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## Abstract

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# 1 Introduction

## 1.1 Why Investigate Cosmic Re-Ionisation

There are a number of different projects in progress investigating this period of the universe and many more in the pipeline. Reionization occurred due to the formation of the first structures in the universe. By probing this period we are able to see the beginnings of this formation and this will enable us to understand the mechanisms by which galaxies and other structures form and evolve.

There are many unanswered questions in cosmology; one of the most crucial is the nature of dark energy and matter which make up 95% of the universe [WMAP9], this is thought to be the key driving force behind the evolution of the universe. By studying and mapping the distribution of Hydrogen during the EoR and tracking the evolution of stars and galaxies we are able to infer more about the effects of dark energy and what it might consist of. Understanding the EoR is the missing link in explaining how the universe went from how it looks in the Cosmic Microwave Background (CMB) to how it appears today. Understanding these mechanisms of structure formation will enable us to more accurately predict where the Universe is headed and how it may eventually end, will it be in a big crunch or a big freeze?

Part I

## General Theory

## Part II

# Predictions

## 2 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.

### 2.1 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.

## 2.2 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,  $\Omega_M$ ,  $\Omega_k$  and  $\Omega_\Lambda$  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 2.1 [2],

$$H^2(z) = H_0^2 \left( \Omega_M(1+z)^3 + \Omega_k(1+z)^4 + \Omega_\Lambda \right) \quad (2.1)$$

where

$$\Omega_k = 1 - \Omega_M - \Omega_\Lambda \quad (2.2)$$

We will use values of  $\Omega_M = 0.27$  and  $\Omega_\Lambda = 0.728 \pm 0.015$ , in accordance with the  $\Lambda$ CDM 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 concern 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 extrapolated to cover the era necessary. 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  $\alpha$ ,  $M^*$  and  $\phi^*$ . The data collected for each of these fits is shown in appendix A.

## Part III

# Observations

### 3 Observing Strategy Group

This primary aim of this subgroup is to formulate an observing strategy capable of probing the depths of the Epoch of Reionization. Our strategy is going to be based upon using optical methods to detect candidate Lyman Break Galaxies (LBG) and confirming them using spectroscopy.

The study of this era in the universes history has come a long way in the past 30 years and with the many new telescopes and arrays being designed currently it is only set to accelerate over the coming decades. It is an understatement to say such distant redshifts are very difficult to see and it is a testament to scientific and engineering achievement that we are able to take the detailed images that we have. The light from these galaxies is so faint that it can take a very long time to see anything. Due to this long project duration, time on telescopes is in high demand.

The strategy must therefore be as complete as possible with as many influencing factors considered. This strategy will focus on using the most efficient methods available in order to limit the observing time required. The second focus will be to probe the beginning of reionization, there have been few observations above  $z=10$  and future telescopes will have the ability to break new frontiers and observe what happened at the earliest moments of structure formation. Our strategy will look to utilise the capabilities of the new technology to further the scientific understanding of the EoR.

The strategy will be established as follows:

- Research possible systems capable of observing high-redshift objects.
- Explore the advantages and disadvantages of ground and space-based telescopes.
- Identify the most efficient telescope for a wide survey of the sky to locate candidates; this will be determined using exposure time calculations and considerations of the etendue...
- Research gravitational lensing and its possible application in assisting our wide surveys.
- Identify the telescope which will produce the highest resolution imaging of the candidates in a narrower deep survey; this will be established using exposure time calculations...
- Identify a telescope capable of spectroscopically confirming the nature and redshift of the candidates.
- Investigate the application of methods such as colour-colour diagrams for selecting candidates and removing contaminants.
- Investigate additional techniques to improve the accuracy of our measurements; such as dithering and post flash...
- Compile a final strategy capable of observing the EoR using the predictions from the predictions subgroup.

