

Hunting for Dark Stars with the James Webb Space Telescope

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Abstract

English

The first stars in the Universe are thought to have formed in high dark matter density minihalos about 200 million years after the Big Bang. If these stars were able to contract dark matter into their stellar core while forming, some of them might have turned into dark stars (DSs) powered by the heat from dark matter annihilation. The possibilities for detection of DSs with the upcoming James Webb Space Telescope (JWST), scheduled for launch in 2021, is investigated in this work. With DS models generated in Spolyar et al. (2009) and atmosphere spectra from Gustafsson et al. (2008), spectral analysis has been carried out in MATLAB to find the unique colors of DSs compared to galaxies generated in Zackrisson et al. (2017) at $z \approx 7 - 11$. It was found that lower temperature DSs ($T_{eff} \leq 7800$ K) are distinguishable from galaxies and that they would be bright enough to be detected with the JWST provided a magnification factor of $\mu \approx 160 - 1000$ with the use of gravitational lensing. More recent DS models reveal that the DS of temperature $T_{eff} = 7800$ K is detectable even without the use of gravitational lensing. However, the probability of finding one today is really small due to DSs' presumably short lifetime. The results of this work are hoped to give a better understanding of the properties of DSs and to increase the probability of finding one in the large imaging survey carried out by the JWST.

Svenska

De första stjärnorna i universum antas ha bildats i minihalos med hög densitet av mörk materia omkring 200 miljoner år efter Big Bang. Om dessa stjärnor kunde dra till sig mörk materia under sitt bildande kan vissa av dem ha utvecklats till mörka stjärnor (s.k. dark stars) med mörk materia som energikälla. I detta arbete undersöks möjligheterna att upptäcka dem med det kommande James Webb Space Teleskopet (JWST) som planeras för uppskjutning år 2021. Med dark starmodeller genererade i Spolyar et al. (2009) och atmosfärspektra från Gustafsson et al. (2008) har spektralanalys utförts i MATLAB för att hitta vilka dark stars som går att urskilja från galaxer genererade i Zackrisson et al. (2017) vid $z \approx 7 - 11$. Det visade sig att dark stars med låg temperatur ($T_{eff} \leq 7800$ K) är urskiljbara och att de flesta av dessa dark stars, vid en förstoringsfaktor av $\mu \approx 160 - 1000$ vid användning av gravitationell linsning, är tillräckligt ljusstarka för att kunna detekteras. Jämfört med senare dark star-modeller skulle även $T_{eff} = 7800$ K DSs kunna detekteras utan användning av gravitaionell linsning. Sannolikheten att hitta en dark star är fortfarande väldigt liten på grund av dess förmodade korta livstid. Resultaten av detta arbete hoppas kunna ge en bättre förståelse för egenskaperna hos mörka stjärnor samt öka sannolikheten för detektion med JWST.

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Introduction

The large-scale structures in the Universe are believed to have formed through a process called hierarchical clustering in the early history of the Universe. Dark matter (DM), which constitutes 85% of the matter in the Universe, is believed to be the dominant contributor to the large-scale structures. DM is thought to have dragged small clumps of matter together, which then merged into larger structures creating cold DM minihalos with a mass of ~ $10^5 - 10^6 M_{\odot}$, containing 85% DM and 15% atomic matter created during primordial nucleosynthesis. Consequently, the minihalos then merged into even larger structures, creating the galaxies and galaxy clusters we can observe today. It was in the minihalos where the very first stars in the Universe, called population III stars ($10 - 1000 M_{\odot}$), are believed to have formed (e.g. Spolyar et al. 2009).

The formation of population III stars took place 200 million years after the Big Bang at redshifts $z \approx 10 - 50$. In theory, some of these stars may have dragged DM into their cores gravitationally while forming, increasing their DM density. If the density in the cores of the stars were high enough, the DM may have started to self-annihilate (into fermions and gauge bosons), providing a heat source for the stars. This would have stopped or delayed the formation into population III stars, where heat from nuclear fusion is the power source. They would instead have evolved into so-called dark stars (DSs), with DM annihilation as a power source instead of nuclear fusion. This means that the term 'dark star' does not refer to a star being observationally dark, but referring to a star powered by DM. DSs are predicted to have a low density with a low surface temperature of $T_{eff} = 4000 - 10000$ K, a central temperature of $T_c = 10^5 - 10^6$ K, a size of ~ 10AU, a mass of ~ 1000M_o and a luminosity of 10^6 L_o (Freese et al.2008b). They probably have a metallicity as low as $Z \approx 10^{-9}$ due to the level resulting from Big Bang nucleosynthesis at the time of formation (e.g. Iocco et al. 2008).

DSs have not yet been detected with existing telescopes. If they exist, they would be visible in the infrared wavelength range and therefore might be possible to be detected with the upcoming James Webb Space Telescope (JWST), scheduled for launch in 2021. The JWST will be able to continue the extraordinary image quality that made the Hubble Space Telescope extremely prominent by offering significant improvements in sensitivity in the optical- and infrared wavelength range of $0.6 - 28.5 \mu m$.

The goal of this study is to investigate the potential of successfully detecting DSs with the JWST.

There are difficulties regarding the detectability of DSs due to their faintness, presumed short lifetime, and the fact that they can be confused with other high-redshift objects, such as dusty or passively evolving galaxies. Therefore, the investigation of the detectability begins with an analysis of DSs distinguishability in color from thousands of other objects (focusing on the first generation of galaxies) in a deep-field image obtained by the JWST. The colors are determined by their positions in color-color diagrams. If a DS shows to be distinguishable, it will be detectable if it has a magnitude brighter than the detection limits of the JWST filters. The analysis will be restricted to DSs and galaxies in the redshift range of $z \approx 7 - 11$ as described in detail in Section 3. The results of this work are hoped to increase the probabilities of finding a DS in the large imaging survey carried out by the JWST.

Background

Starting from the early works, in Salati & Silk (1989) for instance, dark matter annihilation was introduced as a potential power source inside stars. These stars were in the beginning referred to as "Dark Matter Burners". Later on, the term "Dark Star" was introduced in Spolyar et al. (2008), who referred to the first stars in the Universe as candidates for stars which may use dark matter annihilation as a power source. The definition of dark stars was afterwards broadened by Scott et al. (2008) to include any star, powered by DM annihilation, and not restrictively the first stars in the Universe.

2.1 The Evolution of Dark Stars

The first stars have been predicted to form 200 million years after the Big Bang at redshifts $z \approx 10 - 50$. These stars are called population III stars. At the time of their formation, the Universe consisted mainly of hydrogen, helium, dark matter and small amounts of metals, such as lithium (Freese et al. 2016). Several studies (e.g. Freese et al. 2008b; Spolyar et al. 2008) have found that if population III stars were formed in very high-density regions of DM, they may have, by a process called adiabatic contraction (no loss or gain of heat) dragged DM into their core gravitationally while forming. This would stop or delay their formation into population III stars and they would instead enter a DS phase, turning into a ~ 1 AU DS when it is powered by DM annihilation instead of nuclear fusion. The regions with high DM densities are $10^5 - 10^6 M_{\odot}$ DM halos which contain 85% DM and 15% atomic matter as H and He. It is in these regions where the formation of DSs are most likely to take place (Yoshida et al. 2003). Each minihalo may have variations in their central DM density or host multiple stars due to historical effects (Stacy et al. 2014). This may lead population III to "wander" out of the halo centre to a region with lower DM density, meaning fewer or more short-lived DSs.

For a DS to be able to form and for it to exist for a reasonable amount of time, three requirements need to be fulfilled. Firstly, regions with high DM densities need to exist for the star to initially take form. Secondly, the products from WIMP annihilation (see Section 2.2.1) need to be trapped inside the star in order for it to be powered by DM. Thirdly, DM heating needs to dominate over all other cooling or heating mechanisms in order for it to be the dominant power source. The density needed for DM heating to dominate over all cooling mechanisms is mainly dependent on the WIMP model (Freese et al. 2008a). The most important cooling mechanism would be H_2 cooling. When DM heating dominates inside the stars, the proto-DS phase begins. For a WIMP model with a WIMP mass of $m_{\chi} = 100 \text{GeV}$, the sizes of the core when they enter the proto-DS phase is ~ 17AU, with masses of ~ 0.6M_{\odot} and luminosities of ~ 140L_{\odot} . Above a certain baryonic density level, which depends on the WIMP mass, the annihilation products that remain trapped in the cores begin to heat the stars. When entering a state of hydrostatic and thermal equilibrium, DSs are created (Spolyar et al. 2008).

