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Study of the Spectral Energy Distribution Model of the Protoplanetary Disk Geometric around the Brown Dwarf CFHT-BD-Tau 4

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Abstract:
The accretion circumstellar disk of young stars and the Brown dwarf plays an essential role in the formation and evaluation of the planet. Our main work in this paper is to investigate the geometrical shape model for the protoplanetary disk around one of the Brown Dwarfs. The photometric measurements for the brown dwarf CFHT-BD-Tau 4 were extracted from the Vizier archive. We used a numerical simulation to build a model of the spectral energy distribution of our target CFHT-BD-Tau 4. The spectral energy distribution model was fitted with observational data for the brown dwarf CFHT-BD-Tau 4. A transitional disk has been assumed around CFHT-BD-Tau 4. We obtained physical properties of the two disks and the size of the gap between them by fitting the SED. The gap in the protoplanetary disk proves that a planet formation process occurred around the Brown dwarf.

Keywords: Photometry, Brown Dwarf, Spectral Energy Distribution (SED), protoplanetary disk, Star formation , CFHT-BD-Tau 4.

دراسة نموذج توزيع الطاقة الطيفية للقرص الهندسي الكوكبي الاولي حول القزم البني CFHT–BD–Tau 4

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الخلاصة

الاقراص النجمية حول النجوم الفتية والاقزام البنية تلعب دور اساسي في تكوين وتطوير الكواكب. يتمثل عملنا الرئيسي في هذا البحث في دراسة نموذج الشكل الهندسي للقرص الابتدائي الكوكبي حول احد الاقزام البنية . القياسات الضوئية للقزم البني (CFHT–BD–Tau 4) تم الحصول عليها من ارشيف (VizieR). استخدمنا محاكاة عددية لبناء نموذج لتوزيع الطاقة الطيفية لهدفنا CFHT–BD–Tau 4 . تم مطابقة الموديل الرياضي لتوزيع الطيفي للطاقه مع البيانات الرصدية للتوزيع الطيفي للطاقة للقزم البني CFHT–BD–Tau 4. تم افتراض بان هنالك قرص انتقالي حول القزم البني CFHT–BD–Tau 4. تم الحصول على الخصاص

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الفيزيائية للقرصين وحجم الفراغ الذي يفصل بين القرصين من خلال مطابقه التوزيع الطيفي للطاقه . وجود
الفراغ في القرص الكوكبي الابتدائي هو دليل على حدوث عملية تكوين الكوكب حول القزم البني.

1. Introduction

There are many previous studies in astronomy and astrophysics based on the study of the photometry for objects in the sky and from these studies extracted the physical properties of these objects [1,2,3,4]. The formation process of substellar objects such as brown dwarfs, which have a mass less than 0.08 $M_{\odot}$ is still not fully understood, but they are similar to the formation of low mass stars. The hypothesis of brown dwarf objects was first assumed by Kumar (1963) and Hayashi & Nakano (1963) through numerical models [5,6].

The first brown dwarfs have been observed, called Teide1, PP115, and Gliese 229B, by Rebolo et al. (1995) and Nakajima et al. (1995)[7,8]. Protoplanetary disks around young brown dwarfs were detected by studying their spectral energy distribution (Luhman et al. (2005), Apai et al. (2004))[9,10]. In addition, protoplanetary disks have been observed around low-mass stars and intermediate-mass stars [11, 12, 13].

Our target is called CFHT-BD-Tau4 (also known as ITG 17, 2MASS J04394748+2601407)[14]. Its position in the sky is the Right Ascension $04^h39^m47.3^s$ and declination $+26^o$ 01″ 39″ (J2000.0). It is a young brown dwarf that has a spectral type M7 and is located close to the Tau III group (Taurus star-forming region) identified by G´omez et al. (1993) at a distance of 147.1±5.2 pc (Gaia Collaboration et al. 2016, 2018), with an estimated age of approximately 1 Myr old (Martín et al.2001). The bolometric luminosity of CFHT-BD-Tau 4 is equal to 0.03 $L_{\odot}$ [14,15,16].

