Extragalactic Astrophysics and Cosmology
Cosmic Re-ionization

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Abstract

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Predictions

1 Predictions Group

In order for those attempting to observe high redshift galaxies to propose a detailed experimental plan, it is important to know how many galaxies one is expecting to observe within a certain volume of the sky. This is the fundamental purpose of the predictions sub-group; to be able to compute this quantity with the depth of the surveyed volume corresponding directly to redshift. In order to do this, a computer program is required to efficiently calculate this number as a function of redshift, field of view and luminosity enabling those observing to make an informed prediction of the telescope one would need and the observing time required to make definitive observation of such elusive galaxies.

This section of the project will be structured as follows:

- Research how early galaxies are professionally predicted.
- Find a general Schechter function in terms of luminosity and/or magnitude.
- Mathematically process this function to ensure it is consistent with the units used by those carrying out the observations.
- Build a computer program to automate the process of calculating the number of galaxies from the Schechter function.
- Find plausible starting parameters to use in primary program.
- Collate parameter data from published papers.
- Determine parameter evolution with time.
- Plot these results to produce a visual description of how these parameters affect the outcome.
- Give expected number of galaxies to the observers.
- Refine technique with the inclusion of more advanced adaptations

In addition to running a program to calculate the total number of galaxies, there will also be a separate program to determine the star formation rate of galaxies. This can then be used to determine an estimate of when the epoch of re-ionization occurred and hence would limit the range of redshifts which it would be necessary to include in the calculation of total number of galaxies.

1.1 Assumptions Made

The mathematical model that will be used in our program is limited by certain assumptions about the universe that we are working in. Some of these are generally held to be true and are accepted widely in the scientific community, others are due to the constraints of what we can mathematically program and the observational data available from previous studies. A major assumption that we are making throughout our work on re-ionisation concerns the type of universe that we exist in. This includes the relative densities of matter with respect to radiation and dark energy, as well as the geometry of the whole universe.

1.2 Parameter Values

It will be assumed that the universe has a curvature of zero, in other words, that the universe is flat. This has been shown before and is generally held to be true, "we now know that the universe is flat with only a 0.4% margin of error" [1]. This means that we do not need to take into account any of the effects of observing objects near the beginning of the universe when it might have had different properties.

A second assumption that will be maintained through our calculations concerns the values of the matter, curvature and dark energy constants, Ω_M, Ω_k and Ω_Λ respectively. We will assume that we are living in a matter dominated universe and that these parameters are related to the value of the Hubble parameter by equation 1.1 [2],

$$H^2(z) = H_0^2 \left(\Omega_M(1+z)^3 + \Omega_k(1+z)^4 + \Omega_\Lambda\right) \tag{1.1}$$

where

$$\Omega_k = 1 - \Omega_M - \Omega_\Lambda \tag{1.2}$$

We will use values of $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.728 \pm 0.015$, in accordance with the ΛCDM model [3].

There are also a number of parameters in the Schechter function that must be specified. In order to find suitable values to use, we collected data from a number of different sources covering several studies. All of the studies that have been performed in the past concer galaxies at lower redshifts than we are expecting to examine. To get an estimate for the value of each of the parameters at higher redshift, the values found were plotted and the fit expropolated to cover the era nessessary. Since some of the fits demonstrate that these parameters are not constant with time, their evolution shall be incorporated into the calculations.

The values in the Schechter function that we have determined fits for are α, M^* and ϕ^*. The data collected for each of these fits is shown in appendix A.

Part III

Observations

2 The Hubble Space Telescope

2.1 Mission Launch

On April 24th 1990 NASA's Space Shuttle Discovery launched the world's first space-based optical telescope; The Hubble Space Telescope (HST), named in honour of American astronomer Edwin P. Hubble. Edwin Hubble's greatest contribution to astronomy was the 'Hubble Law' which states that galaxies are receding from us at a speed directly proportional to their distance from us. This showed that our universe is expanding, a notion which underpins modern cosmological thinking. The telescope sits in a low-Earth orbit, as shown in figure 1, at an altitude of 569 kilometres completing one orbit of the Earth every 97 minutes [4].

Figure 1: *Photograph of HST orbiting the Earth.*

The HST was designed to provide clear and deep views of distant galaxies and stars and most of the planets in our solar system. Hubble's domain extends from the ultraviolet through the visible and into the near-infrared [5].

2.2 Achievements to Date

The HST has provided unprecedented detail in images of star formation allowing astronomers to see the jets and disks present during the birth of new stars. It has also been able to study the atmospheric composition of extra-solar planets and take the first visible light picture of a planet outside our solar system; Fomalhaut b [6].

Many EoR galaxies and candidate galaxies have been identified using HST data. In December 1995 the HST was pointed at what was believed to be a fairly empty and uninteresting patch of sky; 342 separate exposures were taken over 10 consecutive days and formed an image called the Hubble Deep Field (HDF) [7]. The image contains around 3,000 objects of which the vast majority are galaxies, with a few local stars in the foreground. The HDF is one of the most iconic images of the 20th century, and it has since been cited in over 800 scientific papers.