2.2 The Properties of Dark Matter

Weakly interacting massive particles (WIMPs) are hypothetical particles, currently being the best candidates to constitute DM. There are several reasons for their strong candidacy, an example is the "WIMP miracle". WIMPs have a self-annihilation cross section of $\langle \sigma v \rangle \approx 3 \times 10^{-26} cm^3 sec^{-1}$ calculated from the abundance of DM today (assuming a WIMP mass of $m_{\chi} \approx 100$ GeV and that it can interact via electroweak force). Independent of this result, a particle with these properties is predicted by the supersymmetric extensions of the standard model. This coincidence is called the "WIMP miracle". WIMPs also automatically appear in theories that solve particle problems that have nothing to do with DM. Also, models of extra dimensions may contain WIMP DM candidates. In Spolyar et al. (2008) a broader range of WIMP masses ($m_{\chi} \approx 1$ GeV⁻¹⁰ TeV) and cross sections were considered and it was found that these WIMP models applied equally well as the $m_{\chi} \approx 100$ GeV WIMP model when calculating the abundance of DM today. A WIMP pair can self-annihilate to produce standard particles like fermions or gauge bosons (e.g. photons). The environment in the minihalos in the early Universe was more beneficial for the creation of DSs than today because of no pre-existing stars which could affect the cooling of gas in the regions with highest DM densities (Spolyar et al. 2008).

2.2.1 Dark Matter Annihilation Inside the First Stars

Population III stars, the first stars in the Universe, consist mainly of helium, hydrogen and less than 1% of the stellar mass of DM. According to Spolyar et al. (2008), this amount was still high enough for DM to be their main power source. The reason for this is because DM annihilation is much more efficient than nuclear fusion. More precisely, $\sim 70\%$ of the energy due to DM annihilation can be used to power the star where $\sim 30\%$ is lost mainly due to radiation of neutrinos. Only $\sim 1\%$ of the baryonic rest mass energy is used to power ordinary stars. The WIMP annihilation energy rate per unit volume is expressed as

$$\hat{Q}_{DM} = n_{\chi}^2 \langle \sigma v \rangle m_{\chi} \tag{2.1}$$

where n_{χ} is the WIMP density, $\langle \sigma v \rangle$ the annihilation cross section, where σ is the cross section and v is the velocity of the particle and m_{χ} is the mass of the WIMP. The squared WIMP density is due to the fact that two WIMPs have to collide in order to annihilate (Spolyar et al. 2008). When DM starts to annihilate in the cores of the stars, the nuclear fusion processes in the cores stop completely or gets delayed. The DSs are then heated by the energy produced and start to expand. This makes the WIMP density decrease and as they are refueled by more gravitationally contracted WIMPs, they keep expanding. The annihilation process can potentially provide DSs with heat for millions of years resulting in low-density DSs with low surface temperatures of about $T_{eff} = 4000 - 10000$ K, central temperatures of $T_c = 10^5 - 10^6$ K, sizes of ~ 10AU, masses of ~ $1000 M_{\odot}$ and luminosities of ~ $10^6 L_{\odot}$. The DSs are increasing their mass as long as DM fuel persists. During this phase, it is situated on the Hayashi track in the HR-diagram. The more massive they become, the more DM is needed to keep them from contracting. Eventually, they attain temperatures similar to population III stars (~ $10^5 K$) and start to photoionize large volumes of gas in their surroundings. It is when the DM fuel has run out that the end of the DS phase is reached. As no further energy can be supplied, the stars begin to contract, resulting in fusion processes to restart and they turn into huge population III stars. In the HR-diagram, they travel from the Hayashi track on to the main sequence when turning into population III stars again. Different annihilation rates are needed in order for constant equilibrium at different locations on the Hayashi track (Zackrisson et al. 2010a). According to Freese et al. (2008a) and Iocco et al. (2008), the lifetime of DSs can be prolonged if they are dense enough meaning that they could be refueled by capturing of DM (see Section 2.2.2)

2.2.2 Dark Matter Capture

In Freese et al. (2008a) it was proposed that the DS phase may be prolonged by a process called "WIMP capture". This is a process where WIMPS, that have orbits passing through the star from far out in the DM halo, will be captured inside the star and replenish the core with DM so that DM annihilation can persist. The WIMPs passing through will lose energy due to scattering off hydrogen and helium inside the star and will therefore become bound in the core. The capture efficiency is determined by the scattering cross section of WIMP interactions with the atomic nuclei, and the background DM density. The stars can only make use of the energy produced if WIMPs are captured and contributing to the energy of the DSs instead of radiated away. A certain baryonic density threshold in needed in order for the energy to power the DSs (Ripamonti et al. 2007). The annihilation products, DSs energy spectra, and the density needed for capture are dependent on the chosen WIMP model. For example, DSs powered by captured DM are much hotter and denser than those powered by gravitationally contracted DM.

According to Spolyar et al. (2008) and Freese et al. (2008a) DSs may prolong their life for $\sim 10^5 - 10^{10}$ years through WIMP capture because of the prevention of collapse (see Figure 2.1). This is based on calculations assuming properties of the WIMP populations and a constant flow of WIMPs through the star. The evolution of the minihalo determines to what extent infalling WIMPs can prolong the DS phase. However, other assumptions are made in Sivertsson & Gondolo (2011), who have computed simulations of the WIMP capture processes of DSs and found that WIMP capture may be an inefficient way to supply DSs with DM. This means that the possibility for DSs to have their lifetime extended to billions of years due to capture of WIMPS is low. Their main point is that the amount of WIMPs available for capture is rapidly decreasing and the fact that their orbits are not replenished by other WIMPS makes the WIMP capture phase shorter than expected in e.g. Freese et al. (2008a).



Figure 2.1: HR-diagram showing different evolution paths of DSs in the case with WIMP capture (solid lines) and without WIMP capture (dotted lines). The paths in the two cases are dependent of the WIMP mass. DSs in the case of with capture reach a much higher effective temperature ($T_{eff} \ge 10000$ K) than those in the case of without capture ($T_{eff} \le 10000$ K). This is due to that the probability for heavier WIMPs to annihilate is higher than for less massive WIMPs. Figure credit: Freese et al. (2016).

2.3 Supermassive Dark Stars

As long as DSs have access to DM they will grow and become bigger. Therefore, supermassive dark stars (SMDSs), with masses up to $10^5 - 10^7 M_{\odot}$ and luminosities up to $10^8 - 10^{11} L_{\odot}$, may be created. The amount of DM required for a SMDS to be created is nonetheless relatively small; $\sim 100 M_{\odot}$ of DM is required for a SMDS with a mass of $10^5 M_{\odot}$ to be created. SMDSs can arise due to WIMP capture or/and gravitationally contracted DM during the star formation phase. Also, DSs may experience merges and collisions with other DSs. This would result in unexpected SMDSs or DSs with a wide range of masses. Depending on the process, the SMDS will look different. Eventually, when the DM fuel runs out, ordinary DSs will collapse and nuclear fusion in the core sets in. SMDSs on the other hand, may skip the nuclear fusion phase and collapse directly into black holes (Freese et al. 2016).

2.4 Detectability of Dark Stars

The prospects for detection is discussed by firstly presenting the AB magnitude system which will be used in the analysis of this work. Then, information about the processes that contribute to the luminosities of DSs is presented. Lastly, the current prospects of detection are investigated.

2.4.1 AB Magnitude System

The brightness of stars is often discussed in terms of magnitudes. The sun has an apparent magnitude of m = -27.5, our naked eye can detect objects as faint as m = +6 and the JWST can

detect objects with an apparent magnitude of m = +30.5. The apparent magnitude is based on a celestial object's flux seen from Earth, and the absolute magnitude is the apparent magnitude measured at a constant distance of 10pc from the object. In this work, the AB magnitude system has been used where "AB" stands for "absolute" in the sense that no relative reference object is used in this system. Instead, a simple flat spectrum source is used as reference where the zero point is 3631Jy for all filter bands. The AB magnitude is defined in Equation 2.2 as the logarithm of the spectral flux density. The spectral flux density of an object describes the rate at which energy is transferred by electromagnetic radiation through a surface in units of Jansky [Jy].

$$m_{AB} = -2.5 \log_{10} \frac{f_{\nu}}{3631 Jy} =$$

= -2.5 log_{10} \frac{f_{\nu}}{Jy} + 8.90 = (2.2)
= -2.5 log_{10} f_{\nu} - 48.60

where f_{ν} is the spectral flux density of the object and $1 \text{Jy} = 10^{23} \text{erg}^{-1} \text{s}^{-1} \text{Hz}^{-1}$.

2.4.2 Luminosities of Dark Stars

It is shown in Spolyar et al. (2008) that the luminosity of DSs is mainly provided by four contribution sources:

$$L_{tot} = L_{DM} + L_{grav} + L_{nuc} + L_{cap}$$

$$\tag{2.3}$$

where L_{DM} is the dominating term, provided from DM annihilation of adiabatically contracted DM (see Equation 2.4), L_{grav} from gravitational contraction, L_{nuc} from nuclear fusion and L_{cap} from annihilation by captured DM (see Equation 2.5). DSs contain less than 1% of DM but it still shines mainly through DM heating.

$$L_{DM} = \frac{2}{3} \frac{1}{m_{\chi}} \int \rho(r)^2_{DM} \langle \sigma v \rangle dV$$
(2.4)

where m_{χ} is the mass of the DM particle, $\rho(r)_{DM}$ is the DM density inside of the star ans $\langle \sigma v \rangle$ is the annihilation cross section in units of cm³sec⁻¹.

$$L_{cap} = 2f_Q \int \rho_{cap}^2 \langle \sigma v \rangle / m_\chi dV \tag{2.5}$$

Where ρ_{cap} is the captured DM and $f_Q = 2/3$ is the annihilation energy and the factor 2 represents the fact that there have to exist two WIMPs in order for interaction and annihilation. The luminosity and mass of an object is directly related as $L \propto M^{3.5}$. This means that if the luminosity is determined, the mass can be calculated and vice versa.

