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Determination of the Physical Properties of the Protoplanetary Disk Around WW Cha Stars

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Abstract

The main goal of this work is to put a simple model of the spectral energy distribution of binary stars called WW Cha. This model is built up on the extracted data from various telescopes and archives for the target WW Cha stars and then analyzing them using a python environment. The result of the fitting proposes that there are two protoplanetary disks around the WW Cha star, with different physical properties for each disk, such as the size of the inner disk being 10 AU, while the size of the outer disk being 300 AU. The shape of the outer disk is a flaring disk not a flat disk according to the value of the power law for the surface density (1.5). The emission in the disk is caused by small amorphous olivine grains ranging in size from 0.1 to 3000 micrometers.

Keywords: Photometry, Binary Stars, Spectral Energy Distribution (SED), Protoplanetary disk, Star, WW Cha.

تحديد الخصائص الفيزيائية للقرص الكوكبي الأولي حول نجوم *WW Cha*

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الخلاصة

الهدف الرئيسي من هذا العمل هو وضع نموذج بسيط لتوزيع الطاقة الطيفية للنجوم الثنائية التي تسمى WW Cha. تم بناء هذا النموذج من البيانات المستخرجة من التلسكوبات وأرشيفات مختلفة للنجوم WW Cha ومن ثم تحليلها باستخدام برنامج بايثون. تم بناء نموذج لتوزيع الطاقة الطيفية ومطابقته مع التوزيع الطاقة الطيفية المرصودة للنجوم الثنائية WW Cha. نتائج المطابقة افترضت بوجود قرصين كوكبيين أوليين حول النجم الثنائي WW Cha ومنها تم الحصول على الخصائص الفيزيائية لكل قرص مثل حجم القرص الداخلي هو تقريبا 10 وحدة فلكية، بينما حجم القرص الخارجي هو 300 وحدة فلكية. ان شكل القرص الكوكبي يزداد ارتفاعة كلما زادت المسافة عن النجم وليس مسطح وذلك استنادا الى قيمة الاسية لكثافة سطح القرص (1.5). وان الانبعاثات الصادرة من القرص الكوكبي هي ناتجة من وجود حبيبات صغيرة من الزبرجد الزيتوني الغير متبلور والتي حجمها يتراوح بين 0.1 إلى 3000 مايكرومتر.

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Introduction

This study came to examine WW Cha (which is known as T44) located in the Chamaeleon cloud complex, and it is a T Tauri star. It is located in the southern sky with coordinates of right ascension $11^h\ 10^m\ 00.1^s$ and declination $-76^o\ 34'\ 57.9638''$ (J2000.0)[1].

There are several studies conducted in Iraq, especially at the Astronomy and Space Department, College of Science, University of Baghdad. These studies were focused on the photometry and spectral field; the most important ones were (Adnan and Ahmed 2018), (Y. Rashed, J. Zuther, A. Eckart et al. 2013), (A. Ahmed, G. Ali, and M. Amin 2014) [2, 3, 4]. Another study by (Al-baqir, Ahmed, and Gamal 2019) examined the photometric properties of two types of galaxies (spiral and elliptical galaxies) using surface photometric techniques with griz-filters, the same technique studied NGC 3 lenticular galaxy[5]. On the other hand, (Taha et al. 2018) and (Taha et al. 2021) [6,7], investigated the properties of the protoplanetary disk around one of the Herbig stars, HD 179218, and presented mid-infrared imaging observations of the debris disk around one of the main sequence stars, Epsilon Eridani, in the Q-band at (20.5 µm) and (17.6 µm).

Beside these studies, a numerical simulation was carried out to investigate the possibility of observing an extrasolar planet nearby star via optical telescopes by (Jallod and Mohammed 2013, A. Talib, A. D'Onofrio, and F. Terrasi 2017) [8,9].

In 1992, Gauvin classified WW Cha as a spectral type K5 for the first time after using the observations data from the IRAS (The Infrared Astronomical Satellite) space telescope at three filters: 12µm, 25µm, 60µm, and 100µm [1].

