High redshifts

1. Basics

High redshift is a relative term that always implies $z > 0.2$ but in the modern era more commonly signifies $z > 1$, at which epochs the galaxy and quasar populations are much different, revealing the statistical properties the local population would have had much earlier in time.

1.1. Detection of high redshift galaxies

The study of high redshifts in the optical and infrared requires large aperture telescopes (> 4 meter). Infrared observations are required to obtain the same rest-frame measurements as exist at low redshift. Space-based observations or adaptive optics are required to resolve galaxy structures well. A particularly troublesome effect is the $(1+z)^{-4}$ scaling of the observed surface brightness, which leads to difficulties in detecting resolved galaxies above background noise, and to a very steep decline in total flux for both resolved and unresolved galaxies.

Determining redshifts is most reliably performed with spectra. At high redshift, obtaining large numbers of spectra becomes increasingly expensive for the reasons stated above. Between about $z \sim$1–2, galaxies have few identifiable features in the optical, leading to the *redshift desert*, mitigated with near infrared spectra. The

The largest available samples of high redshift galaxies tend to be from *photometric redshifts*. As the spectral energy distribution of galaxies K-corrects with redshift, its colors change. If fluxes are measured in enough bandpasses, both the intrinsic color of the galaxy and the redshift can be inferred. With high precision photometry over 4–5 optical bandpasses, redshift errors $\delta z/(1+z) \sim 0.02$ are achievable, although some fraction of large outliers do persist.

Although precise photometric redshifts involve using the full spectral energy distribution shape, at some wavelengths strong breaks in the flux are particularly useful. For red galaxies, the 4000 Åbreak is particularly informative, as it redshifts through the g-band and to redder and redder bands. For galaxies with younger stellar populations, the somewhat bluer Balmer break is more prominent (and this can cause degeneracies between models of intrinsically blue galaxies at one redshift and models of somewhat redder galaxies at redshifts $\delta z/(1+z) \sim 0.1$ closer). For all galaxies, a break at 912 Åis prominent since essentially no flux can be transmitted blueward due to the high photoionization cross-section of neutral hydrogen inside and around the galaxies. Galaxies identified as high redshift with this break are known as *Lyman break* galaxies.

At redshifts $z > 2.5$ there are substantial numbers of Ly-α emitting galaxies, which can be selected with narrow band imaging. A given narrow band observation is sensitive to a particular range of redshifts.

Because high angular resolution space-based imaging currently only covers at most a few tens of degrees of the sky, there are a handful of fields that have been investigated in detail by many groups. In particular, the Great Observatories Origins Deep Surveys (GOODS), Galaxy Evolution from Morphology and SEDS (GEMS), the Extended Groth Strip (EGS), and the COSMOS field.

1.2. Demographics of high redshift galaxies

The optical luminosity functions and stellar mass functions can be measured out to $z \sim 1$–3. Beyond that redshift, only the most highly star forming galaxies are easily visible, typically in the rest-frame ultraviolet or at sub-mm wavelengths.

At all of these redshifts, the star forming main sequence is well established. It may evolve in shape but since $z \sim 2$ the star formation rate at a given stellar mass has declined (Whitaker et al. 2014).

Between $z \sim 3$ and $z \sim 1$, the inferred build up of total stellar mass density is rapid, increasing by around a factor of around 5–10. At these redshifts, the red sequence and blue star forming sequence of galaxies are already established. This growth is accompanied by a growth in the fraction of red galaxies (e.g. Mortlock et al. 2015). The growth in the fraction of red galaxies occurs at all stellar masses, but at the highest stellar masses results in red galaxies dominating by $z \sim 1$. During this same time period, the star formation rate density is at its highest, experiencing a long plateau.

Between $z \sim 1$ and $z \sim 0$, the inferred build up of total stellar mass density appears to nearly stall. The growth in the fraction of red galaxies continues, again at all stellar masses. The total star formation rate density declines sharply during this period, falling by a factor of ten.

The highly star forming galaxies at $z \sim 3$ are unusual relative to typical galaxies at low redshift. They are often photometrically and kinematically irregular starburst galaxies. Meanwhile, the red galaxies at these redshifts tend to be very compact relative to similarly massive galaxies today; these galaxies probably become lower density over time through minor mergers.

2. Commentary

Measurement and detection of galaxies at high redshift is still extremely challenging. The surface brightness incompleteness effects may be altering our view of high redshift in a manner not sufficiently understood to correct for. Furthermore, inferences of total integrated properties of the population like stellar mass density and star formation rate often depend on extrapolation of increasing function to low stellar mass or star formation ratios.

3. Key References

- *Madau & Dickinson*
- *CANDELS*

Gunn et al. (2006)

4. Analytic Exercises

1. Growth by merging and density

5. Numerics and Data Exercises

1. Lookback times at high redshift
2. Photometric redshifts

REFERENCES

Gunn, J. E., et al. 2006, AJ, 131, 2332

Mortlock, A., Conselice, C. J., Hartley, W. G., et al. 2015, MNRAS, 447, 2

Whitaker, K. E., Franx, M., Leja, J., et al. 2014, ApJ, 795, 104

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