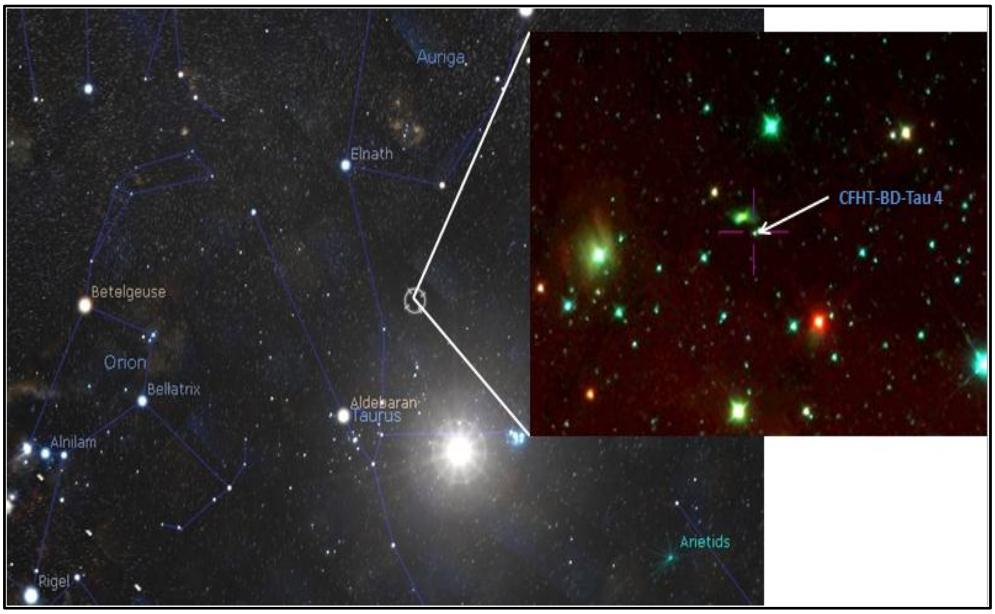


Figure 1: Position of CFHT-BD-Tau 4 in the sky between two famous stars Alnath and Aldebaran in the constellation Taurus. The image in the right corner represents the CFHT-BD-Tau 4 image from the WISE telescope [Aladine Atlas Sky].

CFHT-BD-Tau 4 has the highest Hα emission among the Taurus brown dwarfs (Martín et al. 2001) and, emits X-ray radiation (Mokler & Stelzer 2002) and mid-infrared emission detected (Pascucci et al. 2003)[14,17,18].

CFHT-BD-Tau4 was observed using a T-ReCS mid-infrared detector mounted on the Gemini South 8 m-telescope in service mode (D. Apai et al.,2004)[9]. Three filters with central wavelengths of 7.9 μm, 10.38 μm and 12.33 μm were used to observe the brown dwarf. They detected a peak emission in the infrared spectrum that came from silicate features, which led to an optically thin flared disk around the brown dwarf CFHT-BD-Tau 4 [9].

The first detection of cold dust in the disk around CFHT-BD-Tau 4 was performed using a millimeter continuum survey (R. K LEI et. al., 2004)[19]. Surveys were obtained from different bolometer arrays SCUBA at the JCMT and MAMABO at the IRAM telescope. They estimated the total dust mass in the disk around CFHT-BD-Tau 4 to be a few Jupiter masses [19].

CFHT-BD-Tau 4 was observed in the near-infrared using a J-band filter and a long slit Intermediate Resolution Infrared Spectrograph (LIRIS) using the William Herschel Telescope (4.2 meter). They observed polarization that comes from light scattering within dust particles in the disk (P. A. Miles-P´aez et al., 2017)[20].

The photometric measurement data were taken from the Telescope Kepler K2 mission for the very young brown dwarf CFHT-BD-Tau 4. Two super flares were observed from the photometric measurements, and the total bolometric energies for the two flares were estimated to be 2.1×10^{38} erg and 4.7×10^{36} erg [21].

The total mass in the protoplanetary disk around CFHT-BD-Tau 4 was estimated to be $0.42 M_{Jup}$ and the size of the disk is 160 AU, where the data were taken from Atacama Large Millimeter/submillimeter Array images (Rilinger A., 2019)[22].
Our main goal in this paper is to study different regions in the protoplanetary disk around the brown dwarf CFHT-BD-Tau 4 such as the geometry of the inner disk and outer disk, flaring or flat disk, surface densities, temperature, and chemical compositions of the disk and obtain a better fit for the spectral energy distribution model with observations and photometric measurements.

2. Photometric measurements and the SED model

The photometric measurements of the brown dwarf CFHT-BD-Tau 4 from visible to millimeter wavelengths were taken from VizieR. We plotted the observational spectral energy distribution for the brown dwarf CFHT-BD-Tau 4, as shown in Figure 2.

The plot shows extended emission in the infrared and longer wavelengths. The infrared emission comes from warm dust particles and the longer wavelength comes from cold dust. This emission can be considered a perfect proof of the existence of a protoplanetary disk around the brown dwarfs. Observations of the spectral energy distribution constructed from the photometric measurements shown in Figure 2.