The temperature of the star's surface is 4350k, and the star is at a distance of 190 pc from the Earth[10]. The luminosity of the star is $11L_\odot$, and the mass of the star is 1M [11].

The object WW Cha was observed by using ATCA (Australia Telescope Compact Array) at wavelengths 3, 7, and 17 millimeters. Observations showed that there is a thermal emission from millimeters size of the grains to centimeters which indicates that this emission comes from the protoplanetary disk [12]. The data of the observations from Herschel at wavelengths WISE (*Wide-field Infrared Survey Explorer*) 12 µm - PACS(PACS (Photoconductor Array Camera and Spectrometer) 70 µm showed that WW Cha is an embedded object and for this reason probably could not detect a transitional disk [13]. The previous observations supposed that WW Cha is a single star until 2015 when the new observations discovered that WW Cha has a very close companion at 1 A.U [14]. The age of the star was estimated to be 0.4Myr, the extinction was extracted as $A_j = 1.35$ [14].

Recently, interferometry techniques were used by Very Large Telescope Interferometer (VLTI) with a different instrument in near- infrared to study WW Cha stars. The orbital elements and total mass were extracted as follows: semi-major axis a=1.01 au, high eccentricity e=0.45, inclination i= 37.7°, and the longitude of node Ω =37.7. The time period of the second star around the primary stars has been calculated to be T=206.55 days [15] .

The observation of the WW Cha by using ALMA (Atacama Large Millimeter/Sub-millimeter Array) at 6 bands showed an asymmetric structure for the disk, no gap between the rings in the disk, and there were two peaks of emission at 40 and 70 AU [16].

The Spectral Energy Distribution (SED) represents the relation between the flux density observed from young stellar objects and the wavelength. One of the most important and easy ways to study young stellar objects is by SED. Therefore, the SED is used to classify young stellar objects for different types according to the shape of the SED [17]. Spectral energy distribution fitting is very important in the study of protoplanetary disk around single stars and binary stars.

The aim of this paper is to extract the physical properties of the two protoplanetary disks around WW Cha stars such as temperature, density, size, scale height, and chemical compositions of the disks using SED fitting.

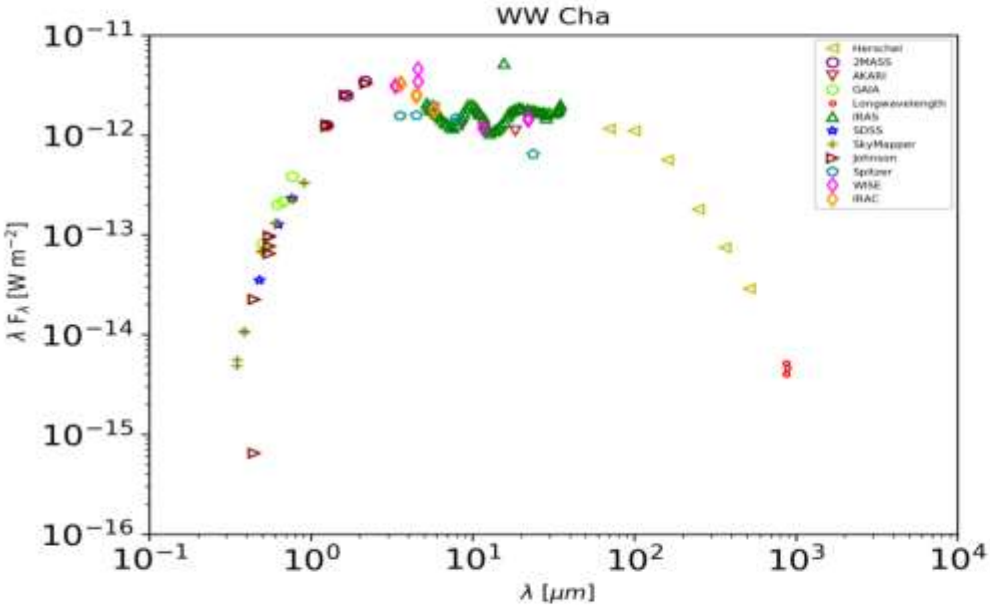

Figure 1: The flux density of the binary in the unit (W/m^2) as a function of wavelength (micrometer), for the binary stars WW Cha from different telescopes.