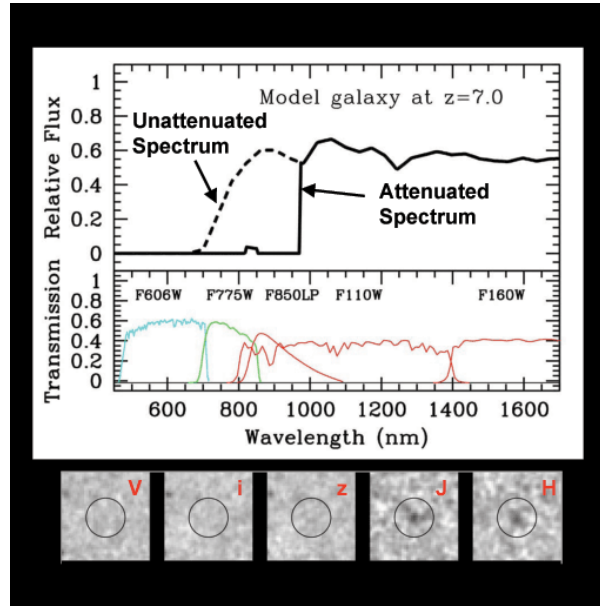
### 4 Determining Redshift

Need a section on candidates and how the contaminants are eliminated. (COMBINE WITH JOE'S COLOUR STUFF?)

Section ? described how contaminants could be eliminated from the large number of potential high redshift galaxies. Taking the remaining objects, the following methods are used to check whether they are in fact LBGs.

#### 4.1 Filters and the Dropout Technique

Using photometry, the redshift of a LBG can be estimated using the dropout technique: The flux from the galaxy can be measured in three different bands, ideally two above and one below the Lyman break. If the galaxy is a high redshift Lyman break galaxy, it would be expected that, so long as the filters were correct for the redshift expected, one image would not see the galaxy whereas the other two would observe flux. Below in figure 1, the dropout technique is shown for a model galaxy of redshift seven.



**Figure 1:** Dropout technique for model redshift 7 galaxy [4].

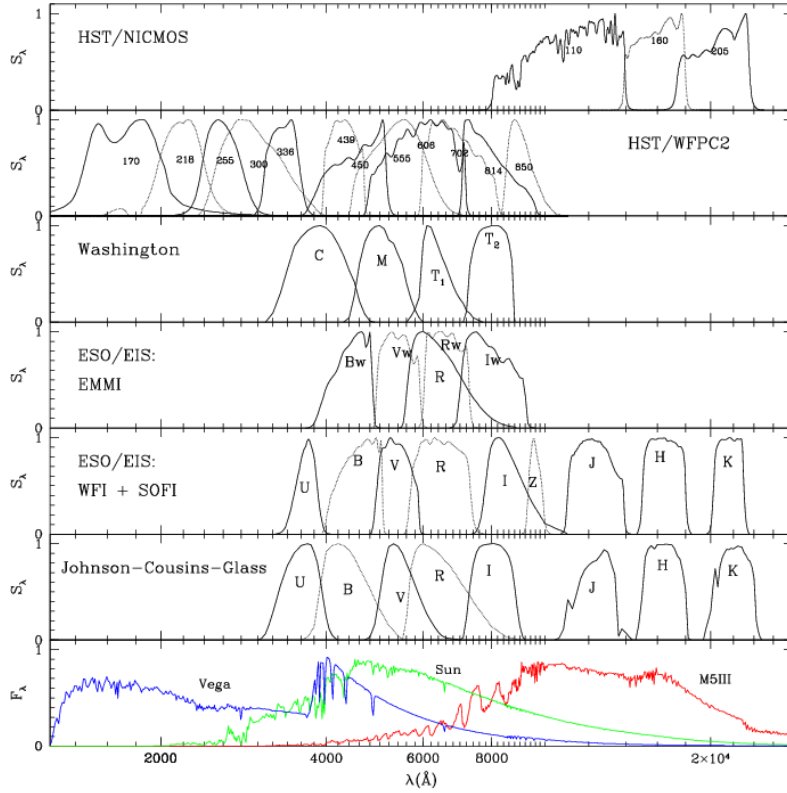
The neutral hydrogen has attenuated almost all flux at wavelengths shorter than approximately 1 micrometre. The galaxy has been imaged in several different bands, and the longer wavelength filters show flux, whereas those at wavelengths corresponding to blue-ward of Lyman alpha do not. The galaxies that the group look to study have been shifted such that the drop happens in the infra-red. The wavelength of the drop can be worked out using the known rest wavelength of Lyman alpha, as well as the factor by which the wavelength shifts due to the expansion of the universe, as shown in equation 4.1.

