunn-Peterson_trough).[[1]](http://en.wikipedia.org/wiki/Reionization#cite_note-1)

The redshifting that occurs allows for temporal information about reionization to be learned. Since an object's redshift corresponds to the time at which it emitted the light we see, it is possible to determine when reionization ended. Quasars below a certain redshift will not show the Gunn-Peterson trough (though they may show the [Lyman-alpha forest](http://en.wikipedia.org/wiki/Lyman-alpha_forest)), while quasars emitting light prior to reionization will feature a Gunn-Peterson trough. In 2001, four quasars were detected by the [Sloan Digital Sky Survey](http://en.wikipedia.org/wiki/Sloan_Digital_Sky_Survey) with redshifts ranging from *z* = 5.82 to *z* = 6.28. While the quasars above *z* = 6 showed a Gunn-Peterson trough, indicating that the IGM was still at least partly neutral, the ones below did not. As reionization is expected to occur over relatively short timescales, the results suggest that the universe was approaching the end of reionization at *z* = 6.[[2]](http://en.wikipedia.org/wiki/Reionization#cite_note-2) This, in turn, indicates that the universe must still have been almost entirely neutral at *z* > 10.

[[edit](http://en.wikipedia.org/w/index.php?title=Reionization&action=edit&section=4)]**CMB anisotropy and polarization**

The anisotropy of the [cosmic microwave background](http://en.wikipedia.org/wiki/Cosmic_microwave_background) on different angular scales can also be used to study reionization. Photons undergo scattering when there are free electrons present, in a process known as [Thomson scattering](http://en.wikipedia.org/wiki/Thomson_scattering). However, as the universe expands, the density of free electrons will decrease, and scattering will occur less frequently. In the period during and after reionization, but before significant expansion had occurred to sufficiently lower the electron density, the light that composes the CMB will experience observable Thomson scattering. This scattering will leave its mark on the CMB [anisotropy](http://en.wikipedia.org/wiki/Anisotropy" \o "Anisotropy)map, introducing secondary anisotropies (anisotropies introduced after recombination).[[3]](http://en.wikipedia.org/wiki/Reionization#cite_note-3) The overall effect is to erase anisotropies that occur on smaller scales. While anisotropies on small scales are erased, [polarization](http://en.wikipedia.org/wiki/Polarization_(waves)) anisotropies are actually introduced because of reionization.[[4]](http://en.wikipedia.org/wiki/Reionization#cite_note-4) By looking at the CMB anisotropies observed, and comparing with what they would look like had reionization not taken place, the electron column density at the time of reionization can be determined. With this, the age of the universe when reionization occurred can then be calculated.

The [Wilkinson Microwave Anisotropy Probe](http://en.wikipedia.org/wiki/Wilkinson_Microwave_Anisotropy_Probe) allowed that comparison to be made. The initial observations, released in 2003, suggested that reionization took place from 11 <*z* < 30.[[5]](http://en.wikipedia.org/wiki/Reionization#cite_note-5) This redshift range was in clear disagreement with the results from studying quasar spectra. However, the three year WMAP data returned a different result, with reionization beginning at *z* = 11 and the universe ionized by *z* = 7.[[6]](http://en.wikipedia.org/wiki/Reionization#cite_note-6) This is in much better agreement with the quasar data.

[[edit](http://en.wikipedia.org/w/index.php?title=Reionization&action=edit&section=5)]**21-cm line**

Even with the quasar data roughly in agreement with the CMB anisotropy data, there are still a number of questions, especially concerning the energy sources of reionization and the effects on, and role of, [structure formation](http://en.wikipedia.org/wiki/Structure_formation) during reionization. The [21-cm line](http://en.wikipedia.org/wiki/Hydrogen_line) in hydrogen is potentially a means of studying this period, as well as the "dark ages" that preceded reionization. The 21-cm line occurs in neutral hydrogen, due to differences in energy between the parallel and anti-parallel spin states of the electron and proton. This transition is [forbidden](http://en.wikipedia.org/wiki/Forbidden_line), meaning it occurs extremely rarely. The transition is also highly[temperature](http://en.wikipedia.org/wiki/Temperature) dependent, meaning that as objects form in the "dark ages" and emit Lyman-alpha [photons](http://en.wikipedia.org/wiki/Photon) that are absorbed and re-emitted by surrounding neutral hydrogen, it will produce a 21-cm line signal in that hydrogen through [Wouthuysen-Field coupling](http://en.wikipedia.org/wiki/Wouthuysen-Field_coupling" \o "Wouthuysen-Field coupling).[[7]](http://en.wikipedia.org/wiki/Reionization#cite_note-7)[[8]](http://en.wikipedia.org/wiki/Reionization#cite_note-8) By studying 21-cm line emission, it will be possible to learn more about the early structures that formed. While there are currently no results, there are a few projects underway which hope to make headway in this area in the near future, such as the [Precision Array for Probing the Epoch of Reionization](http://en.wikipedia.org/wiki/Precision_Array_for_Probing_the_Epoch_of_Reionization) (PAPER), [Low Frequency Array](http://en.wikipedia.org/wiki/LOFAR) (LOFAR),[Murchison Widefield Array](http://en.wikipedia.org/wiki/Murchison_Widefield_Array) (MWA), [Giant Metrewave Radio Telescope](http://en.wikipedia.org/wiki/Giant_Metrewave_Radio_Telescope) (GMRT), and the Large-Aperture Experiment to Detect the Dark Ages (LEDA).