Data and Reduction

The SED observations for our target WW Cha have been extracted from numerous telescopes; space and ground-based telescopes. All the data can be found in the Vizier data archive (https://vizier.u-strasbg.fr/viz-bin/VizieR). We have built a code in Python to plot the flux density of the target with wavelength, as shown in Figure (1).

There are some exaggeration points (out of the shape of the SED) in the observational data of the SED, as shown in Figure (1). Therefore, we have discarded them from the data to get a better plot for the observational SED. These discarded points do not affect the shape of the SED, as shown in Figure (2).

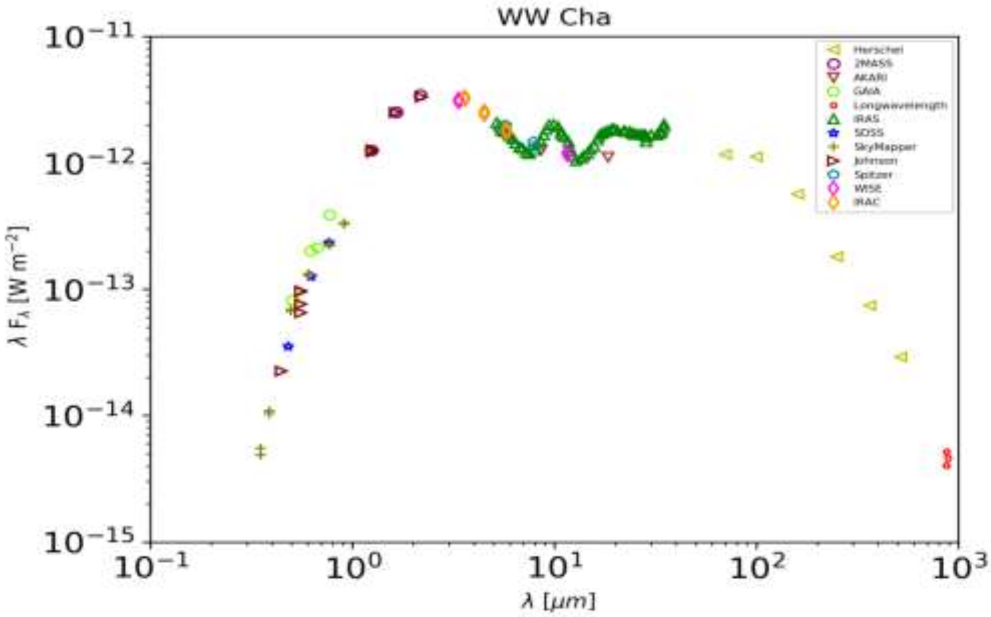

Figure 2: The result of the re-plot of Figure (1) with less number of points.

Modeling of Flux and Temperature Gradient

All of the flux coming from the star and the disk at the different regions on the disk can be expressed mathematically as black body radiations; as given by [17]:

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k T_*}} - 1} \qquad \text{--------------- (1)}$$

Where c is the speed of light, h Planck constant = 6.6261*10^{-34} m^2 Kg/s, k =1.3806*10^{-23} m^2 Kg/s k,
λ is the wavelength, T_* is the temperature of the star.

