

With photometric sky surveys, the two-dimensional distribution of galaxies on the sphere can be mapped. To also determine the third spatial coordinate, it is necessary to measure the redshift of the galaxies using spectroscopy, deriving the distance from the Hubble law (or some model of $a(t)$). Actually performing such (spectroscopic!) surveys is daunting, and was not practical until the advent of CCDs and high-multiplexity spectrographs, which could take spectra of several thousand objects simultaneously. Modern surveys are defined by two parameters: the angular size of the sky covered, and the brightness cutoff of objects being observed.

Major galaxy surveys include the two-degree Field Galaxy Redshift Survey (2dFGRS, or 2dF for short), which covered approximately 1500 square degrees and objects with $B \lesssim 19.5$, and the Sloan Digital Sky Survey (SDSS), which covered a quarter of the sky, with a limiting surface brightness of about 23 magnitudes/arcsec² (SDSS 2012).

1.18.2. What about three or higher point correlation functions?

This information is from Schneider (2006), pg. 282.

Higher point correlation functions can be defined in the same manner that we have defined the two point correlation function. It can be shown that the statistical properties of a random field are fully specified by the set of all n-point correlations. Observationally, these functions are significantly harder to map, though.

1.19. Question 18

QUESTION: Consider a cosmological model including a positive cosmological constant. Show that, in such a model, the expansion factor eventually expands at an exponential rate. Sketch the time dependence of the expansion factor in the currently favoured cosmological model.

This question has been entirely answered in Secs. 1.1.4 and 1.10. Followups can be found there as well.

1.20. Question 19

QUESTION: Define and describe the epoch of reionization. What are the observational constraints on it?

This information is from a collection of sources (mostly Schneider (2006)); see my other document for details.

After recombination (3.8×10^5 yrs after the Big Bang) the vast majority of matter in the universe was neutral hydrogen. The epoch of reionization is the period in the universe's history over which the matter in the universe became ionized again. An understanding of reionization is important because of the role reionization plays in large-scale structure formation. The nature of reionization is directly linked to the nature of the reionizing sources, the first stars and active galactic nuclei in the universe (studies could shed light into everything from the early stages of metal enrichment in the universe and the clumpiness of the IGM, to the formation of the first supermassive black holes). Moreover, IGM ionization and temperature regulate galaxy formation and evolution.

It is currently believed that the first several generations of stars were the primary producers of photoionizing radiation during the epoch of reionization. The pre-population III star universe was a metal-free environment, meaning that the only methods of cooling involved H and He. All collapsing dark matter halos in the early universe had small masses, corresponding to low virial temperatures on the order of 10^3 K. Only H₂ emission cools baryons at $T_{\text{vir}} \approx 10^3$ K efficiently; as a result, the baryon clouds formed $\gtrsim 100 M_{\odot}$ stars. When the baryon clouds corresponding to these small CDM halos collapse to form population III stars, the immediate regions surrounding these halos is ionized by the stars' radiation. Moreover, the radiation dissociates most of the H₂ in the universe (the dissociation energy is 11.3 eV, below the 13.6 eV minimum absorption energy of neutral ground-state H, so H₂-dissociating photons can travel without impediment) and prevent further star formation. After they die, population III stars seed the IGM with metals, which provide cooling for gas at much higher virial temperatures. Therefore baryons associated with larger halos can now collapse to form stars. The greater volume of ionizing photons from these stars begins ionizing more and more of the IGM. Eventually different expanding patches of ionized IGM merge, greatly accelerating reionization (since photons can now freely travel between bubbles). Eventually the last regions of the universe become fully ionized. This process can be seen in cartoon form in Fig. 26.

Because the recombination time for the IGM becomes longer than a Hubble time at $z \sim 8$, very complicated reionization histories are allowed, and it is unclear exactly how longer reionization took. We know that reionization must occur over a time period of longer than $\Delta z > 0.15$, but it is very likely much longer.

Despite the fact that the universe is now fully ionized, the average density of HII in the universe is too low for the universe to again become opaque; assuming the universe somehow remained ionized *ad infinitum*, it would still have become transparent after 20 Myr.

Observational constraints on reionization include:

- **Ly- α observations** constrain the redshift at which recombination must have ended. Ly- α absorption lines (and, at high column densities, continuum absorption due to the Lyman limit at 912 Å) are created in quasar spectra by