

Implications of Spectral Energy Distribution in Cosmic Dust Analysis via THESAN Simulations

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Abstract. As a matter of fact, analysis of cosmic dust features remains a hot topic in cosmology and astrophysics. In recent years, a state-of-art astrophysics simulations project, i.e., the THESAN project, provides high-resolution simulations in the universe, shedding new lights on novel cosmology areas such as study of cosmic dust. As previous observations have been confined to $z \leq 5$, advanced simulation like THESAN is essential for a deeper understanding of cosmic dust in the early universe, which provides valuable information of numerous astrophysical processes. With this in mind, this study used Spectral Energy Distribution (SED) data of thousands of simulated galaxies from THESAN data to study and investigate cosmic dust's impact on energy. According to the analysis, it is suggested cosmic dust components and correlation between dust temperature, redshift, and SFR (Star Formation Rate) at high redshifts ranging from six to ten. Overall, these results shed light on guiding further exploration of cosmic dust.

Keywords: Cosmic dust; THESAN project; SED; high-redshift.

1. Introduction

Cosmic dust, or intergalactic dust, is the microscopic, solid particles in outer space. The study of cosmic dust is important in astrophysics for several reasons. For instance, understanding how galaxies, stars or planets form is made possible through analyzing how dust particles aggregate into larger bodies. In addition, cosmic dust can provide valuable information about the chemical composition of celestial bodies. The concept of cosmic dust has been suggested for centuries, dating from an Italian astronomer Giovanni Domenico Cassini in 1683. The serious study of cosmic dust began more than five decades ago. Meanwhile, early observational work laid the foundation for the understanding of cosmic dust in the 21st century. Recently, as more and more advanced observational techniques like the Atacama Large Millimetre Array (ALMA) [1] emerge, the observational reach of the universe expands. As a result, the exploration of dust-rich environments in distant galaxies at $z > 1$ comes to reality.

However, current observational instruments are not able to observe MIR wavelengths when $z > 5$ [2]. Therefore, for the study of cosmic dust, simulation data becomes an invaluable approach to understand properties of cosmic dust in the early universe. The Illustris project is an international collaboration led by key researchers Volker Springel of the Max-Planck-Institut für Astrophysik and Mark Vogelsberger of MIT. The project focuses on astrophysical simulations to study galaxy formation and evolution. The Illustris framework has given rise to several spin-off projects since 2015. Of note is the THESAN project, which stands as the latest in a series of subsequent simulation endeavors of the year 2023 (future projects, such as MillenniumTNG and TNG-Cluster are planned for public release in the coming years). Notably, the THESAN project offers public access to "Galaxy Spectral Energy Distribution (SED) catalogs" dataset produced by post processing the raw data of simulation, which is closely relevant to SED method of studying cosmic dust.

Given the limitations of current observational techniques and the appreciated data from THESAN project, it is aimed to utilize this simulated SED data to gain deeper insights into cosmic dust at high redshifts ($z=6\sim 10$). With relevant data, this study attempts to explore dust properties in the early universe, including the temperature and possible composition of cosmic dust. In addition, by employing THESAN data of SFR, galaxy masses and redshift, it is attempted to study the relationship among these variables.

The paper is structured as follows. Section 2 summarizes basic descriptions of cosmic dust in previous research. Section 3 introduces the method of SED results to study cosmic dust. Section 4 presents a detailed overview of the THESAN project which the study is based on. Section 5 presents the methodologies adopted and the analysis of cosmic dust based on THESAN data, including the potential composition of intergalactic dust, the relationship between estimated temperature of cosmic dust, SFR and redshift. In Section 6, a summary of the results is given.