The star is surrounded by dust and gas materials from all directions; therefore, the starlight will be affected by absorbing and scattering before it reaches the Earth. The extinction A_λ is related to the apparent magnitude of the observed object, as represented by [17]:

$$m_\lambda = M_\lambda + 5 \, log \left(\frac{d}{10 \, pc}\right) + A_\lambda \qquad \text{-------------(2)}$$

Where m_λ is the apparent magnitude of the object. M_λ is the absolute magnitude as a distance of 10 pc. d is the distance of the star in parsecond. A_λ is the extinction at a specific wavelength and can be described for the V band (i.e. $A_\lambda = A_V$) using this formula [*18*]:

$$A_V = E_{B-V} \, . R \qquad \text{--------------------(3)}$$

Where E_{B-V} represents the color excess and it is the different magnitudes at different bands. R equal to be 3.1.

By substituting equation 2 into equation 1, the final flux radiation of the star has a surface temperature (T_*), and it can be expressed by [*18*]:

$$F_{\lambda,star} = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT_*}}-1}.10^{(0.4A_\lambda)}.\frac{\pi R_*^2}{(1''.\ d)^2} \qquad \text{------------------ (4)}$$

Where $F_{\lambda,star}$ represents the flux of the star at specific wavelength, R_*^2 is the radius of the star in AU, $(1''.\ d)$ is the angle at distance d to the star ($1''=\frac{\pi}{64800}rad$).

The flux that emits from the disk around the star is not equal in all places in the disk. The center star heats the disk, so the temperature on the disk depends on the distance from the star. Therefore, the temperature in the disk is assumed to be a gradient, and the temperature at a specific radius from the star is given by [18]:

$$T(r) = T_0\left(\frac{r}{r_0}\right)^{-q} \qquad \text{-------------------------(5)}$$

Where T_0 is the temperature at radius r_0, r_0 is the distance at 1 AU. q is the exponent of the power law. The value of the flaring disk is 0.5 (flaring disk means increasing the high scale of the disk with a distance from the star), and the value of the flat disk is 0.75 (flat disk means the high scale of the disk remains constant without change with distance from the star).
The flux that comes from the whole disk can be calculated using the equation [19]:

$$F_{\lambda,disk} = \frac{\pi}{(1''.\ d)^2}\int_{r_{in}}^{r_{out}} r\, B_{\lambda,ext}(T_{disk}(r))\epsilon_{\mathcal{T}}\ dr \text{-------------(6)}$$

Where r_{in} and r_{out} are the limit of the integration, r_{in} is the inner radius of the disk and r_{out} is the outer radius of the disk. ϵ_T is the emissivity factor (ϵ_T=1- e-T) and dependent on the optical depth of the disk [18]:

$$\mathcal{T}_\lambda(r) = \frac{\mathcal{K}_\lambda}{\cos(i)}\sum(r) \text{--(7)}$$

Where K_λ is the opacity of the dust in the disk, i is the inclination of the disk toward the observer. If $i = 0^o$ means the disk observed face-on, but when $i = 90^o$ means the disk observed face-off.
$\sum$ (r) represents the surface density of the disk and can be described by using this equation [20]:

$$\sum(r) = \sum_{in}\left(\frac{r}{r_{in}}\right)^{-p} \qquad \text{--------------(8)}$$

$\sum_{in}$ represents the surface density of the inner disk.

Result and Discussion

The total flux from the star and the disk would be $F_{\lambda,total} = F_{\lambda,star} + F_{\lambda,disk(i)}$. We have used a Python code that has been built by Eupen to make a SED model and plot $\lambda\ F_{\lambda,total}$ against λ, then fit the model of the SED with the observations of the SED for the binary WW Cha. The result of the SED fitting is shown in Figure (3).