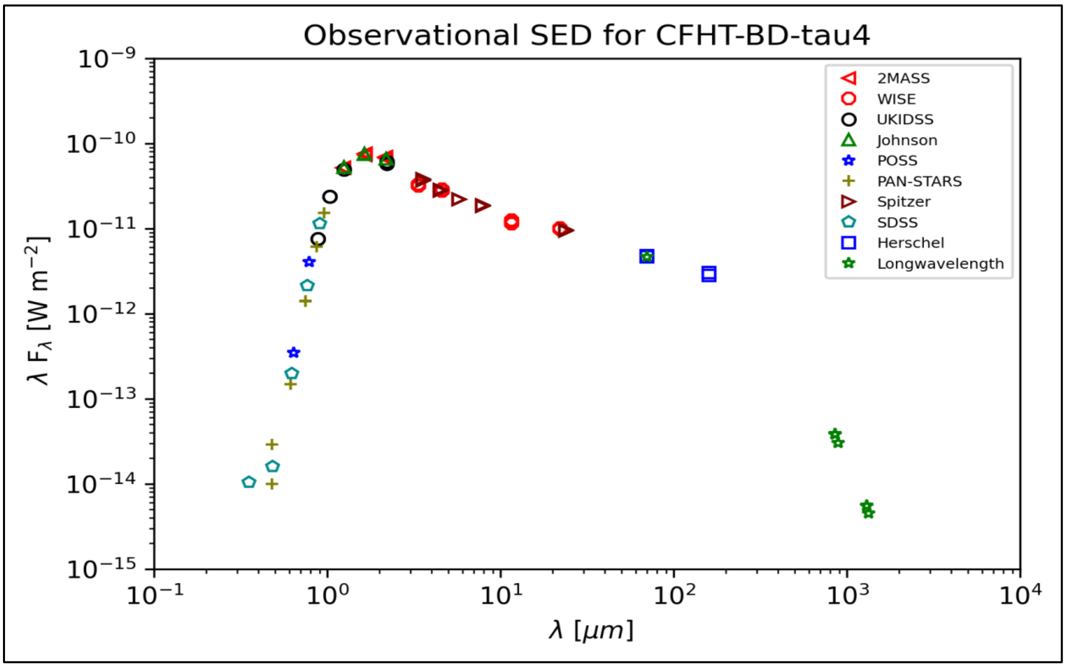


Figure 2: The observational spectral energy distribution for our target CFHT-BD-tau 4, which has been extracted from the VizieR archive, is re-plotted and different colors refer to different telescopes data. The plot shows the change in flux density in units (w.m^{-2}) with wavelength in units (µm).

We extracted magnitude values for CFHT-BD-Tau 4 from the flux density. The table below shows the magnitude values for each filter. The values of the magnitudes for the target show that the target is brighter in the infrared than visible [1].

Table 1: Values of the magnitude for CFHT-BD-Tau 4 in different filters.

Wavelength (µm)	Flux in (Jy)	Magnitudes
(SDSS:u) 0.3519	1.23E-06	23.565
(SDSS:g) 0.4819	2.57E-06	22.858
(SDSS:r) 0.6246	4.10E-05	19.868
(SDSS:i) 0.7635	5.44E-04	17.061
(SDSS:z) 0.9018	3.44E-03	15.039
(2MASS:J) 1.239	5.18E-14	12.2
(Johnson:J) 1.25	2.17E-02	12.2
(Johnson:K) 2.19	4.82E-02	11.8
(Johnson:H) 1.63	4.11E-02	11
(2MASS:H) 1.649	7.54E-14	11
(2MASS:H) 1.649	7.54E-14	10.8
(Johnson:K) 2.19	4.81E-02	10.4
(2MASS:Ks) 2.163	6.88E-14	10.3

[1] https://irsa.ipac.caltech.edu/data/SPITZER

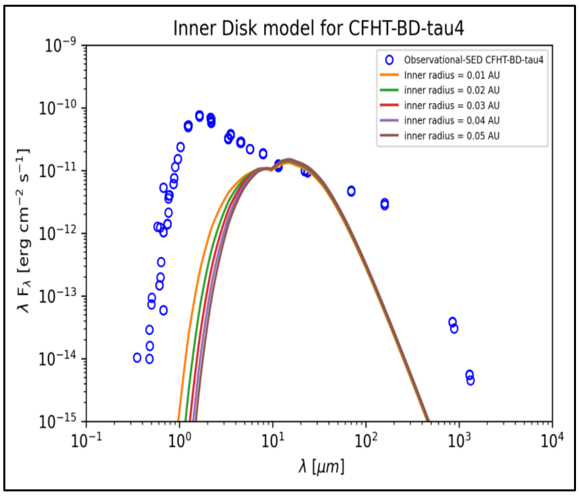
3. Geometrical model of the transition disk

We examined the shape of the protoplanetary disk around the brown dwarf CFHT- Tau 4 such as the inner disk, outer disk, and gap. The inner and outer disks around the brown dwarf CFHT- Tau 4 are assumed to have an inner radius, an outer radius, a temperature, the power law of the surface density, and the surface density of the dust in the inner and outer disks. The physical parameters used to fit the observed spectral energy distribution for CFHT-BD-Tau 4 with the spectral energy distribution model are listed in table 2.