In 2004 its successor was revealed, the Hubble Ultra Deep Field (UDF); a million-second exposure in a $200'' \times 200''$ area of sky containing 10 000 galaxies stretching back 13 billion years [8]. This exposure utilised the recently installed Advanced Camera for Surveys (ACS). This survey was further refined in September 2012 in the Hubble eXtreme Deep Field (XDF) which utilised the recently installed WFC3 camera as well as combining over 2000 separate exposures from different sources [7].

2.3 Operation

The HST is operated remotely from the earth, it has 4 antennae which can send and receive signals from the Flight Operations Team at Goddard Space Flight Center in Greenbelt, Maryland via the Tracking and Data Relay Satellite system. For communication to be possible HST must have a direct line of sight to at least one of these 5 satellites.

The HST is powered using 2 arrays of solar panels each capable of converting the sun's rays into 2800 watts of electricity. The arrays are able to store the electricity in batteries allowing the HST to remain active while in the Earth's shadow (approximately 36 minutes out of every 97 minute orbit).

Orbiting the Earth subjects the HST to extreme conditions due to the effect of zero gravity and the variation in temperature (up to around 40 K) during each orbit. The optical system is held together using a skeleton (truss) constructed from Graphite epoxy. Graphite epoxy, commonly found in racquets and golf clubs is a stiff and lightweight material able to resist expansion and contraction due to temperature changes [9].

2.4 Performance and Optical Telescope Array

The HST is constructed using a Ritchey-Chretien Cassegrain design; this allows high-performance over a wide field of view. The incoming light enters a tube with baffles removing any unwanted stray light, as shown in figure 2 below. The light is then collected by the concave Primary mirror and reflected towards the smaller convex Secondary mirror. This light is then reflected back through a hole in the centre of the Primary mirror where it is focused onto a small area to be picked up by the instruments [10].

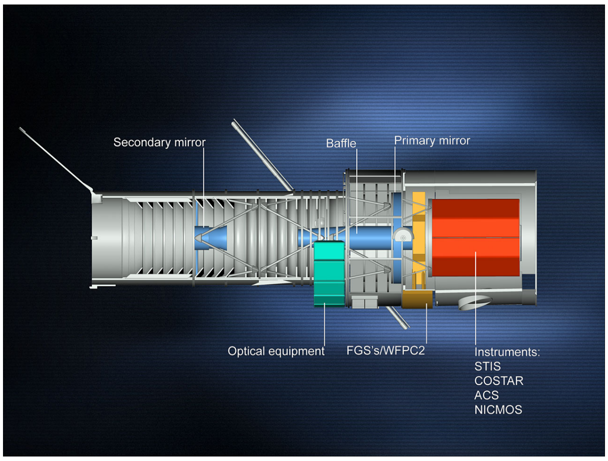

Figure 2: *Diagram showing basic systems of HST, note that WFC2 has since been replaced by WFC3.*

The mirrors have been polished to an accuracy of better than the wavelength of visible light. When the HST was first launched the scientists soon realised that the curve to which the mirrors had been ground was not correct resulting in an error known as spherical aberration which blurred the images. A servicing mission in December 1993 deployed 5 pairs of mirrors which were able to successfully correct the error and allow Hubble to take the images it was intended to [11].

There have been 4 servicing missions sent to the HST with the final mission taking place in May 2009. Over its lifetime the cameras and instruments have undergone many improvements and replacements. The camera currently operating that is of interest to this project is the WFC3/IR camera, installed in 2009. This camera is able to observe in the near-infra-red where we expect to see the Lyman-break galaxies. Table 1 shows the key technical data for the HST, amazingly the HST is so precise it is able to lock onto a target at a distance of 1 mile without deviating more than the width of a human hair.

Primary Mirror Diameter	2.4 m
Secondary Mirror Diameter	0.3 m
Wavelength range	800 - 1700 nm
Total Field of View	$123'' \times 136''$ ($16\,728''^2$)
Pixel Size	$18 \times 18\,\mu$m
Plate Scale	$0.13\,''\,\mathrm{pix}^{-1}$
Quantum Efficiency	77% at 1000 nm 79% at 1400 nm 79% at 1650 nm
Dark count	$0.048\,\mathrm{e}^-\,\mathrm{s}^{-1}\,\mathrm{pix}^{-1}$
Readout noise	$12.0\,\mathrm{e}^-\,\mathrm{s}^{-1}\,\mathrm{pix}^{-1}$
Full Well	$77\,900\mathrm{e}^-$
Gain	2.28 - $2.47\mathrm{e}^-\,\mathrm{ADU}^{-1}$
Operating Temperature	145 K
FWHM	$0.151'$ at 1600 nm

Table 1: *Technical data for HST WFC3/IR camera system [12]*

A Parameter Fit Data

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