2. Basic Descriptions

Cosmic dust refers to tiny solid particles that are present in space between galaxies. It is not uniformly distributed. In fact, it can be found in a variety of settings. This includes the diffuse clouds of the interstellar medium, molecular clouds, the circumstellar regions around young stellar objects, and within planetary systems such as the own Solar System. For instance, studies indicate that Earth receives about 40,000 tons of meteoritic material each year, the majority of which is cosmic dust [3]. Moreover, cosmic dust is an integral part of Interstellar Medium (ISM, the matter and radiation that fill the space between stars in a galaxy). This includes serving as the building blocks for star formation and affecting the radiative properties of celestial objects. By studying cosmic dust, one can gain valuable insights into astrophysical processes, the lifecycle of stars, and the composition and evolution of galaxies [4]. In addition to various distributions, cosmic dust has different types of particles as are photographed in Fig. 1. Seen from the results, the light source is from the right side of the image. Within this small section, you can observe different kinds of particles: a compact particle (labeled as "a"), a broken cluster (labeled as "b"), a cluster that appears to be glued together (labeled as "c"), and a large pile of rubble (labeled as "d") [5].

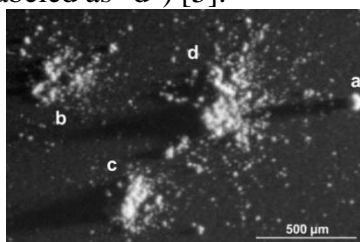


Fig. 1 The photo shows a variety of cosmic dust particle types found on a single target area measuring 2.5 mm across.

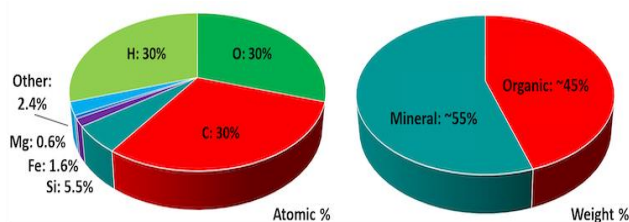


Fig. 2 The chemical composition of dust particles (left) from comet 67P and the mean weight distribution of minerals and organic substances in the dust (right).

As for composition, cosmic dust is generally believed to be composed of complex materials such as silicates, carbonaceous substances, and metals. Fig. 2 was pictured by using data from the COSIMA instrument on the Rosetta spacecraft. According to this research, cosmic dust is mostly made of 60% hydrogen and oxygen, 30% carbon, and a mix of other elements like silicon, iron, magnesium makes up the remaining 10%. Furthermore, cosmic dust has various origins, including remnants of supernovae, material ejected from stars, and collisions between planetary bodies [6].

3. SED Method

A core method employed in this research is the analysis of Spectral Energy Distributions (SEDs). An SED is a plot that shows how much energy is emitted by an astronomical object varies with

wavelength or frequency. In the SED plots used in this research, the x-axis represents wavelength, measured in micrometers (μm) or nanometers(nm). The y-axis represents flux density, measured in Janskys ($1 \text{ Jansky} = 10^{-26} \text{ Wm}^{-2} \text{ Hz}^{-1}$). The flux density values are standardized for 10 Megaparsecs (Mpc) from the object under study, so the unit of flux density is represented as "Jansky at 10 Mpc". The Spectral Energy Distribution (SED) offers a comprehensive overview of an object's radiative properties. The plot serves as an essential tool for identifying radiation characteristics of cosmic dust in this study [7, 8]. Specifically, the SED reveals two main types of information. At shorter wavelengths, the SED can show features like absorption lines. These spectral lines are often indicative of the chemical composition of the object. At longer wavelengths, the SED often shows details of thermal emission. This thermal radiation pattern can be useful for understanding the temperature of an object. This methodology of using two different pieces of information is not new and has been effectively employed in previous research works. For instance, a study by Davies et al. employed this modeling approach to analyze cosmic dust: "through the extinction it causes in the UV and optical and through its direct thermal emission at FIR/sub-mm wavelengths [9]. By interpreting the SEDs separately at longer wavelengths and at shorter wavelengths, one can gain understanding of its chemical composition and temperature.

4. THESAN Project

The THESAN project is "a suite of large volume radiation hydrodynamic simulations that self-consistently model the reionization process and the galaxies responsible for it with unprecedented physical fidelity" [10]. The simulations were completed in 2021 and presented in three simultaneous papers [11-13]. According to THESAN Collaboration, numerical simulations play a pivotal role in astrophysics, as they offer manipulable representation of the Universe. With simulations, one can not only passively receive limited observational data from telescopes, but also do virtual experiments and make reasonable predictions based on physics models to deepen the understanding of reality.