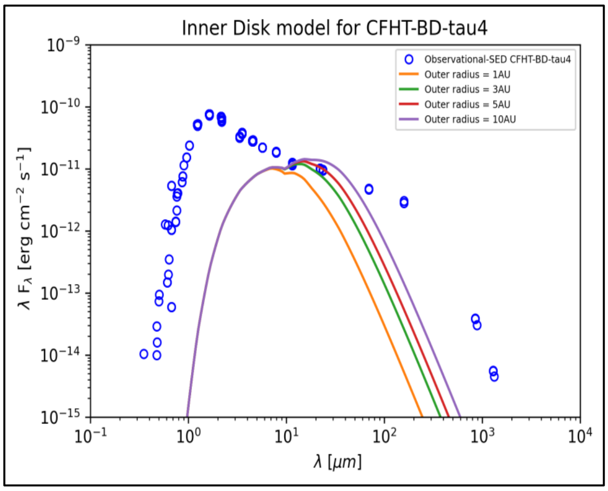
Table 2: Input physical parameters for our target CFHT-BD-Tau 4.

Parameters	Values	references
Temperature	2880 K	[23,24]
Mass	0.095 $M_{\odot}$	[23,25]
Radius	1.68 $R_{\odot}$	[23]
Extinction (A_v)	6.37	[16]
Distance	147 pc	[16]

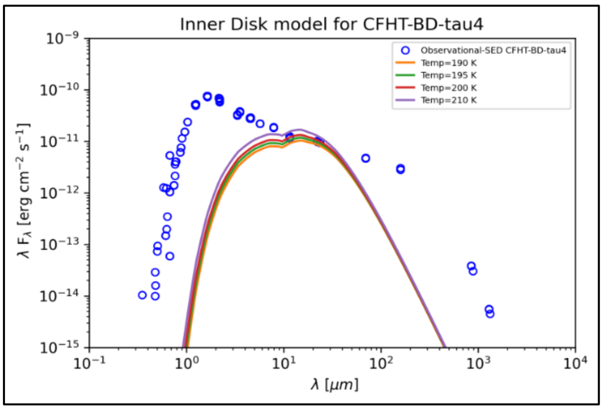
The inner region of the protoplanetary disk around the brown dwarf emits in the infrared band. As a first step, we have examined the inner disk for our target until we get a better fit between observational SED and model SED by changing its physical properties, such as inner radius size, outer radius size, temperature, surface density, and power-law of the surface density, as shown in the Figure 3.



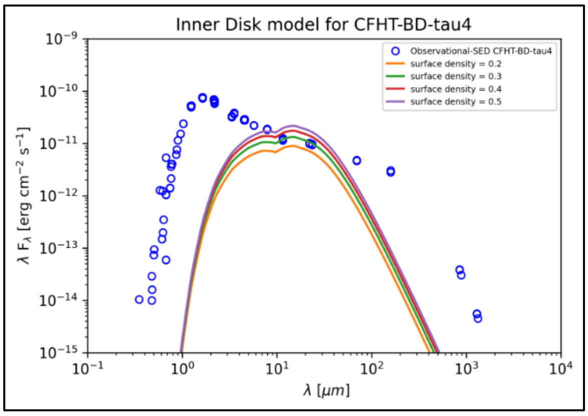
(a) Inner radius of the inner disk for different values (r_{in}=0.01 AU, 0.02 AU, 0.03 AU, 0.04 AU, and 0.05 AU).



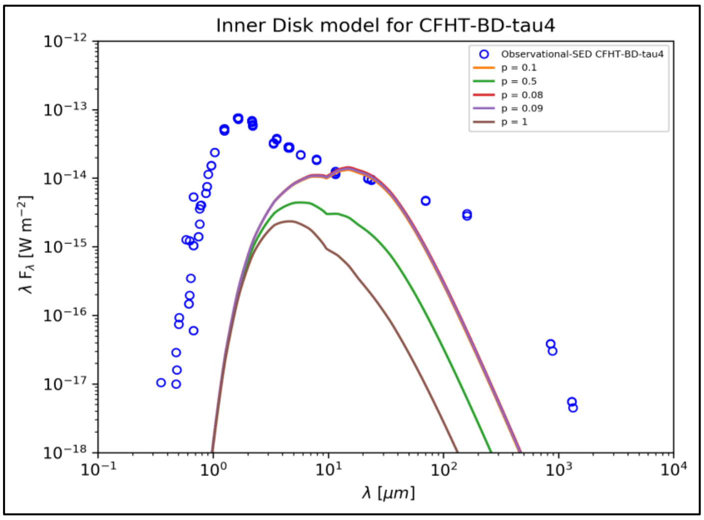
(b) Outer radius of the inner disk for different values (r_{outer} =1 AU, 3 AU, 5 AU, and 10 AU).