$$\text{Rest wavelength of Lyman alpha} \times (1 + z) = \text{observed wavelength of drop} \quad (4.1)$$

Since the rest wavelength of Lyman alpha is known and the observed wavelength of the drop can be measured, the redshift of the galaxy can be determined. This is only a rough estimate when doing photometry since the flux is simply a number in each of the bands. For example, if the bands do not overlap, and the drop happens between two bands, it will not be known at what point the drop occurred, only the range in which it occurred. This motivates the use of bands which are close together or potentially even overlapping. Figure 2 shows some different bands and their bandwidth, for different filter systems. Johnson-Cousins- Glass is one of the oldest and still the most commonly used system [5].

The bandwidth (or passband) is the wavelength range that can pass through the filter. Filters in different parts of the spectrum are given a common name, for example I band at 806 nanometres.





**Figure 2:** Various filtering systems [6].

When observing LBGs, it is beneficial to have three filters in a row so that the position of the drop can be more accurately measured. As can be seen, there are gaps between the J H and K filters, meaning if the drop occurs between J and H, full flux should be observed in H and K and virtually no flux should be seen in J. (the panels beneath figure 2 show an image (or lack thereof) of the  $z=7$  galaxy in each of the V, I, z, J and H bands)

Table 1 below shows a list of filter names, the central wavelength of that filter, the bandwidth the filter covers, and range of redshifts for which the Lyman alpha drop would be covered. (This range assumes the bandwidth covers 50% either side of the central wavelength)

filter	Central wavelength	bandwidth	Redshift coverage
V	551 nm	88 nm	3.17–3.90
i	806 nm	149 nm	5.01–7.25
Y	1020 nm	120 nm	6.90–7.88
J	1220 nm	213 nm	9.16–9.91
H	1630 nm	307 nm	11.14–13.67
K	2190 nm	390 nm	15.41–18.61

**Table 1:** Data highlighting which filters would be useful for observing particular redshift galaxies [7]

Table 1 must be taken into consideration that two filters should be red-ward of the drop and one blue-ward. One the fluxes have been measured in all three bands, if the object is indeed a LBG, there should be a sharp drop in flux in one of the bands. However this does not totally rule out other possibilities: Some other objects could also exhibit a drop in flux, posing as LBGs, so usually a follow up method is used, and this is spectroscopy. Spectroscopy The drop out technique provides a good indication that a galaxy is a high redshift Lyman break galaxy, however the best way to confirm this is with spectroscopy. Spectroscopy involves...

At loads of different wavelengths, measure the spectra. Look for the drop

Use ground based such as KECK or space based, JWST will have one.

## 5 The Hubble Space Telescope

### 5.1 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 3, at an altitude of 569 kilometres completing one orbit of the Earth every 97 minutes [8].



**Figure 3:** *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 [9].

### 5.2 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 [10].

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) [11]. 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 [12]. 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 [11].