2.4.3 The Prospects for Detection with the JWST

It is in high DM regions, such as in DM halos at high redshifts, where the first DSs ever created are expected to lurk. There are difficulties regarding the detectability of DSs due to their faintness, probably relatively short lifetimes, and the fact that they can be confused with other high-redshift objects, e.g. dusty or passively evolving galaxies. DSs have not yet been detected with existing telescopes. If they exist, they would be visible in the infrared wavelengths range and could therefore possibly be detected with the upcoming JWST (see Section 2.4).

To be able to detect DSs, their characteristic colors have to be determined for us to be able

to extract them in deep-field images obtained by the JWST. When extracted, we may be able to detect DSs brighter than the detection limit of the JWST (m ≈ 30.5). If DSs are fainter than this, they can not be directly detected. However, in Zackrisson (2011) it is proposed that faint objects may be magnified by gravitational lensing by pointing JWST through foreground lensing clusters. A gravitational lens is a distribution of matter (such as a galaxy cluster) between a distant light source (in this case, a DS) and the observer. The massive gravitational lens is capable of bending the light from the source as the light travels towards the observer, resulting in a magnification of the faint DS. This effect is known as gravitational lensing and the amount of bending is predicted by Albert Einstein in his general theory of relativity. Observations using a gravitational lens would reach deeper into space than the deepest non-lensed JWST fields planned. However, This is done at expense of the volume probed. A magnification factor higher than $\mu = 1000$ is difficult to achieve. The probability for detection also depends on the unknown fraction of dark matter halos in the universe that could host a DS (Freese et al. 2008).



Figure 2.2: An illustration of the number of apparent AB magnitudes needed for DSs in order to reach the detection thresholds of the JWST at z = 6 (a) and z = 10 (b). The central wavelengths of the JWST filters are expressed on the x-axis. Each line represents a DS from Table 3.1 colored by their effective temperature where $T_{eff} \leq$ 8000 K is red, 8000 K $< T_{eff} \leq$ 30000 K is green and $T_{eff} >$ 30000 K is blue. The dashed horizontal lines represent the JWST detection limits for different exposure times. Figure Credit: Zackrisson et al. (2010a)

According to Zackrisson et al. (2010b), SMDSs with a mass of $10^7 M_{\odot}$ at $z \le 12$ are bright enough for the Hubble Space Telescope (HST) to already have detected them by the HST extreme ultra deep field surveys. This may mean that the probability for a SMDS with this mass to exist is extremely small or non-existing. In Ilie et al. (2012) the detectability of SMDSs was studied with the conclusion that DSs with masses in the range of $10^6 - 10^7 M_{\odot}$ are bright enough to be detected by the JWST. The lifespan of DSs represents a crucial aspect of the detectability of DSs. They can live forever if there exists DM to fuel them. This means that the last stars of the Universe might well be DSs. However, if DSs can have a long lifetime or not is discussed in Section 2.2.2.

2.4.4 Other Ways to Detect Dark Stars

In Zackrisson et al. (2010a), the possibility to detect DSs in the first galaxies are investigated. DSs could give distinct signatures in the integrated colors of high-redshift galaxies, provided that DSs make up at least ~ 1% of the overall stellar mass in galaxies and that DSs live sufficiently long (t ~ 10^8 yr). According to Scott et al. (2008), later generations of stars may also become DM-powered through capture of DM at the galactic center where the DM density is high. However, these effects would be difficult to detect. According to Moskalenko et al. (2007), today's candidates for WIMP burners are white dwarfs and neutron stars, which may be heated by DM heating. They would then look younger and hotter than expected. In Rindler-Daller et al. (2015) another way to detect DSs is presented, namely through DS oscillations and pulsations. Depending on the choice of WIMP model, the stellar evolution code MESA predicts pulsations with a period of two days up to two years. If DSs have the properties to pulsate, along with being bright enough, this could be a way of distinguishing DSs from other objects and it is proposed that DSs someday be used as novel standard candles for cosmological studies.

2.5 The James Webb Space Telescope (JWST)

The James Webb Space Telescope (JWST) will be able to continue to provide extraordinary images that made the Hubble Telescope extremely prominent. JWST will offer orders of magnitude improvements in sensitivity in the optical- and infrared wavelength range of $0.6 - 28.5\mu$ m. With these technical improvements, it has the potential to study some of the first objects created in the universe over 13.5 billion years ago, the formation of stars, exoplanets and how the first galaxies were created and have developed. The JWST is expected to be operational for at least 5 years, and hopefully for as long as 10 years. The JWST is a collaboration between NASA, the European Space Agency (ESA) and the Canadian Space Agency (CSA). The launch of the JWST is scheduled for 2021 on an Ariane 5 rocket from a launch complex in French Guiana¹.

The JWST has a primary mirror, situated on the Optical Telescope Element (OTE) which is made up of 18 hexagonal mirrors made of beryllium to be lightweight and strong. The mirrors operate as a single 6.5-meter mirror. The JWST has four main-science instruments which are placed inside a chassis called the Integrated Science Instrument Module (ISIM) (see Figure 2.3). The instruments are: the Near-Infrared Spectrograph (NIRSpec), the Guidance Sensor/Near InfraRed Imager and Slitless Spectrograph (FGS/NIRISS), the Near-Infrared Camera (NIRCam) and the Mid-Infrared Instrument (MIRI). NIRSpec is a spectrograph, sensitive over a wavelength range of $0.6 - 5.0\mu$ m. It processes light from an object and transforms it into a spectrum from where we can obtain information about the object's physical properties². The FGS is a guider necessary for high-quality images, it makes the telescope point more precisely and also determines the position for the telescope. NIRISS is packaged with the FGS but is functionally independent. The FGS is capable of wide field slit-less spectroscopy in the range of $1.0 - 2.5\mu$ m and will be important for the detection of exoplanets³. NIRCam is the primary imager sensitive in the range of 0.6 - 5

 $^{^{1}} https://jwst.stsci.edu/about-jwst$

²https://jwst.nasa.gov/nirspec.html

 $^{^{3} \}rm https://jwst.nasa.gov/fgs.html$

 μ m. It is provided with coronagraphs⁴. MIRI is both a camera and a spectrograph and has the widest wavelength range of 5-28 μ m which provides wide-field imaging. This will allow us to see faint redshifted light⁵. The MIRI and NIRCam instruments will be the most important ones for this project and are therefore discussed in more detail in Section 2.5.1 and 2.5.2 respectively.



Figure 2.3: An illustration of the main instruments that the upcoming James Webb Space Telescope will feature (image credit: STSci, 2018).

The JWST will orbit the sun positioned in Lagrange point 2 (L2), 1.5 million kilometers away from Earth. In this point, the telescope will always have the Earth between itself and the sun. This blocks out most of the radiated heat while the remaining heat from other objects as the Earth and the Moon reaching the telescope will be blocked out by a sun shield (see figure 2.3). This will be of great importance as the optimal operating temperature for the JWST will be below 50K.

2.5.1 Mid-Infrared Instrument (MIRI)

MIRI is a mid-infrared instrument situated on the JWST which will, for example, be able to study atmospheres of young exoplanets and gas in young stars and protoplanetary disks. This will be possible due to its two integrated instruments, a camera, and a spectrograph. MIRI will be able to provide four observing modes in the mid-infrared wavelength range of $4.9 - 28.8\mu$ m. These four modes are Imaging, coronagraphic imaging, low-resolution- and medium-resolution spectroscopy. MIRI provides imaging in nine different photometric bands F560W-F2550W illustrated in Figure 2.4. All MIRI filters are broadband ($R \sim 5$), except for F1130W which is a narrower band ($R \sim 16$). The filters cover a wavelength range of $5.6 - 25.5\mu$ m over a field of view (FOV) of 74" × 113". MIRI

 $^{{}^{4}}https://jwst-docs.stsci.edu/display/JTI/NIRCam+Overview$

 $^{^{5}} https://jwst-docs.stsci.edu/display/JTI/MIRI+Overview$

is provided with four coronagraphs, covering wavelength bands from $10 - 23\mu$ m, which block out light from bright objects. MIRI is actively cooled down to a temperature of 7K by a cryocooler due to its high sensitivity to thermal background. An advantage of MIRI is that it can be used parallel with other instruments⁶.



Figure 2.4: The photometric filters are here presented in which MIRI will do measurements are here presented (image credit: STSci, 2018).