According to the THESAN Collaboration, the simulations of the THESAN project were based on a moving mesh approach or the IllustrisTNG galaxy formation model. The THESAN project used the initial condition, which is the density field after the Big Bang, and simulated various contents including dark matter, dark energy, photons, magnetic fields, cosmic dust, baryons and so on. With billions of elements, the simulations were run on a supercomputer- SuperMUC-NG machine and were continuously calculated for 30 million hours with 60,000 processors working together. Regarding cosmic dust, the simulations incorporate a specialized framework for it. During the initial billion years following the Big Bang, plenty of stars in new galaxies inject energy and mass, giving rise to cosmic dust. To assist the study of galaxy formation in the early universe, there is one post-processing product called "Galaxy SED catalogs", which include dust-attenuated SED data set for each of the galaxies and dust-corrected SEDs for the galaxies. By comparing the two data sets, one can reveal the dust effect on SED during the early universe and therefore reveal some of its properties.

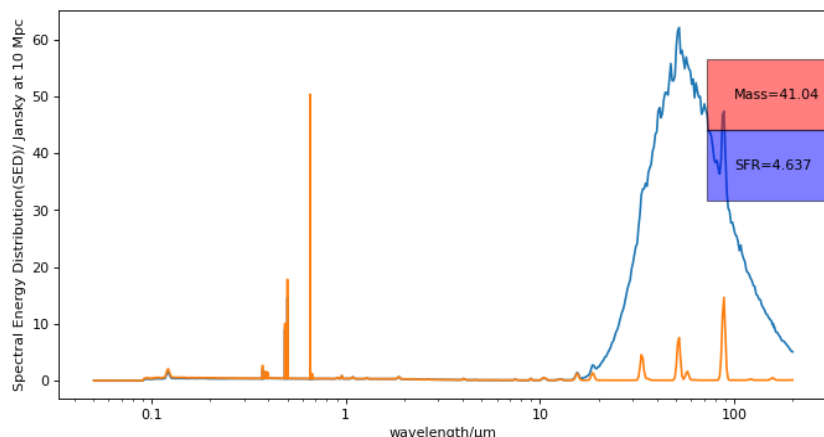


Fig. 3 SED plot of one of the 179 galaxies when $z=10$ from THESAN data.

5. Analysis

5.1. Overview

"Galaxy SED catalogs" consist of SED plots from hundreds of galaxies of different redshift. Specifically, 179 galaxies are simulated when $z=10$, 596 galaxies when $z=9$, 1803 galaxies when $z=8$, 4269 galaxies when $z=7$, and 9987 galaxies when $z=6$. One SED plot accounts for all factors, including cosmic dust; while the other SED plot isolates the effects by excluding dust effects. Each SED plot consists of 657 data points, corresponding to 657 distinct wavelengths, ranging from 5.05 nm to 200 μm . All graphs in this chapter are based on THESAN simulated data. By using Python, one imported ".hdf5" files from the THESAN project and visualized the data with NumPy library and Matplotlib library to get thousands of SED graphs, each representing SED from one galaxy, as one result is shown in Fig. 3. Seen from Fig. 3, the blue line represents a simulated SED line graph considering all factors and the orange line represents SED without considering dust's effect. The unit of Galaxy Mass is 10^6 solar mass (one solar mass is defined as approximately 1.989×10^{30} kilograms). The unit of SFR is "solar masses per year". All units in the subsequent graphs are consistent with those introduced here. This study will try to subtract the two SEDs in one graph to get ΔSED , representing dust's effect on SED, as is shown in Fig. 4 and Fig. 5. The result demonstrate that cosmic dust radiates energy at longer wavelengths while absorbing energy at shorter wavelengths. As is introduced in Section 3, thermal emission is predominant at greater wavelengths, serving as an indicator of the cosmic dust's temperature. Meanwhile, the absorption lines in shorter wavelengths indicate the chemical composition of cosmic dust.