### 5.3 Operation

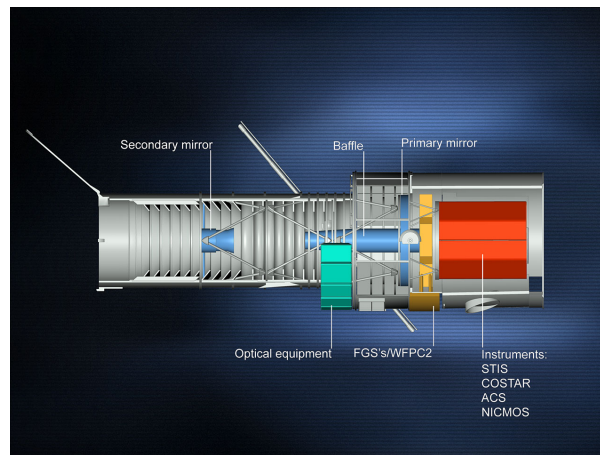
The HST is operated remotely from the earth, it has 4 antennae which can send and receive signals from the Flight Operations Team at Goddard Space Flight Center in Greenbelt, Maryland via the Tracking and Data Relay Satellite system. For communication to be possible HST must have a direct line of sight 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 [13].

### 5.4 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 4 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 [14].



**Figure 4:** 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 [15].

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 2 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.

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

**Table 2:** *Technical data for HST WFC3/IR camera system [16]*

## 5.5 Euclid

### 5.5.1 Mission Overview

The Euclid mission is planned for launch in 2020, at an estimated total cost of 800 million Euros [17]. Its primary goal is to conduct a wide survey; some 15000 degrees of sky is planned to be covered. There is also to be a deep survey which is expected to cover around 40 degrees to a depth 2 magnitudes deeper than the wide survey. It will have a near infra-red camera and spectrometer as well as an optical camera. The primary mission objectives are expected to be completed within 7 years. One of Euclid’s main scientific objectives with the deep field is to study high redshift galaxies at  $z = 6+$  over a very wide survey area. This will give astronomers the opportunity to spectroscopically confirm hundreds of galaxies for use in the study of the EoR. It will help constrain the bright end of the luminosity function at high  $z$ .

### 5.5.2 Capabilities

- Visual Imaging/ Photometry, 550–900nm
- Spectroscopy, 1100–2000nm
- NIR Imaging/ Photometry, 920–2000nm (Y, J,H bands)

Euclid will have two instruments in order to do the above; a wide-band imaging system in the visible (VIS), and an instrument capable of both slit-less spectroscopy as well as NIR imaging. These instruments will be operated simultaneously.

### 5.5.3 Key Technical Data

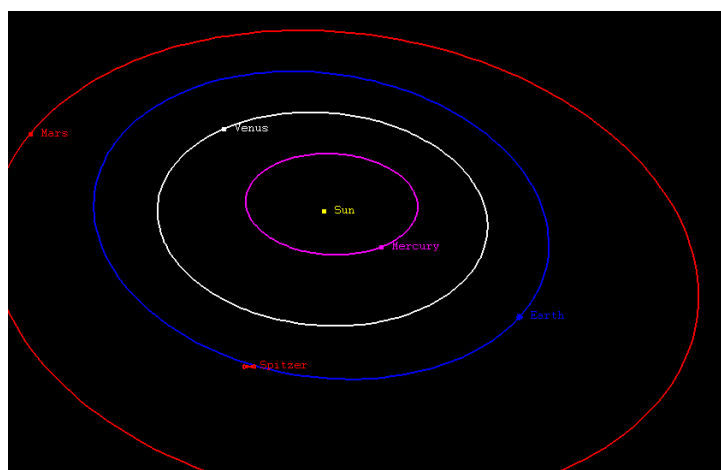
The data in table 3 is quoted for the deep survey NIR photometry. Some data is subject to slight change as the planning stages progress.