2.5.2 Near-Infrared Camera (NIRCam)

NIRCam is a near-infrared camera on the JWST which will be able to detect the first galaxies, star clusters and study star formation and exoplanets in our own galaxy. This will be possible because it features a camera, a coronagraph and a spectrograph. NIRCam will provide five observing modes in the near-infrared wavelength range of $0.6 - 5.0\mu$ m. The modes are imaging, coronagraphic imaging, wide field slitless spectroscopy, time-series imaging and grism time series. NIRCam provides imaging in twenty-nine photometric filters: 2 extra wide-band ($R \sim 1$), 8 wide-band (R 4), 12 medium-band ($R \sim 10$) and 7 narrow-band ($R \sim 100$) filters, all presented in Figure 2.5. The imager consists of 10 mercury-cadmium-telluride (called H2RG) sensors constructed as eight co-aligned modules with a total $2 \times 2.2' \times 2.2'$ FOV which measures in both the long-wavelength channel ($2.4 - 5\mu$ m) and in the short-wavelength channel ($0.6 - 2.3\mu$ m). Each module can be used simultaneously. NIRCam is equipped with ten sensitive filters in the range of $0.6-5\mu$ m. NIRCam will also be equipped with wavefront sensing used to align JWST's primary mirror⁷.

⁶https://jwst-docs.stsci.edu/display/JTI/MIRI+Overview

 $^{^{7}} https://jwst-docs.stsci.edu/display/JTI/NIRCam+Overview$



Figure 2.5: The photometric filters are here presented in which NIRCam will do measurements are here presented (image credit: STSci, 2018).

Method

To be able to distinguish DSs from thousands of other objects (e.g. galaxies) in a deep-field image obtained by the JWST, their characteristic colors have to be determined in different filters available for the NIRCam and MIRI instruments. Their characteristic colors are determined by their positions in color-color diagrams. The analysis will be restricted to DSs and galaxies in the redshift range of $z \approx 7 - 11$. Below z = 7, the probability of finding living DSs is small due to the fact that they will most likely have lived for approximately one billion years, which is longer than the expected lifetimes of DSs. Also, the galaxy simulations have a lower limit of z = 7. The upper limit of z = 11 is chosen due to the low probability of detecting DSs above this range, and time-consuming simulations.

3.1 Dark Star Models

This work is based on 18 dark star models from Spolyar et al. (2009) (see Table 3.1) as well the following atmosphere models: MARCS stellar atmospheres code from Gustafsson et al. (2008) for $T_{eff} \leq 8000$ K objects and the TLUSTY synthetic stellar atmospheres code from Hubeny & Lanz, (1995) for $T_{eff} \geq 10000$ K objects. The MARCS atmosphere code is based on assumptions such as hydrostatic equilibrium, mixing-length convection, and local thermodynamic equilibrium. TLUSTY is based on non-local thermodynamic equilibrium and accounts for black body radiation from the photosphere and the absorption lines coming from gas in the atmosphere. The TLUSTY models cover the restframe wavelength range of $0.015 - 300 \ \mu$ m, whereas the MARCS models cover a wavelength range of $0.13-20 \ \mu$ m. The capture process and evolutionary histories of the first stars are very dependent upon the chosen DM particle and halo models. All models assume primordial abundances of H and He. For computational reasons, the MARCS atmospheres assume an overall metallicity of $Z = 2.5 \times 10^{-7}$ whereas the TLUSTY have been computed at Z = 0. This minor inconsistency for the MARCS atmospheres leads to an uncertainty in the final JWST magnitudes of ~ 0.01 mag. However, this error factor is insignificant for this study.

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WIMP mass	T _{eff} [K]	${f M}$ [${f M}_{\odot}$]	$\log_{10}(\mathrm{g})^a$	Atmosphere ^b
1 GeV	5400	106	-0.612	MARCS
	5900	371	-0.170	MARCS
	7500	690	0.879	MARCS
	10000	756	1.865	TLUSTY
	30000	793	3.511	TLUSTY
	110000	824	5.512	TLUSTY
100 GeV	5800	106	0.458	MARCS
	7800	479	0.955	MARCS
	23000	716	2.895	TLUSTY
	55000	756	4.399	TLUSTY
	110000	787	5.492	TLUSTY
10TeV	6000	106	1.463	MARCS
	8000	256	1.846	MARCS
	10000	327	2.036	TLUSTY
	25000	399	3.085	TLUSTY
	32000	479	3.879	TLUSTY
	95000	550	5.307	TLUSTY
	110000	553	5.503	TLUSTY

Table 3.1: All 18 DSs that have been analyzed in this work are here listed with their stellar evolution parameters together with the WIMP mass used to obtain the parameters.

 $^{\rm a}$ In units of $g\ cm^{-1}s^{-2}$

 $^{\rm b}$ Atmosphere model MARCS obtained in Gustafsson et al. (2008) and TLUSTY obtained in Hubeny & Lanz, (1995)

3.2 Galaxy Models

The synthetic spectra for galaxies at z = 7 - 11 used in this work are generated in Zackrisson et al. (2017) by the use of cosmological simulations described in Shimizu et al. (2014). The cosmological simulations give us the star formation histories and metallicity distributions of galaxies in the reionization epoch. By taking snapshots of the cosmological structure at each redshift with the resolution of $\Delta z = 0.001$, a grid of synthetic galaxy spectra with individual variations in star formation history and metallicity distributions at each redshift is obtained. The simulations are computed in a wavelength range relevant for JWST/NIRSpec observations and are far more advanced than the toy models used in Zackrisson et al. (2010a).

3.3 Photometry Using NIRCam/MIRI Filters

Spectroscopy is a method used to measure the spectra of objects. These spectra are used to determine the chemical composition and physical properties of an object, for example the effective temperature of a star. Photometry is used to obtain color-color diagrams by measuring the flux of

objects in the sky in different filters. Tables 3.2 and 3.3 give the NIRCam and MIRI filters used to analyze the characteristic colors of DSs. These filters are unique for the James Webb Space Telescope.

NIRCam Filters

Table 3.2: The eight NIRCam filters used are here presented together with the corresponding filter sensitivity in units of nJy with a signal-to-noise ratio of S/N = 10 and an exposure time of 10^4 s.

Filter	F090W	F115W	F150W	F200W	F277W	F356W	F410M	F444W
Sensitivity [nJy]	15.3	13.2	10.6	9.1	14.3	12.1	24.7	23.6

MIRI Filters

Table 3.3: The four MIRI filters used in this work are here presented together with the corresponding filter sensitivity in units of nJy with a signal-to-noise ratio of S/N =10 and an exposure time of 10^4 s.

Filter	F560W	F770W	F1000W	F1130W
Sensitivity [nJy]	120	240	500	1150

3.4 Processing Spectra

The DS models contain a spectrum with flux and wavelength and the filters contain transmission profiles available for the NIRCam and MIRI instruments for the chosen range of redshift z = 7-11. The apparent magnitudes for each DS at each redshift in steps of $\Delta m_{AB} = 0.05$ for each filter were calculated in MATLAB by processing the DS spectra with the transmission profiles and then calibrated using the AB magnitude system (see Section 2.4.1). The code are presented in Appendix. This procedure was repeated for all the DSs and then the AB magnitudes obtained for each filter were plotted in color-color diagrams (see Section 3.5). Every DS at a specific redshift appears as a dot in the diagrams. When the DSs are plotted at all redshifts, each DS forms a curve. Galaxy colors were plotted in the same diagrams. A total of 18 DS models (see Table 3.3) were processed and analyzed and plotted together with ~ 2500 simulated galaxies.

3.5 Color-Color Diagrams

Analyzing data from large observational surveys, such as the JWST, can be challenging due to the extremely large quantities of data produced. For such surveys, color-color diagrams are used because they can handle a large amount of data to find outliers. Once outliers are identified, they can be studied in more detail. In astronomy, a color is defined as the difference between two filters' magnitudes, for example, m277-m500 is a color. It is clear that color-color diagrams plot a color versus another color, and from these the characteristic colors of objects can be determined. In this work, a total of 18 DS models and ~ 2500 simulated galaxies at $z \approx 7 - 11$ were compared and analyzed in color-color diagrams. By including all redshifts in the range, each DS forms a curve in the color-color diagram. By plotting galaxies, obtained in Zackrisson et al. (2017), in the same diagram, at the same range of redshift, there are regions where DSs and galaxies overlap. There are also unique areas where only DSs appear. These DSs, in these unique regions, were extracted and further analyzed (see Table 4.1). It is these DSs that can be extracted from the large imaging survey of the JWST.

When the magnitudes of the DSs were obtained by processing spectra, they were compared to detection limits of the JWST in each filter. The JWST will be able to detect objects with magnitudes of m ≈ 30.5 . If DSs are fainter than this, they will need to be magnified through gravitational lensing (see Section 2.4.3) in order to enable detection.

Results

The final color-color diagrams of the most promising DSs are here presented. From these diagrams conclusions can be drawn regarding which DSs that are distinguishable from galaxies and in which colors. The DSs positioned outside the region of galaxies are the ones that can be distinguishable. If these DSs are likely to actually be detected with the JWST is discussed in Section 5. Firstly, a comparison of the SED (Spetral Energy Distribution) of one of these DSs with a galaxy is presented. Secondly, an example of a DS spectrum and the behavior of a color at different redshifts is shown. Lastly, the color-color diagrams obtained are presented.

4.1 Distinguishable Dark Stars

The DSs found to be distinguishable are presented in Table 4.1. The selection was based upon the DSs being located outside the area of galaxies and therefore being distinguishable (see section 4.2). The DSs' evolution parameters are generated in a model from Spolyar et al. (2009) and the atmosphere model MARCS are generated in Gustafsson et al. (2008).