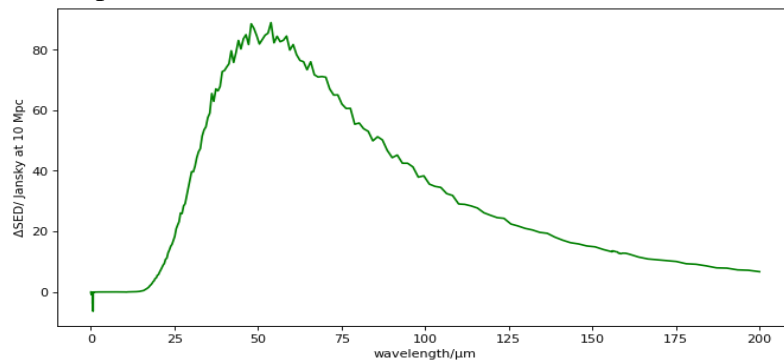


Fig. 4 Dust's effect on the SED plot of one of the 179 galaxies when $z=10$.

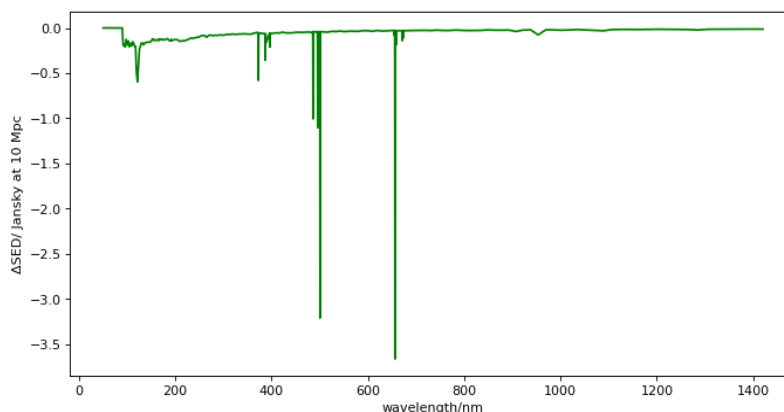


Fig. 5 Wavelengths are smaller than 1400 nm, with other conditions consistent with Fig. 4.

5.2. Absorption Lines

Firstly, this study focus on shorter wavelengths. By importing the SciPy library from Python which specializes in scientific computing, one obtains the peak wavelengths of each SED graph at shorter wavelengths, as two examples are shown in Fig. 6. Once the peaks of hundreds of graphs were identified, one counted the frequency of these peaks from data of 179 simulated galaxies when $z=10$.

After counting the frequencies, it is noticed that some peak wavelengths were approximately the same but not identical. To tackle this, one sorted the data and grouped similar wavelengths within a tolerance level. Then, one developed a function to match peak wavelengths with known elemental emission lines from the NIST (National Institute of Standards and Technology) database which provide sufficient data of strong emission or absorption lines of elements [14]. One calculated the absolute differences between each grouped peak and known emission lines for elements and stored them in an array, the smallest one identifying the closest matching emission line. A match was accepted if it fell within a set tolerance level (2 nm). The result is shown in Table 1, which is based on the shorter wavelengths range of SED data and NIST emission lines database. The "% of Counts" column quantifies the frequency of each peak wavelength within the data set.

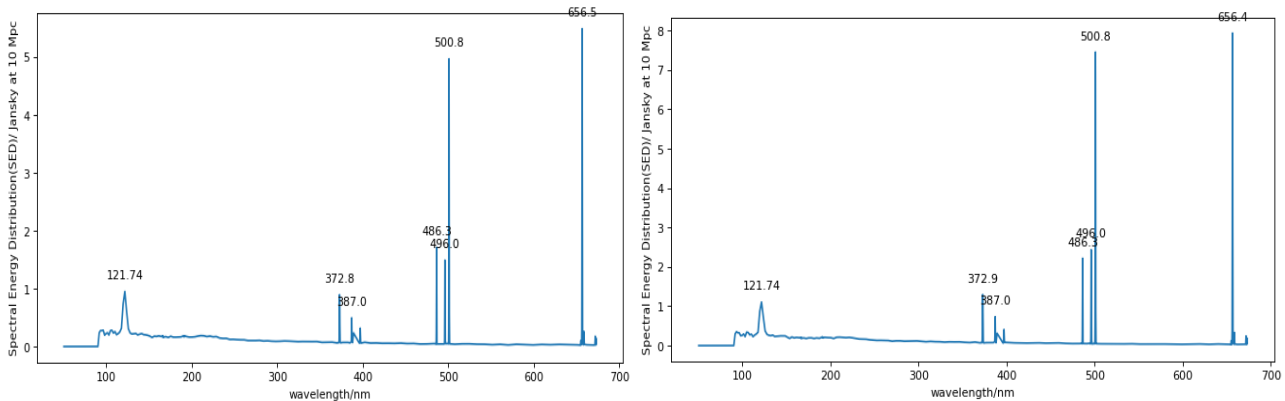


Fig. 6 Wave spectrum.