Component	Details
Primary mirror	1.2 m
FoV	$0.763 \times 0.763^{\circ 2}$
Pixel size	$0.3'' \times 0.3''$
Detector Array	$(2 \times 10^3) \times (2 \times 10^3)$ pix
Resolution	0.3 to $0.6''$ (in J band)
Plate Scale (infra-red)	$0.3'' \text{ pix}^{-1}$

**Table 3:** *Technical data for HST WFC3/IR camera system [16].*

## 6 Spitzer Space Telescope

Spitzer Space telescope was launched by NASA on 25th August 2003 [18] and is designed for use in the infra-red. It was the last of NASA’s “Great Observatories”, working alongside HST in the optical, Compton Gamma Ray Observatory and Chandra X-ray Observatory. The telescope is 85 cm in diameter, and sits in an Earth-trailing orbit around the Sun, shown in figure 5. It is a Cassegrain telescope, meaning it has primary and secondary hyperbolic mirrors to focus the light and reduce spherical aberration, in a similar manner to Hubble. The majority of Spitzer’s instrumentation is now non-operational due to a lack of cryogen, but some photometry remains possible.



**Figure 5:** *The Spitzer Space Telescope’s Orbit [19].*

### 6.1 Capabilities

Spitzer had the capabilities detailed in table 4:

It employed three scientific instruments which helped it do the above:

- Infrared Array Camera (IRAC): an imaging camera working in the near IR at wavelengths of 3.6, 4.5, 5.8 and 8 micrometres.
- Infrared Spectrograph (IRS): performing spectroscopy from 5 to 40 micrometres.

Component	Details
Imaging/Photometry	3–180 $\mu\text{m}$
Spectroscopy	5–40 $\mu\text{m}$
Spectrophotometry	50–100 $\mu\text{m}$

**Table 4:** *Technical data for the Spitzer orbiting telescope [16].*

- Multiband Imaging Photometer (MIPS): detected wavelengths in the far IR, at 24, 70 and 160 micrometres.

The telescope was cryogenically cooled to around 1.4 K, allowing all the instruments to function without excessive thermal interference from the telescope itself. The mission, labelled the ‘Cold Mission’, was estimated to last between 2 and 5 years, depending on when the cryogen ran out. During this time, Spitzer imaged in all four NIR filters simultaneously, as well as doing spectroscopy, and some imaging in the far infra-red. In 2009, when the cryogen ran out, the longer wavelength filters became non-operational, and the Spitzer ‘Warm Mission’ continued imaging with the nearest IR filters (3.6 and 4.5 micrometres). This was made possible because Spitzer’s orbit keeps it substantially cooler than an Earth-centred orbit would, due to the lack of IR radiation received from Earth. Furthermore it is made mostly of beryllium which has a low heat capacity at low temperatures, helping to keep it cool.

In order to keep enough sunlight on the solar panels, Spitzer cannot point further than 120 degrees away from the Sun. However, it also cannot get closer than 80 degrees towards the Sun in case damage is done to the scientific instruments. This is a limitation on the area of sky which can be observed, meaning that some regions can only be seen for 40 days semi-annually, whilst other areas can be observed all year round.

The spectrograph (IRS) operated at wavelengths too long to be of use to study the EoR, as did the far IR photometry (MIPS), however the near IR photometry capabilities of both the Spitzer warm and cold missions have been used to study high redshift galaxies, and in conjunction with HST have confirmed galaxies at redshifts as far back as  $z \approx 10$ . Particularly the 3.6 and 4.5 micrometre filters observe significant flux from such galaxies, and so these have been used in a number of studies looking for high redshift galaxies.

## 6.2 Studies involving Spitzer

Coe et al (2012) [20] reports a  $z \approx 11$  candidate which had been observed using HST (WFC3, ACS) and Spitzer (IRAC) for longer wavelengths. This is one of the highest redshift candidates to date. The Spitzer data was taken over a total integration time of 5 hours.

An earlier study in 2008 by Richard et al also used Hubble to detect galaxies greater than redshift seven (making use of gravitational lenses). Spitzer imaged these galaxies to help confirm that they were not foreground objects of a different nature, by looking at the flux in longer wavelength filters [21].

In 2005, during the cold mission, a study was made by Spitzer on a confirmed  $z = 6.56$  galaxy (HCM 6A) lensed by a cluster (Abell 370). The study was used to detect the rest frame optical emission of this galaxy in order to better understand the physical properties of objects at such high redshifts [22]. Several other papers have also used Spitzer data in the study of high redshift galaxies.