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Table 4.1: The DSs that are distinguishable from galaxies at $z \approx 7 - 11$ are here listed.	The DSs
are ordered according to their effective temperature.	

\mathbf{Color}^{a}	T_{eff} [K]	${f M}$ $[{f M}_{\odot}]$	$\log_{10}(\mathrm{g})^b$	WIMP mass [GeV]	Atmosphere
*	5400	106	-0.612	1	MARCS
*	5800	106	0.458	100	MARCS
*	5900	371	-0.17	1	MARCS
*	6000	106	1.46	10000	MARCS
*	7500	690	0.879	1	MARCS
*	7800	479	0.955	100	MARCS

^a Colors representing dark stars with different effective temperatures in the color-color diagrams

 $^{\rm b}$ In units of $g\ cm^{-1}s^{-2}$



Figure 4.1: The spectral energy distribution (SED) of the $371M_{\odot}$, $T_{eff}=5900$ K DS (orange line), and a randomly chosen galaxy (black line) at redshift z = 10. The diagram presents the variation of flux as a function of wavelength. It can clearly be seen that the DS is fainter than the galaxy. The steep slope in the galaxy SED is due to a break in the spectrum of the galaxy.



Figure 4.2: (a) The stellar atmosphere spectrum of the $479M_{\odot}$, $T_{eff} = 7800$ K DS. The abrupt break at 3646Å is the Balmer break. (b) The color indices $m_{F200} - m_{F277}$ at different redshifts $z \approx 7 - 11$. The rapid shift in flux at z = 7.5 is an effect due to the Balmer break.

The shape of the spectrum shown in figure 4.2 mainly depends on T_{eff} but also on the metallicity Z and surface gravity log(g). The spectra also contain a large number of absorption lines, which will have a small effect of the broadband fluxes in (b). When the spectrum in (a) gets redshifted, breaks and absorption lines enter into new filters, resulting in a changes of flux in each filter. This

is the reason behind the shape of the DSs in the color-color diagrams.

4.2 Color-Color Diagrams

The final color-color diagrams are here presented with the six out of 18 most promising DSs (see Table 4.1). The code to obtain these diagrams is presented in Appendix. The appearances of the galaxies is due to their emission lines entering different photometric filters, giving changes in flux. The reason behind the DSs' appearance is explained in figure 4.2.









Figure 4.7: Color-color diagrams (a)-(j) showing the colors of six DSs (RGB colored) with a $T_{eff} \leq 7800$ K and ~ 2500 galaxies (black dots) at $z \approx 7 - 11$ with a resolution of $\Delta z = 0.001$. The red DS is the hottest (7800K) and the blue DS is the coldest

(5400K). The physical properties of each DS are listed in Table 4.1. DSs being located outside the area of galaxies have characteristic colors. Galaxies of the same redshift are collected in the same red shift bin in the diagrams. The number of bins depend on the resolution of redshift.

Discussion

After analyzing how the mass, gravity and effective temperature affect the colors of DSs, it has been found that the effective temperature T_{eff} is the primary parameter for their position in color-color diagrams. A total of 18 DS models were first analyzed whereby six of them (see Table 4.1) were clearly distinguishable. This proved to be a result of their effective temperature being $T_{eff} \leq 7800$ K. If the T_{eff} of DSs are higher than 10.000K, closer to 20.000K, they photoionize the gas in their surroundings. This make the gas shine, leading to a contribution of emission lines and nebular continuum in the spectra (Zackrisson et al. 2010a). The DS models used in this work do not take this into account. By inclusion of this, the hot DSs would presumably have had different positions in the color diagrams.

Two out of ten color-color diagrams have been selected for deeper analyze due to the clear distinguishability of DSs from galaxies in these diagrams (see Figure 5.1).



Figure 5.1: The two most promising color-color diagrams obtained. It can clearly be seen that DSs (RGB colored) at redshifts between z = 7 - 11 with a low effective temperature $T_{eff} \leq 7800$ K are easily distinguishable from galaxies (black dots) in these colors.

The appearances of the DSs in Figure 5.1 are due to different continuum breaks and absorption lines entering different filters when increasing the redshift. This may rapidly change the flux in each filter. A DSs metallicity affects which absorption lines that appear in the spectrum. Measurements of galaxies always have an error which for faint objects is noticeably big. Therefore, the selection was also based on the fact that the distribution of the galaxies did not increase a lot while increasing the resolution Δz in (c) and (d) as in all other diagrams in Figure 4.7. Furthermore, it is easy to obtain good data in the filters F150W to F356W because of the high sensitivity of NIRCam in these filters.

As concluded, DSs with $T_{eff} \leq 7800$ K are distinguishable from galaxies, but are they bright enough for the JWST to be able to detect them? In order for DSs to be detectable they need to have magnitudes below the detection limits of the JWST filters. The integrated luminosity over a whole DS spectrum can not be measured. Therefore, the measurements are restricted to smaller luminosity measurements in so-called filters. Each filter then have its own detection limit as explored in more detail in Zackrisson et al. (2010a). The JWST filters have a detection limit of about $m_v \approx 30.5$ while the brightest DSs analyzed have magnitudes at around $m_v \approx 34.3$. The deepest non-lensed JWST fields planned will therefore not be able to detect low-temperature DSs. However, according to Zackrisson (2011), gravitational lensing can be used to probe deeper into space compared to the deepest non-lensed JWST fields planned. By pointing the JWST through foreground lensing clusters an object can be magnified by a factor of $\mu = 1000$ as a rough approximation of the maximum. For each 2.5 magnitudes a magnifying factor of $\mu = 10$ is needed. This means that DSs can not have magnitude higher than $m_v \approx 38$ in order for detection (see Figure 2.2). By analyzing the magnitudes of the DSs in Figure 5.1 a magnifying factor of $\mu = 160 - 1000$ is needed for DSs at redshifts z = 7 - 11. All DSs, except the $T_{eff} = 6000$ K DS due to its high surface gravity, would then be detectable by the NIRCam instrument but not the MIRI instrument due to its low sensitivity.

By comparing the DS models used in this work to more recent DS models in Freese et al. (2016) (see Figure 2.1) it can be seen that the $T_{eff} = 7800$ K DS do not undergo WIMP capture and will obtain masses in the range of ~ $10^3 M_{\odot}$ which is more massive than predicted in the 2009 model. This mass range corresponds to luminosities of $10^7 L_{\odot}$ which are luminosities that can be detected with the NIRCam/JWST without the use of gravitational lensing. The probability to find DSs is highly dependent on their regularity throughout the universe. DSs have to be quite common (minihalos must host at least ~ 0.1% DSs) and long-lived ($t \ge 10^7$ yr) for them to be detected today (Zackrisson, 2011). However, whether or not a DS can prolong its DS phase and become long-lived by WIMP capture, is questioned by Sivertsson and Gondolo (2010) who have made simulations which show that DSs quickly obtain a DM cavity while capturing WIMPS and therefore finish their DS phase sooner than expected in Freese et al. (2016). Also, Stacy et al. (2014) have done realistic simulations of gas collapse in the inner parts of a DM halo and have found that WIMP capture processes do not lead to any persistent DSs. This means, independent of the effective temperatures of DSs, that they will probably not be able to be detected due to their short lifetimes.

5.1 Future Prospects

To get an even better understanding of which DSs that are detectable with the JWST, the physical processes of hot DSs with $T_{eff} \geq 10000$ K should also be taken into consideration. This could increase the probability of detecting DSs if they have characteristic colors different from galaxies.

Also, there exist stars in the Milky Way at redshift z = 0 with strange spectra. These stars could be mistaken for DSs as they may hold similar JWST colors. The model for the JWST used in this work does not take this into account. For future and similar work, it would therefore be important to analyze both cold stars at redshift z = 0 and hot DSs and plot them in the equivalent color-color diagrams. The detection of DSs would be important for our understanding of DM and it would even be evidence for a new phase of stellar evolution.

Conclusion

In this work, the detectability of various DSs has been investigated by first finding the properties of the DSs that distinguishes from galaxies and then by comparing the distinguishable DSs magnitudes to detection limits of the JWST. The results show that DSs with $T_{eff} \leq 7800$ K (except the 6000K DS) may be detected if they are magnified by a factor of $\mu = 160-1000$ with the use of gravitational lensing. If these kinds of DSs exist they are expected to be found in the redshift range of z = 7-11. Compared to the more recent DS model, the $T_{eff} = 7800$ K DS may be bright enough for detection without the use of gravitational lensing. However, such cold DSs do probably not undergo WIMP capture and will therefore probably not be long-lived. This means that the probability of finding DSs decreases tremendously. It is clear that more knowledge about the nature of DM is needed in order for us to be able to better understand the possible properties and behaviors of Dark Stars.