Table 1. Likely Chemical Components in Cosmic Dust when $z=10$.

Peak Wavelengths (nm)	Suggested Component	Known Wavelength (nm)	Percentage
656.1~656.7	H_alpha (Balmer series)	656.3	15.09%
486.0~486.4	H_beta (Balmer series)	486.1	13.60%
500.6~501.0	O_III	500.7	12.40%
495.9~496.2	O_II	495.9	9.53%
372.8~373.0	O_I	372.8	6.66%
121.735129	H (Ly_alpha)	121.6	5.56%
386.9~387.0	Fe_II	386.9	4.31%
96.49	Unknown	N/A	3.40%
93.34	Unknown	N/A	3.26%
104.84	C (103.70 nm)	103.70	3.21%
101.42	Unknown	N/A	3.02%
110.19	Unknown	N/A	2.78%
119.73	Si (119.45nm)	119.45	2.54%
134.49	Si (135.01 nm)	135.01	2.25%
397.0	Unknown	N/A	2.06%
91.80	C (90.45nm)	90.45	1.87%
106.59	Unknown	N/A	1.77%
389.14	Fe_III	388.7	1.77%
115.82	Unknown	N/A	1.72%
113.91	Unknown	N/A	1.63%
99.75	Si (99.3 nm)	99.3	1.58%

5.3. Thermal Emission

To estimate the temperature of cosmic dust from the SED graph, it is assumed that cosmic dust behaves as a black body. Consequently, one can employ Wien's Law for the calculations. For each galaxy, it is estimated the temperature by using Wien's Law:

$$\lambda_{max} = \frac{b}{T} \tag{1}$$

where $b \approx 2.897 \times 10^{-3} \text{ m} \cdot \text{K}$. To get data of λ_{max} , one calculated the largest SED value and output its index, using the index to fetch the corresponding wavelength from the list. Then, one calculated the average temperature of each redshift. The result is shown in Fig. 7 and Table 2.

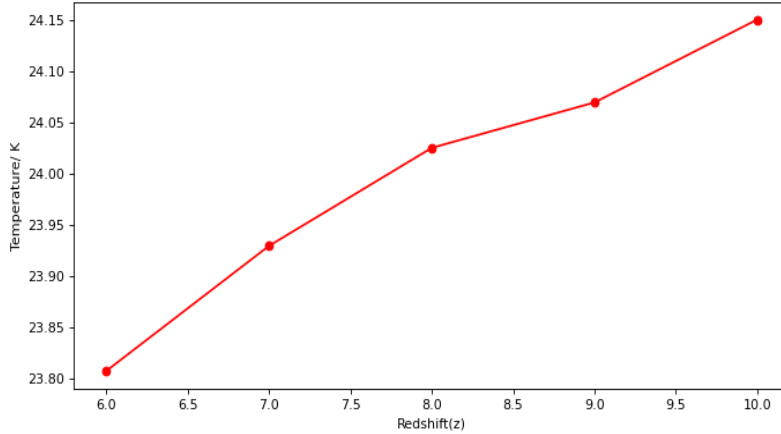


Fig. 7 Average Temperatures by Redshift

Table 2. Average Temperatures by Redshift

Redshift (z)	Average Temperature (K)	Number of Galaxies
6	23.8071	9987
7	23.9294	4269
8	24.0253	1803
9	24.0697	596
10	24.1508	179

The increasing trend in temperature of cosmic dust by redshift corresponds to findings from other studies, as is shown in Fig. 8 [2, 8, 15, 16]. One also visualized the relationship between estimated temperature of cosmic dust and the galaxy's SFR as is represented in Fig. 9. Based on the figure, there appears to be a potential correlation between increased SFR and increased temperature of cosmic dust, as when SFR is greater than 20 solar masses per year, most temperatures are significantly higher than the average. There is a possible explanation that when stars are forming rapidly, they release much energy into ISM, heating the cosmic dust as well. However, one must note that further analysis is required to confirm this relationship.