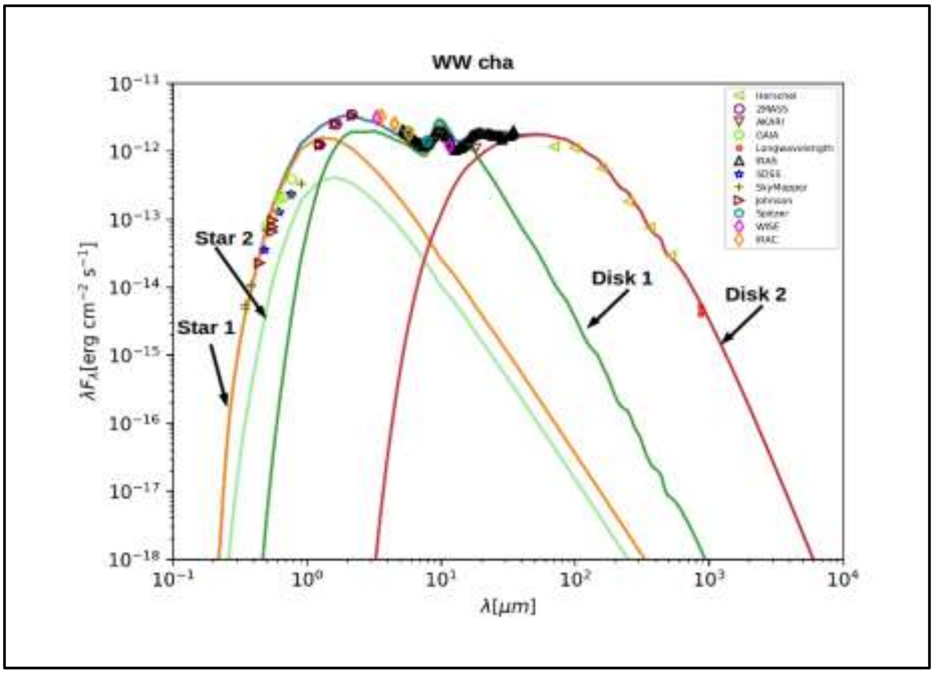

Figure 3: Fitting the model of the spectral energy distribution with observational flux for the WW Cha stars.

The lines represent the model of the SED and point in different shapes that represent the observational SED.

The model that we have used to fit the observational SED is based on assuming binary stars in the system with two protoplanetary disks without a gap between the two disks. The plot in Figure (3) shows that the blue line represents the total model flux from the binary stars and the two disks. The orange line represents the photosphere flux from the first star, and the light green line represents the photosphere flux from the second star. The dark green line is the thin inner disk, and the red line is the thick outer disk.

We have assumed that the inner radius of the disk is 0.32 AU, and the outer radius of the inner disk is 10 AU. The model of the SED for the inner disk shows that most of the emission comes from the inner radius, as shown in Figure (3). In addition to that, the emission in the inner disk is dominant in the spectral energy distribution compared to the binary stars. We have also assumed that the inner radius of the outer disk is 3 AU and the outer radius of the outer disk is 300 AU.

According to the many researches about the chemical composition of dust particles in the protoplanetary disk, the dust particles consist of the silicate dust mixtures olivines, pyroxenes, forsterite, and enstatite [*21*,*22*]. We have supposed that the chemical composition is amorphous olivine for the dust particles in the protoplanetary disk around WW-Cha binary stars.
Some values for the input parameters are taken from recent studies; such as the distance of the star is 190 pc, according to the new measurements from Gaia telescope [*20*]. The inclination and longitude of node Ω =37.7 are taken from [*16*]. The best input parameters used to fit the observational spectral energy distributions with the model of the spectral energy distributions for WW Cha stars are listed in table (1):

Table 1: The binary stars and two disks parameters that have been used to fit the SED for the WW Cha stars

(a) Input parameters for the first star. .

Parameters	Value
Temperature (T_*)	3350 K
Radius of the star	3 $R_\odot$
A_j (Extinction)	1.3

(b) Input parameters for the second star

Parameters	Value
Temperature (T_*)	4450 K
Radius of the star	4 $R_\odot$
A_j (Extinction)	1.3

(c) Input parameters for the inner disk

Parameters	Value
Temperature (T_*)	680 K
R_{in}	0.23 AU
R_{out}	10 AU
Size of disk	9.77 AU
P (surface density)	1.1
q (flaring disk)	0.54
Density	0.1 kg/m^2

(d) Input parameters for the outer disk.