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Appendix

7.1 Processing spectra.m

Script for processing dark stars spectra to obtain their AB magnitudes. Based on code by Erik Zackrisson.

```
1 clear
2 format long
3
4 % Constants
5 % -----
6 c=3e8; % m/s
7 pc=3.086e16; % m
  Jy=1e-23; % erg/s/cm^2/Hz
9 H0=72; % km/s/Mpc
10 Omega_M=0.27;
  Omega_Lambda=1-Omega_M;
11
12
13 % Filter parameters
   8 _____
14
15 Nint=1e4; % Number of interpolated data points within each transmission curve
16 filteralt=2; % 2 = JWST filters
17 mag_opt=1; % 1 = Apparent magnitudes except at z=0
18 outdir='ABmag6.5/';
  filterlist='JWST_filters2017.txt'; % Name of file containing list of transmission curves
19
  filter_dir='';
20
^{21}
  % Parameters for the input spectrum
22
  e _____
23
   input_format=3; %3 = Darkstar format (Wavelength in A, Flux in erg/s/A)
^{24}
25
26 z_range=[6.5:0.05:10.5]; % Redshifts for which magnitudes will be computed
27 extopt=0;
                   % 1 = Calzetti 1997 extinction (E(B-V)stars = 0.44 * E(B-V)neb)
                     % 2 = Pei (1992) Milky Way extinction
28
                     % 3 = Pei (1992) LMC extinction
29
                     % E(B-V) (stellar, in the case of Calzetti 2000)
30 ebv=0.00;
31 Lyalphaabs_alt=3; % 3 = Complete abs at <1220 A at z≥z_reion
32 z_reion=6;
infile_spec= 'Darkstars/Atmos_formatted/MARCS_479M_Teff7800_logg0.955_Z-5.dat';
```

```
34 outfile='MARCS_479M_Teff7800_logg0.955_Z-5.dat';
```

```
35
  %Dark Stars
36
   %MARCS_106M_Teff5400_logg-0.612_Z-5.dat
37
   %MARCS_106M_Teff5800_logg0.458_Z-5.dat
38
   %MARCS_371M_Teff5900_logg-0.17_Z-5.dat
39
   %MARCS_106M_Teff6000_logg1.46_Z-5.dat
40
   %MARCS_690M_Teff7500_logg0.879_Z-5.dat
41
^{42}
   %MARCS_479M_Teff7800_logg0.955_Z-5.dat
43
44
  % Load spectrum
45
  8 -----
46
   % Dark star format
47
      raw_spec=load(infile_spec);
^{48}
      wave_spec=raw_spec(:,1)'; % A
49
      flux_spec_flambda(1,:)=raw_spec(:,2)'; % erg/s/A
50
      spectra=1;
51
      ind=size(wave_spec,2);
52
53
  % For all filter profiles listed in the file list
54
   olg _____
55
56 names_mod=char(textread(filterlist,'%q'));
   for filter=1:(size(names_mod,1))
57
      disp(['Processing filter: ' num2str(filter)])
58
      current_filter=names_mod(filter,:); % Extract name of current model
59
60
      while (current_filter(size(current_filter,2)) == ' ')
          current_filter=current_filter(1:(size(current_filter,2)-1));
61
      end
62
63
       % Load transmission curve
64
65
       § _____
      raw_trans=load([current_filter]);
66
      wave_trans=raw_trans(:,1); % A
67
      trans=raw_trans(:,2);
68
69
70
      % For every redshift
       8 _____
71
       for j=1:size(z_range,2)
72
73
          z=z_range(j);
74
          % Correct spectrum for redshift
75
           8 _____
76
          wave_spec_z=wave_spec.*(1+z);
77
          flux_spec_flambda_z=flux_spec_flambda./(1+z);
78
79
80
           % Absorption shortward of (and possibly including) Lya
81
           og _____
          if (Lyalphaabs_alt==2 & z>z_reion)
82
              ind_abs=find(wave_spec_z < 1220.*(1+z));</pre>
83
              flux_spec_flambda_z(ind_abs)=0;
84
          end
85
          if (Lyalphaabs_alt==3 & z>z_reion)
86
              ind_abs=find(wave_spec_z < 1210.*(1+z));</pre>
87
              flux_spec_flambda_z(ind_abs)=0;
88
          end
89
90
```

```
91
```

```
% Fix problems in TLUSTY spectra
 ^{92}
                                 § _____
 93
 94
                        for k=2:size(wave_spec_z,2)
 95
                                 if (wave_spec_z(1,k) == wave_spec_z(1,k-1))
 96
                                         wave_spec_z(1,k) = wave_spec_z(1,k)+0.1;
 97
                                end
 98
 99
                        end
100
                        % Convert spectrum and transmission curve to fnu & nu
101
102
                        % _____
                        for k=1:spectra
103
104
                                 freq_spec_z(k,1:ind(k))=c./(wave_spec_z(k,1:ind(k)).*le-10); % Hz
                        end
105
106
                        freq_trans=c./(wave_trans.*1e-10); % Hz
107
                        for k=1:spectra
108
                                flux_spec_fnu_z(k, 1: ind(k)) = flux_spec_flambda_z(k, 1: ind(k)) . * 1e10. * (wave_spec_z(k, 
109
110
                                 % erg s^-1 Hz^-1
                                flux_spec_fnu_z(k,1:ind(k))=flux_spec_fnu_z(k,1:ind(k))./(4.*pi.*(10.*pc.*100).^2);
111
112
                                 % erg/s^-1/cm^-2/Hz^-1
                        end
113
114
                        % Interpolate spectrum and transmission curve to common frequency scale
115
                        8 -----
116
117
                        freq_trans_min=min(freq_trans);
                        freq_trans_max=max(freq_trans);
118
                        Delta_freq=(freq_trans_max-freq_trans_min)./(Nint-1);
119
120
                        freq_trans_int=freq_trans_min: _ freq:freq_trans_max;
121
                        trans_int=interp1(freq_trans,trans,freq_trans_int);
122
123
                        for k=1:spectra
                                flux_spec_fnu_z_int(k,:)=interpl(freq_spec_z(k,1:ind(k)),flux_spec_fnu_z(k,1:ind(k)),freq_trans
124
                                 ind_nan=find(isnan(flux_spec_fnu_z_int(k,:))==1);
125
                                 flux_spec_fnu_z_int(k,ind_nan)=0;
126
127
                          end
128
                        % Compute absolute AB magnitude
129
                        <u>_____</u>
130
                        Sum_Tnu_dnu=sum(trans_int).*A_freq;
131
                        for k=1:spectra
132
                                Sum_Fnu_Tnu_dnu(k) = sum(flux_spec_fnu_z_int(k,:).*trans_int).*Delta_freq;
133
                                M_AB(k,filter,j)=-2.5.*loq10(Sum_Fnu_Tnu_dnu(k)./Sum_Tnu_dnu)-48.60;
134
135
                        end
136
137
                % End loop over all redshifts
                e _____
138
                end
139
140
141
       % End loop over all filters
142
143
        <u> ୧</u> -----
144
       end
145
        % Derive luminosity distance
146
       8 -----
147
148 for j=1:size(z_range,2)
```

```
d_L(j)=(1+z_range(j)).*le-3.*c./H0.*quadl('distfunc',0,z_range(j),[],[],Omega_M,Omega_Lambda);
149
           % Mpc
150
151
    end
152
153
    % Derive apparent magnitude
    8 -----
154
    for j=1:size(z_range,2)
155
156
        if (z_range(j)==0)
            m_AB(:,:,j)=M_AB(:,:,j); % m_AB(timestep,filter,z)
157
158
        end
        if (z_range(j) \neq 0)
159
            if (mag opt==1)
160
                m_AB(:,:,j)=5.*log10(d_L(j))+25+M_AB(:,:,j); % m_AB(timestep,filter,z)
161
            end
162
            if (mag_opt==2)
163
                m_AB(:,:,j)=M_AB(:,:,j);
164
            end
165
166
        end
167
    end
168
169
   % Set NaNs to 999
170
    % _____
171
    if filteralt==2
172
        m_F070W=m_AB(:,1,:);
173
174
        m_F115W=m_AB(:,2,:);
        m_F150W=m_AB(:,3,:);
175
        m_F200W=m_AB(:,4,:);
176
177
        m_F277W=m_AB(:,5,:);
        m_F356W=m_AB(:,6,:);
178
        m_F444W=m_AB(:,7,:);
179
180
        m_F560W=m_AB(:,8,:);
        m_F770W=m_AB(:,9,:);
181
        m_F1000W=m_AB(:,10,:);
182
        m_F1130W=m_AB(:,11,:);
183
        m_F1280W=m_AB(:,12,:);
184
        m_F1500W=m_AB(:,13,:);
185
        m_F1800W=m_AB(:,14,:);
186
        m_F2100W=m_AB(:,15,:);
187
        m_F2550W=m_AB(:,16,:);
188
        m_F090W=m_AB(:,17,:);
189
190
            m_F410M=m_AB(:,18,:);
    end
191
192
    ind_nan=find(isnan(m_AB)==1);
193
    ind_inf=find(isinf(m_AB)==1);
194
    m_AB(ind_nan)=999.0;
195
   m_AB(ind_inf)=999.0;
196
197
    lambda=wave_spec; % wavelength micron
198
199
   % Present result
200
   8 _____
201
202 % Write results to output file
    ۶ _____
203
204
            fid1=fopen([outdir '/JWST_NIRCam_ABmag_' outfile], 'w');
205
```

```
if (spectra==1)
206
               fprintf(fid1,'Redshift F070W F090W F115W F150W
                                                                             F200W
207
                        F356W F410M F444W \n');
               F277W
208
               for i=1:size(z_range,2)
209
                   fprintf(fid1,'%5.3f %9.3f %9.3f %9.3f %9.3f %9.3f %9.3f %9.3f ...
210
                       %9.3f\n',[z_range(i) m_AB(1,1,i) m_AB(1,17,i) m_AB(1,2,i) ...
                       m_AB(1,3,i) m_AB(1,4,i) m_AB(1,5,i) m_AB(1,6,i) m_AB(1,18,i) ...
                       m_AB(1,7,i)]);
               end
211
           else
212
               fprintf(fid1,'Redshift Age(yr) Mstars
                                                           Mconsumed
                                                                              F070W ...
213
                       F090W
                                   F115W
                                              F150W F200W F277W
                                                                           F356W ...
                   F410M
                                F444W\n');
               for i=1:size(z_range,2)
214
                   for k=1:spectra
215
                       fprintf(fid1,'%5.3f %13.2e %9.3e %9.3e %9.3e %9.3e %9.3f %9.3f ...
216
                           %9.3f %9.3f %9.3f %9.3f %9.3f\n',[z_range(i) age_spec(k) ...
                           Mstars(k).*rescale(k) Mconsumed(k).*rescale(k) m_AB(k,1,i) ...
                           m_AB(k,17,i) m_AB(k,2,i) m_AB(k,3,i) m_AB(k,4,i) m_AB(k,5,i) ...
                           m_AB(k,6,i) m_AB(k,18,i) m_AB(k,7,i)]);
217
                   end
               end
218
219
           end
220
           fclose(fid1);
221
222
           fid2=fopen([outdir '/JWST_MIRI_ABmag_' outfile],'w');
           if (spectra==1)
223
               fprintf(fid2,'Redshift F560W
                                               F770W
                                                         F1000W F1130W F1280W ...
224
                      F1500W F1800W
                                        F2100W F2550W \n');
               for i=1:size(z_range,2)
225
                   fprintf(fid2,'%5.3f %9.3f %9.3f %9.3f %9.3f %9.3f %9.3f %9.3f ...
226
                       %9.3f\n',[z_range(i) m_AB(1,8,i) m_AB(1,9,i) m_AB(1,10,i) ...
                       m_AB(1,11,i) m_AB(1,12,i) m_AB(1,13,i) m_AB(1,14,i) m_AB(1,15,i) ...
                       m_AB(1,16,i)]);
               end
227
228
           else
229
               fprintf(fid2,'Redshift Age(yr) Mstars
                                                          Mconsumed
                                                                        F560W
230
                           F1000W F1130W
                                               F1280W F1500W F1800W F2100W ...
                   F770W
                      F2550W\n');
               for i=1:size(z_range,2)
231
                   for k=1:spectra
232
                       fprintf(fid2,'%5.3f %13.2e %9.3e %9.3e %9.3f %9.3f %9.3f %9.3f ...
233
                           %9.3f %9.3f %9.3f %9.3f %9.3f \n',[z_range(i) age_spec(k) ...
                           Mstars(k).*rescale(k) Mconsumed(k).*rescale(k) m_AB(k,8,i) ...
                           m_AB(k,9,i) m_AB(k,10,i) m_AB(k,11,i) m_AB(k,12,i) ...
                           m_AB(k,13,i) m_AB(k,14,i) m_AB(k,15,i) m_AB(k,16,i)]);
                   end
234
235
               end
236
           end
237
           fclose(fid2);
238
239
240 % Plot results
   8 -----
241
242 figure(2)
```

```
32
```