(c) Temperature of the inner disk for different values (T =190 k, 195 k, 200 k, and 210 k).



(d) Surface density of the inner disk for different values (Σ=0.2, 0.3, 0.4, and 0.5 kg/m^2).



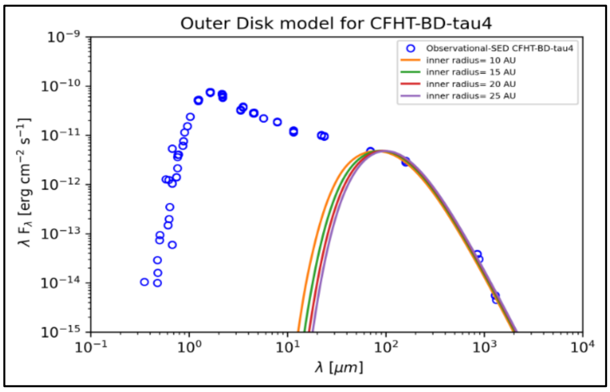
(e) Power law of density for the inner disk for different values (P = 0.1, 0.5, 0.08 and 1).

Figure 3: Model of the inner disk for a protoplanetary disk around CFHT-BD-Tau 4. (a) Represents the different values for the inner radius size in unit (AU). (b) Represents the different values for the outer radius size in unit (AU). (c) Represents the different values of the temperature in the inner disk in unit (k). (d) Represent the different values of the surface density of the dust in the inner disk in unit (kg/m^3).). (e) Represent the different values of the power law of the surface density in the inner disk.

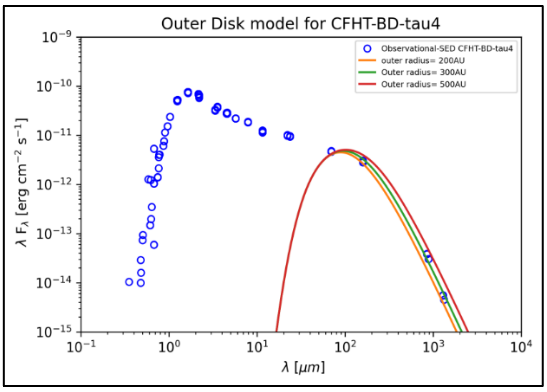
Figure (3-a), shows that the inner radius of the inner disk should be small, which is 0.02 or 0.025 AU, to fit the model of the spectral energy distribution with the observational spectral energy distribution. An increase the size of the inner radius larger than 0.025 AU will puff up the inner radius of the disk. Therefore, the value that fits the inner disk SED model should be less than 0.02 AU.

The outer radius of the inner disk is shown in Figure (3–b). We have chosen different values for the outer radius of the inner disk. Figure (3-c) shows the different values of the temperature for dust in the inner (190 k, 195 k, 200 k, 210 k). Figure (3-d) shows the surface density of dust grains in the inner disk has been examined by selecting different values for the surface density (Σ=0.2, 0.3, 0.4, and 0.5 kg/m^2)

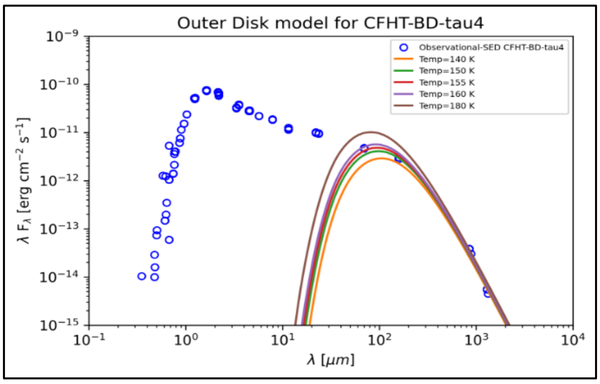
In addition to that, outer region of the protoplanetary disk around the brown dwarf CFHT-BD-Tau 4 has been examined in the same way as the inner region. The geometry of the outer disk consists of the inner radius, outer radius, temperature, surface density, and power-law of the surface density for the dust grains in the disk. Figure 4 shows the different values used to fit the model of the SED with observations.



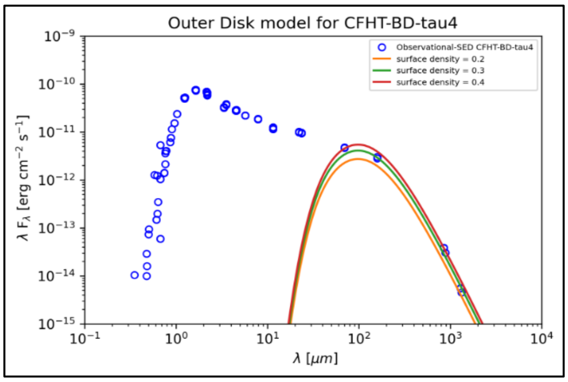
(a) Inner radius of the outer disk for different values (r_{in}=10AU, 15AU, 20AU and 25 AU).