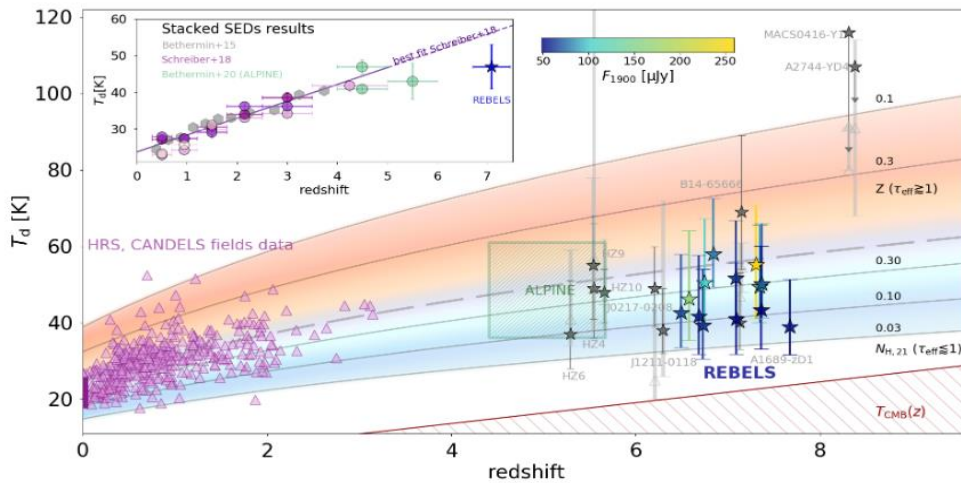


Fig. 8 Previous studies in the relationship between cosmic dust temperature and redshift.

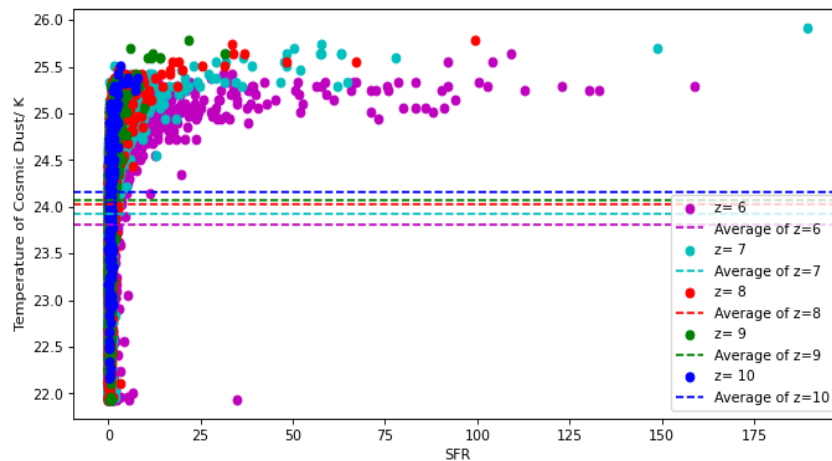


Fig. 9 Average Temperatures by SFR. Each dot represents cosmic dust data from one galaxy.

6. Conclusion

To sum up, this study analyzed cosmic dust’s properties in the early universe by utilizing data from recent THESAN project simulation. By post-processing SED data and separately gaining insights from UV and FIR/sub-mm wavelengths, it is identified potential components of cosmic dust that align with prior observations, and estimated temperature of cosmic dust from different galaxies over different redshifts. Moreover, it is presented findings on the temperature’s correlation with both redshift and SFR. As for the former, the data shows cosmic dust temperature rises with increasing redshift, aligning with findings in other studies. As for the latter, it is suggested a link between higher cosmic dust temperatures and increased SFR. When SFR exceeds 20, dust temperatures are notably higher, possibly due to energy from intense star formation heating the dust. It is anticipated that further observational data, more advanced simulation techniques and similar studies will enhance the understanding of cosmic dust properties in the early universe.

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