wave_filter=[0.7 0.9 1.15 1.50 2.0 2.77 3.56 4.10 4.44 5.6 7.7];

243

```
f_Jy=3631.*10.^([m_F070W(i) m_F090W(i) m_F115W(i) m_F150W(i) m_F200W(i) ...
244
                 m_F277W(i) m_F356W(i) m_F410M(i) m_F444W(i) m_F560W(i) m_F770W(i)]./-2.5);
245
        for i=1:size(z_range,2)
             plot(wave_filter,[m_F070W(i) m_F090W(i) m_F115W(i) m_F150W(i) m_F200W(i) ...
246
                 m_F277W(i) m_F356W(i) m_F410M(i) m_F444W(i) m_F560W(i) m_F770W(i)],'.-k');
             hold on
247
        end
248
249
        set(gca, 'FontSize', 14)
        set(gca, 'YDir', 'reverse')
250
        title('NIRCam/MIRI SED')
251
        ylabel('m_{AB}')
252
        xlabel('Wavelength (micron)')
253
254
    figure(3)
255
        for i=spectra;
256
           plot(wave_filter, le6.*f_Jy, '.-k');
257
           hold on
258
        end
259
260
        set(gca, 'FontSize', 14)
        set(gca, 'YDir', 'reverse')
261
        title('NIRCam/MIRI SED')
262
        ylabel('Spectral Flux Density [{\mu}Jy]')
263
        xlabel('Wavelength (micron)')
264
265
    figure(4)
266
267
        plot(lambda,flux_spec_flambda);
        title('Dark Star Spectrum')
268
        set(gca, 'FontSize', 14)
269
270
        ylabel('Flux [erg/s/A]')
        xlabel('Wavelength [A]')
271
        axis([1200 7500 0 6.5*10^36])
272
273
        x = [0.36 \ 0.42];
        y = [0.39 \ 0.31];
274
275
    figure(5)
276
        set(gca, 'FontSize', 14)
277
        plot(z_range,m_F200W(1,:)-m_F277W(1,:),'--')
278
        x = [0.4175 \ 0.38];
279
280
        y = [0.3 \ 0.19];
        annotation('textarrow', x, y, 'String', {'break', 'in spectrum'})
281
        set(gca, 'FontSize', 14)
282
        title('AB Magnitute Difference')
283
        ylabel('mF200-mF277')
284
        xlabel('z')
285
```