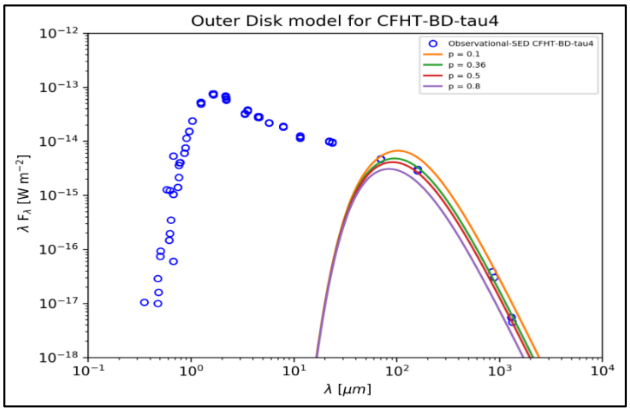
(b) Outer radius of the outer disk for different values (r_{outer} =200 AU, 300 AU, and 500 AU).



(c) Temperature of the outer disk for different values (T =140 k, 150 k, 155 k, 160 k and 180 K).



(d) Surface density of the outer disk for different values (Σ=0.2, 0.3 and 0.4 kg/m^2).



(e) Power law of density for the inner disk for 0.8 different values (P = 0.1, 0.36, 0.5 and 0.8).

Figure 4: Model of the outer disk for a protoplanetary disk around CFHT-BD-Tau 4. (a) Represents the different values for the inner radius size in unit (AU). (b) Represents the different values for the outer radius size in unit (AU). (c) Represents the different values of the temperature in the outer disk in unit (K). (d) Represent the different values of the surface density of the dust in the outer disk in unit (kg/m^3). (e) Represent the different values of the power law of the surface density in the inner disk

Figures (4: a,b,c,d) show that the size of the inner radius of the outer disk starts at 20 AU and the outer radius of the outer disk ends at 300 AU. The temperature of the dust used to fit the SED in the outer disk is 150 K, and the surface density of the grains in the outer disk is 0.3 kg/m^2.
The whole observational SED and model SED have fitted visually, and the final values that we have chosen to get the best fit are listed in Table 3.

Table 3: Best physical parameters for protoplanetary inner and outer disk around CFHT-BD-Tau 4

Inner Disk	
Parameters	**Values**
Inner radius in AU	0.02
Outer radius in AU	5
Temperature (K)	200
Density (kg/m^2)	0.3
P (Power-law density)	0.1

Outer Disk	
Parameters	**Values**
Inner radius in AU	20
Outer radius in AU	300
Temperature (K)	150
Density (kg/m^2)	0.3
P (Power-law density)	0.36

In the end, the result of the best values chosen to fit the model of the SED with photometric observations is shown in Figure 5.

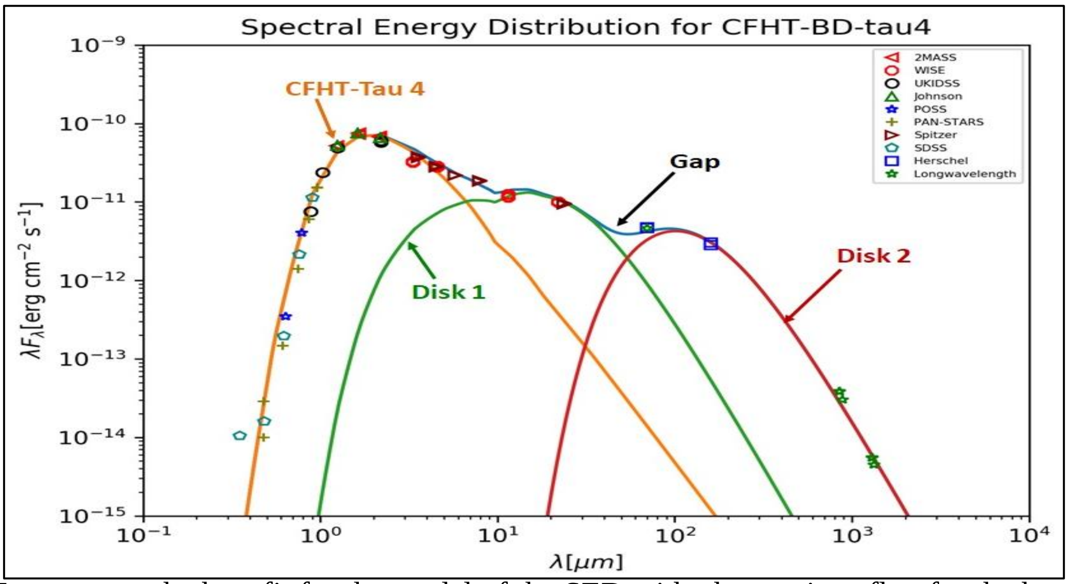


Figure 5: represent the best fit for the model of the SED with observations flux for the brown dwarf CFHT-BD-tau.