The data in table 5 shows some of the key technical data available for the telescope.

Component	Details
Primary mirror	0.85 m
FoV	$5.2' \times 5.2'$
Pixel size	$1.2'' \times 1.2''$
Detector Array	$256 \times 256$ pix
Full well	145,000 at $3.6 \mu\text{m}$
	140,000 at $4.5 \mu\text{m}$

**Table 5:** *Technical data for the Spitzer orbiting telescope [23].*

### 6.3 Contaminants

#### 6.3.1 Low Mass Stars

These can easily be identified due to the high resolution imaging provided by .... The Point-spread function (PSF) obtained will allow us to determine which sources are point-like and which are extended. We should be able to avoid significant contamination by removing any point-like sources from the results as all galaxies should have a great enough diameter.

#### 6.3.2 Spurious Sources

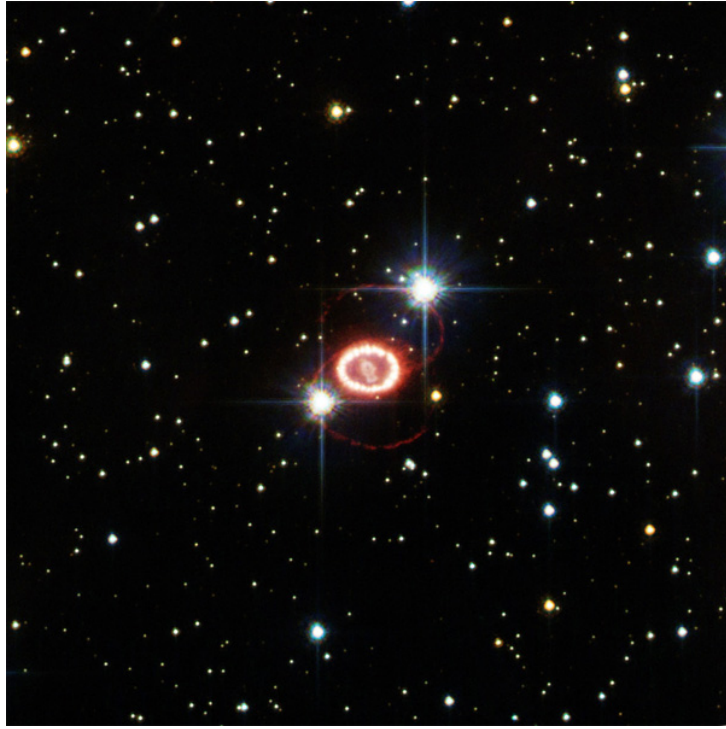
By stipulating that we will be requiring detections in two bands the influence of spurious sources will be negligible. Finding detections in 2 bands at reasonable confidence interval (?3sig?) is very improbable. By inspecting the negative with the same requirements for detection we are able to identify any such sources easily [Bouwens2011].

#### 6.3.3 Supernovae and other transient sources

Events such as Supernovae happen incredibly quickly releasing a vast amount of energy, as seen in figure 6. These events can spoil images due to their short duration by introducing new data in only a portion of the sample. These effects are usually only considered when taking exposures years apart or when combining multiple sources over a long timescale. Such events are very unlikely to contaminate our results as we propose to take our images close in time.

#### 6.3.4 Lower Redshift Sources and photometric scattering

This category is likely to provide the greatest source of contamination for the surveyed area. It will do so increasingly at high redshifts where its affect on the faintest magnitudes is most greatly felt. Its affect is most influential with a small S/N ratio for the observations, by fixing this at a level of  $S/N = \dots$  we can be confident that the contamination will be low. Detecting a source in another band such as b435, v606, i775 for YJH photometry would class it as a contaminant and then should be removed from sample.



**Figure 6:** *The shockwave from Supernova 1987a imaged by HST in 2006.*

## A Parameter Fit Data



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