7.2 Color_diagrams.m

Script to obtain color-color diagrams of dark stars and galaxies.

```
1 clear all
2 z_range=[6.5:0.05:10.5]; % Redshifts for which magnitudes will be computed
3
4 %All dark stars
5 N='NIRCam.txt';
```

```
6 M='MIRI.txt';
7 %All Galaxies
 8 GN0_01 ='GalaxiesNIRCam0.01.txt';
   GM0_01 ='GalaxiesMIRI0.01.txt';
9
10
  %Distinguishable Dark stars
11
12 LTN='LowtemperatureNIRCam.txt';
13 LTM='LowtemperatureMIRI.txt';
14
15 %Processing galaxies
16 fid3=fopen([GN0_01]);
17 slask3=fscanf(fid3,'%s',13);
   GalaxN=fscanf(fid3,'%f',[13,inf])';
18
   GalaxN(GalaxN == 999)=NaN;
19
20
^{21}
      %NIRCam
       Gm_F070W=GalaxN(:,5);
^{22}
       Gm_F090W=GalaxN(:,6);
23
^{24}
       Gm_F115W=GalaxN(:,7);
       Gm F150W=GalaxN(:,8);
25
26
       Gm_F200W=GalaxN(:,9);
       Gm_F277W=GalaxN(:,10);
27
       Gm_F356W=GalaxN(:,11);
28
       Gm_F410M=GalaxN(:,12);
29
       Gm_F444W=GalaxN(:,13);
30
31
32 fid4=fopen([GM0_01]);
33 slask4=fscanf(fid4,'%s',13);
   GalaxM=fscanf(fid4, '%f',[13,inf])';
^{34}
   GalaxM(GalaxM == 999)=NaN;
35
36
37
   %MIRI
       Gm_F560W=GalaxM(:,5);
38
       Gm_F770W=GalaxM(:,6);
39
       Gm_F1000W=GalaxM(:,7);
40
       Gm_F1130W=GalaxM(:,8);
41
       Gm_F1280W=GalaxM(:,9);
42
       Gm_F1500W=GalaxM(:,10);
43
^{44}
       Gm_F1800W=GalaxM(:,11);
45
       Gm_F2100W=GalaxM(:,12);
       Gm_F2550W=GalaxM(:,13);
46
47
   %Processing dark stars
48
   names_modN=char(textread(LTN, '%q'));
49
   for modeN=1:(size(names_modN,1));
50
       disp(['Processing filter: ' num2str(modeN)])
51
       current_filterN=names_modN(modeN,:); % Extract name of current model
52
       while (current_filterN(size(current_filterN,2)) == ' ')
53
           current_filterN=current_filterN(1:(size(current_filterN,2)-1));
54
       end
55
       fid1=fopen(['ABmag6.5/' current filterN]);
56
       slask1=fscanf(fid1,'%s',10);
57
       rawdatal=fscanf(fid1,'%f',[10,inf])';
58
       rawdata1(rawdata1 == 999)=NaN;
59
60
      %NIRCAM
61
       m_F070W=rawdata1(:,2);
62
```

```
m_F090W=rawdata1(:,3);
63
        m_F115W=rawdata1(:,4);
64
        m_F150W=rawdata1(:,5);
65
        m_F200W=rawdata1(:,6);
66
        m_F277W=rawdata1(:,7);
67
        m_F356W=rawdata1(:,8);
68
        m_F410M=rawdata1(:,9);
69
70
        m_F444W=rawdata1(:,10);
71
        names_modM=char(textread(LTM,'%q'));
72
        current_filterM=names_modM(modeN,:); % Extract name of current model
73
        while (current_filterM(size(current_filterM,2)) == ' ')
74
            current_filterM=current_filterM(1:(size(current_filterM,2)-1));
75
        end
76
        fid2=fopen(['ABmag6.5/' current_filterM]);
77
        slask2=fscanf(fid2,'%s',10);
78
        rawdata2=fscanf(fid2, '%f',[10,inf])';
79
        rawdata2 (rawdata2 == 999)=NaN;
80
81
        %MIRI
82
        m_F560W=rawdata2(:,2);
83
        m_F770W=rawdata2(:,3);
84
        m_F1000W=rawdata2(:,4);
85
        m_F1130W=rawdata2(:,5);
86
        m_F1280W=rawdata2(:,6);
87
88
        m_F1500W=rawdata2(:,7);
        m_F1800W=rawdata2(:,8);
89
        m_F2100W=rawdata2(:,9);
90
^{91}
        m_F2550W=rawdata2(:,10);
92
        %Colors of dark stars in plot
93
^{94}
        if modeN == 1;
        a = [0 0 1]; %blue
95
        end
96
        if modeN == 2;
97
         a= [0 0.6 1]; % cyan
98
        end
99
         if modeN == 3;
100
101
         a= [0 1 0.1]; %green
102
         end
         if modeN == 4;
103
104
         a= [1 0.9 0]; %yellow
         end
105
         if modeN == 5;
106
         a= [1 0.6 0]; %orange
107
108
         end
109
         if modeN == 6;
         a= [1 0 0]; %red
110
         end
111
112
113 %Plot results
114 %Plot NIRCam/MIRI and galaxy SED
115 figure(1)
        set(gca, 'FontSize',14)
116
        wave_filter=[0.7 0.9 1.15 1.50 2.0 2.77 3.56 4.10 4.44 5.6 7.7];
117
118
119 if modeN == 3; %The 371M dark star
```

```
j=71; %z=10
120
        plot(wave_filter,[m_F070W(j) m_F090W(j) m_F115W(j) m_F1200W(j) ...
121
             m_F277W(j) m_F356W(j) m_F410M(j) m_F444W(j) m_F560W(j) m_F770W(j)],'.-r');
    end
122
        j=435322;%z=10
123
        plot(wave_filter,[Gm_F070W(j) Gm_F090W(j) Gm_F115W(j) Gm_F150W(j) Gm_F200W(j) ...
124
             Gm_F277W(j) Gm_F356W(j) Gm_F410M(j) Gm_F444W(j) Gm_F560W(j) Gm_F770W(j)],'.-k');
125
        hold on
        legend({'Dark star at z=10', 'Galaxy at z=10'}, 'FontSize', 10)
126
        hold on
127
        set(gca, 'FontSize', 14)
128
        set(gca, 'YDir', 'reverse')
129
        title('NIRCam/MIRI and Galaxy SED')
130
        ylabel('m_{AB}')
131
        xlabel('Wavelength [\mu m]')
132
133
    %Plot color-color diagrams
134
135
     figure(2)
136
        set(gca, 'FontSize', 14)
        if modeN ==1:
137
138
         plot(Gm_F090W-Gm_F115W,Gm_F115W-Gm_F150W,'k.')
        end
139
140
        hold on
        plot(m_F090W-m_F115W,m_F115W-m_F150W,'*','color',a)
141
        title(['NIRCam colors'])
142
        xlabel('m090-m115');
143
        ylabel('m115-m150');
144
        axis('tight');
145
146
        legend({'Galaxies', 'Dark stars'}, 'FontSize', 10)
        box on
147
148
149
     figure(3)
        set(gca, 'FontSize', 14)
150
        if modeN==1;
151
         plot (Gm_F115W-Gm_F150W, Gm_F150W-Gm_F200W, 'k.')
152
153
        end
154
        hold on
        plot(m_F115W-m_F150W,m_F150W-m_F200W,'*','color',a)
155
156
        title(['NIRCam colors'])
        xlabel('m115-m150');
157
        ylabel('m150-m200');
158
        axis('tight')
159
        legend({'Galaxies', 'Dark stars'}, 'FontSize', 10)
160
161
        box on
162
163
     figure(4)
164
        set(gca, 'FontSize', 14)
        if modeN==1;
165
         plot(Gm_F150W-Gm_F200W,Gm_F200W-Gm_F277W,'k.')
166
        end
167
        hold on
168
        plot(m_F150W-m_F200W,m_F200W-m_F277W,'*','color',a)
169
        title(['NIRCam colors'])
170
        xlabel('m150-m200');
171
        ylabel('m200-m277');
172
        axis('tight')
173
        legend({'Galaxies','Dark stars'},'FontSize',10)
174
```

```
176
177
     figure(5)
        set(gca, 'FontSize', 14)
178
        if modeN==1;
179
             plot(Gm_F200W-Gm_F277W,Gm_F277W-Gm_F356W,'k.')
180
        end
181
182
        hold on
        plot(m_F200W-m_F277W,m_F277W-m_F356W,'*','color',a)
183
        title(['NIRCam colors'])
184
        xlabel('m200-m277');
185
        vlabel('m277-m356');
186
        axis('tight')
187
        legend({'Galaxies', 'Dark stars'}, 'FontSize', 10)
188
        box on
189
190
     figure(6)
191
        set(gca, 'FontSize', 14)
192
193
        hold on
        if modeN==1;
194
             plot(Gm_F277W-Gm_F356W,Gm_F356W-Gm_F410M,'k.')
195
        end
196
        hold on
197
        plot(m_F277W-m_F356W,m_F356W-m_F410M,'*','color',a)
198
        title(['NIRCam colors'])
199
200
        xlabel('m277-m356');
        ylabel('m356-m410');
201
        axis('tight');
202
203
        legend({'Galaxies', 'Dark stars'}, 'FontSize', 10)
        box on
204
205
206
     figure(7)
        set(gca, 'FontSize', 14)
207
        if modeN==1;
208
             plot(Gm_F356W-Gm_F410M,Gm_F410M-Gm_F444W,'k.')
209
210
        end
        hold on
211
        plot(m_F356W-m_F410M,m_F410M-m_F444W,'*','color',a)
212
        title(['NIRCam colors'])
213
214
        xlabel('m356-m410');
        ylabel('m410-m444');
215
216
        axis('tight');
        legend({'Galaxies', 'Dark stars'}, 'FontSize', 10)
217
        box on
218
219
     figure(8)
220
^{221}
        set(gca, 'FontSize', 14)
222
        if modeN==1;
             plot(Gm_F410M-Gm_F444W,Gm_F444W-Gm_F560W,'k.')
223
224
        end
        hold on
225
        plot(m_F410M-m_F444W,m_F444W-m_F560W,'*','color',a)
226
        title(['NIRCam/MIRI colors'])
227
        xlabel('m410-m444');
228
        ylabel('m444-m560');
229
        axis('tight')
230
        legend({'Galaxies', 'Dark stars'}, 'FontSize', 10)
231
```

box on

175

```
232
        box on
233
^{234}
     figure(9)
        set(gca, 'FontSize', 14)
235
        if modeN==1;
236
             plot(Gm_F444W-Gm_F560W,Gm_F560W-Gm_F770W,'k.')
237
        end
238
239
        hold on
240
        plot(m_F444W-m_F560W,m_F560W-m_F770W,'*','color',a)
        title(['NIRCam/MIRI colors'])
241
242
        xlabel('m444-m560');
        ylabel('m560-m770');
243
        axis('tight')
244
        legend({'Galaxies', 'Dark stars'}, 'FontSize', 10)
^{245}
        box on
246
247
     figure(10)
^{248}
        set(gca, 'FontSize', 14)
249
250
        if modeN==1;
            plot(Gm_F560W-Gm_F770W,Gm_F770W-Gm_F1000W,'k.')
251
252
        end
253
        hold on
        plot(m_F560W-m_F770W,m_F770W-m_F1000W,'*','color',a)
254
255
        title(['MIRI colors'])
        xlabel('m560-m770');
256
        ylabel('m770-m1000');
257
        axis('tight')
258
        legend({'Galaxies', 'Dark stars'}, 'FontSize', 10)
259
260
        box on
261
     figure(11)
262
263
        set(gca, 'FontSize', 14)
        if modeN==1;
264
             plot(Gm_F770W-Gm_F1000W,Gm_F1000W-Gm_F1130W,'k.')
265
        end
266
        hold on
267
        plot(m_F770W-m_F1000W,m_F1000W-m_F1130W,'*','color',a)
268
        title(['MIRI colors'])
269
        xlabel('m770-m1000');
270
271
        ylabel('m1000-m1130');
        axis('tight')
272
        legend({'Galaxies', 'Dark stars'}, 'FontSize',10)
273
        box on
274
275 end
```