Figure 5 shows that the whole model SED of the brown dwarf CFHT-BD-Tau 4. The color points in the plot represent the flux values observed from different telescopes at different wavelengths (optical to sub-millimeter), which have been extracted from VizieR data archive. The lines represent our model of the SED that fits observation points, where the yellow line represents the brown dwarf photosphere, the green line represents the inner disk, the red line represents the outer disk, and the blue line represents the total flux that comes from the whole source.

Transitional disks have been approved around many young stellar objects: low-mass stars, intermediate-mass stars, and brown dwarfs [26,27,28,29,30]. In our model, we have assumed a transitional disk around the brown dwarf CFHT-BD-Tau 4 to fit the theoretical SED with the observational SED as shown in Figure 5.

Interstellar extinction happens when the light of stars goes through Earth's atmosphere. Where the light of stars suffers from absorption and scattering because of the dust and gas particles in the Earth's atmosphere. The interstellar extinction depends on two factors wavelength and dust particle size, therefore should be considered when fitting the SED.

When the value of interstellar extinction is higher for the short wavelengths and smaller for long wavelengths, this is known as "redding". The value of the extinction for our target CFHT-BD-tau that used to fit SED in the V-band is A_v=6.37, then we have used this equation $A_J = A_V/3.55$ to get extinction value in the J-band, which means A_J =1.5 (Mathis, 1990) [31].

4.Conclusions:

1.We have obtained the best visual fitting between the spectral energy distributions of our mathematical model with observational spectral energy distribution for brown dwarf CFHT-BD-Tau 4.

2.The protoplanetary disk geometry consists of an inner optically thick disk with a small puff up in the short infrared wavelength (flared disk). The properties of the outer disk are optically thin, flat, and extend for a large distance of 300 AU.

3.The inner region size in the protoplanetary disk is approximately 4.98 AU and the outer region size is approximately 280 AU.

4.The existence of the gap in some of the protoplanetary disks around brown dwarfs has been approved in different researches. The radius of the gap that splits between two disks (inner and outer disks) is less than 15 AU.

References

[1] Z. Adnan and A. K. Ahmed, " Photometric investigations of NGC 2577 and NGC 4310 Lenticular Galaxies," Iraqi Journal of Science, vol. 59, no. 2C, pp. 1129–1138, June 2018.

[2] S. H. . Ali and M. S. . Shafeq, “Photometric Investigations of Peculiar spiral galaxy NGC 2608 Using Multiband CCD Camera”, Iraqi Journal of Science, vol. 57, no. 3A, pp. 1853–1859, April 2022.

[3] H. R. Al-baqir, A. K. Ahmed, and D. Gamal, "Surface Photometry of NGC 3 Lenticular Galaxy," Iraqi Journal of Science, vol. 60, no. 9, pp. 2080-2086, September 2019.

[4] H. Ali, S. “Photometric Properties of Isolated Spiral Galaxies NGC 4800 and NGC 2715”, Iraqi Journal of Science, 57(3A), pp. 2096–2103, March 2023.

[5] S. S. Kumar, “The Structure of Stars of Very Low Mass,” The Astrophysical Journal, 137, 1121, 1963.

[6] C. Hayashi, T. Nakano,” Evolution of Stars of Small Masses in the Pre-Main-Sequence Stages,” Progress of Theoretical Physics, vol. 30, no. 4, pp. 460–474, 1963.

[7] T. Nakajima, et al., “Discovery of a cool brown dwarf”, Nature, 378, pages 463–465, 1995.

[8] B. R. Oppenheimer, S. R. Kulkarni, K. Matthews, and T. Nakajima,“ Infrared Spectrum of the Cool Brown Dwarf Gl 229B,” Science, Vol. 270, Issue 5241, pp. 1478-1479, 1995.

[9] K. L. Luhman, “Young Low-Mass Stars and Brown Dwarfs in IC 348”, The Astrophysical Journal,. 525, 466, May 1999.

[10] D. Apai, et al.," Grain growth and dust settling in a brown dwarf disk - Gemini/T-ReCS observations of CFHT-BD-Tau 4", Astronomy & Astrophysics, 426 3 (2004) L53-L57, 2004.
[11] E. I. Chiang, P. Goldreich," Spectral Energy Distributions of T Tauri Stars With Passive Circumstellar Disks", The Astrophysical Journal, Volume 490, Issue 1, pp. 368-376, 1997.
[12] Acke, B. and van den Ancker, M. E." ISO spectroscopy of disks around Herbig Ae/Be stars", Astronomy & Astrophysics, 426, 151–170, 2004.
[13] C.P. Dullemond, C. Dominik and A. Natta," PASSIVE IRRADIATED CIRCUMSTELLAR DISKS WITH AN INNER HOLE", THE ASTROPHYSICAL JOURNAL, 560 : 957-969, October 2001
[14] E. L. Martı´n, et al.," FOUR BROWN DWARFS IN THE TAURUS STAR-FORMING REGION", The Astrophysical Journal, 561:L195–L198, November 2001.
[15] M. Gomez, et al.," On the spatial distribution of pre-main-sequence stars in Taurus", Astronomical Journal, vol. 105, no. 5, p. 1927-1937, 1993.
[16] Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. .," Gaia Data Release 2. Summary of the contents and survey properties", Astronomy & Astrophysics, 616, A1 2018.
[17] F. Mokler and B. Stelzer," X-ray emission near the substellar limit: The σ Orionis and Taurus star forming regions", Astronomy & Astrophysics, 391, 1025–1032, 2002.
[18] I. Pascucci, D. Apai, and Th. Henning, "THE FIRST DETAILED LOOK AT A BROWN DWARF DISK", The Astrophysical Journal, 590:L111–L114, June 2003.
[19] R. Klein, et al.," FIRST DETECTION OF MILLIMETER DUST EMISSION FROM BROWN DWARF DISKS", The Astrophysical Journal, 593:L57–L60, August 2003.
[20] P. A. Miles-Páez , et al.," Optical and near-infrared linear polarization of low and intermediate-gravity ultracool dwarfs", Monthly Notices of the Royal Astronomical Society, Volume 466, Issue 3, Pages 3184–3198, April 2017.
[21] R. R. Paudel, et al.," K2 ULTRACOOL DWARFS SURVEY. IV. MONSTER FLARES OBSERVED ON THE YOUNG BROWN DWARF CFHT-BD-TAU 4", The Astrophysical Journal, , 861:76 (7pp), July 2018.
[22] A. M. Rilinger, C. C. Espaillat, and E. Macías, "Modeling the Protoplanetary Disks of Two Brown Dwarfs in the Taurus Molecular Cloud", The Astrophysical Journal, Vol. 878, No. 2, June 2019.
[23] A. M. Rilinger, C. C. Espaillat," Disk Masses and Dust Evolution of Protoplanetary Disks around Brown Dwarfs", The Astrophysical Journal, Vol. 921, No. 2, 2021.

[24] L. Ricci, et al.,"BROWN DWARF DISKS WITH ALMA", The Astrophysical Journal, Vol.791, No. 1, 2014.

[25] Z. ZHANG, et al.," THE PAN-STARRS1 PROPER-MOTION SURVEY FOR YOUNG BROWN DWARFS IN NEARBY STAR-FORMING REGIONS. I. TAURUS DISCOVERIES AND A REDDENING-FREE CLASSIFICATION METHOD FOR ULTRACOOL DWARFS", The Astrophysical Journal, Vol. 858, No. 1, 2018.

[26] A. S. Taha, L. Labadie, E. Pantin, A. Matter, C. Alvarez, P. Esquej, R. Grellmann1, R. Rebolo, C. Telesco and S. Wolf," The spatial extent of polycyclic aromatic hydrocarbons emission in the Herbig star HD 179218", Astronomy & Astrophysics, 612, A15 ,2018.
[27] A. S. Taha, Y. E. Rashed, and A. A. Kadhem, "Resolve partially the inner disk for Epsilon Eridani," Journal of Physics: Conference Series, vol. 1818, no. 1, p. 012031, March 2021.
[28] Á. Ribas, B. Merín, H. Bouy, C. Alves de Oliveira, D. R. Ardila, E. Puga, Á. Kóspál, L. Spezzi, N. L. J. Cox, T. Prusti, G. L. Pilbratt, Ph. André, L. Matrà and R. Vavrek, "Identification of transitional disks in Chamaeleon with Herschel," Astronomy and Astrophysics Journal, vol. 552, no. A115, pp. 1 - 11, April 2013.
[29] C. Espaillat, E. Furlan, P. D'Alessio and et al, "A SPITZER IRS STUDY OF INFRARED VARIABILITY IN TRANSITIONAL AND PRE-TRANSITIONAL DISKS AROUND T TAURI STARS," The Astrophysical Journal, vol.728:49, p. 25, February, 2011.
[30] A.Matter, L. Labadie, A. Kreplin1, B. Lopez, and et al., "Evidence of a discontinuous disk structure around the Herbig Ae star HD 139614", Astronomy & Astrophysics Journal, vol. 561, pp. 627 - 636, January 2014.

[31] J. S. Mathis," Interstellar dust and extinction", Annual Review of Astronomy and Astrophysics, 28, 37-70, 1990.