Parameters	Value
Temperature (T_*)	350 K
R_{in}	3 AU
R_{out}	300 AU
Size of disk	297 AU
P (surface density)	1.5
q (flaring disk)	0.5
Density	70 kg/m^2

Conclusions

1. The inner disk in the SED starts to emit in the near infrared and mid-infrared. The peak of the emission in the inner disk is at 10 µm, we have fitted the peak by selecting the value for the power law of the surface density (p) a positive value (p=1.1). If we have selected the negative value of the power law, it would not have shown that much increase in the emission at 10 µm.
2. Most of the emission in the outer disk comes from the far infrared and sub-millimeter wavelengths. The power law of the surface density is positive (p=1.5), the disk is flaring.
3. The surface layer of the inner disk is hotter than the surface layer of the outer disk. The temperature in the inner disk is (680 k), and in the outer disk is (350 k).
4. The value of the surface density in the outer disk is (70 kg/m^2) while the value of the surface density in the inner disk is (0.1 kg/m^2). That means that the outer disk is denser than the inner disk.

References

[1] L. S. Gauvin, and K. M. Strom, "A Study of the Stellar Population in the Chamaeleon Dark Clouds ," *The Astrophysical Journal*, vol.385 , pp. 217–231, January 1992.

[2] Z. Adnan and A. K. Ahmed, "Surface Photometry of Spiral Galaxy NGC 5005 and Elliptical Galaxy NGC

4278," *Baghdad Science Journal*, vol. 15, no. 3, pp. 314-323, September 2018.

[3] Y. E. Rashed, J. Zuther, A. Eckart and and et al., "High-resolution observations of SDSS J080800.99+483807.7 in the optical and radio domains," *Astronomy & Astrophysics Journal*, vol. 558, A. 5, 2013.

[4] A. K. Ahmed, G. B. Ali and M. Y. Amin "Detailed Surface Photometry of the Spiral Galaxies NGC 7339, NGC 7537, and NGC 7541," *International Journal of Advanced Research*, vol. 2 no. 1, pp. 1103-1121, Jan 2014.

[5] 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.

[6] A. S. Taha, L. Lucas. L. Pantin, and et al., "The spatial extent of polycyclic aromatic hydrocarbons emission in the Herbig star HD 179218," *Astronomy & Astrophysics Journal*, vol. 612, A.15, 2018.

[7] 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.

[8] U. E Jallod and A. T. Mohammed, "Computer Simulations of Direct Imaging of Extrasolar Planets," *Iraqi Journal of Science*, vol. 54, no. 2, pp. 493-501, 2013.

[9] A. Talib, A. D'Onofrio, F. Terrasi, "Methods and Simulations used to Detect Photons from Exoplanets of a Parent Star," *Iraqi Journal of Science*, vol. 58, no. 2B, pp. 961-970, 2017.

[10] S. J. Kenyon and L. Hartmann, "Pre-main-sequence evolution in the Taurus-Auriga molecular cloud," *The Astrophysical Journal Supplement Series*, vol. 101, p. 117, 1995.

[11] K. L. Luhman, "The Stellar Population of the Chamaeleon I Star-forming Region," The Astrophysical Journal Supplement Series, vol. 173, pp. 104 -136, November 2007.

[12] D. Lommen, S. T. Maddison, C. M. Wright and et al., "Large grains in discs around young stars: ATCA observations of WW Chamaeleontis, RU Lupi, and CS Chamaeleontis," Astronomy and Astrophysics Journal, vol. 495, pp. 869-879, March 2009.

[13] Á. Ribas, B. Merín, H. Bouy and et al., "Identification of transitional disks in Chamaeleon with Herschel," *Astronomy and Astrophysics Journal*, vol. 552, no. A115, pp. 1 - 11, April 2013.

[14] F. Anthonioz, F. Ménard, C. Pinte and et al., "The VLTI/PIONIER near-infrared interferometric survey of southern T Tauri stars. I. First results," Astronomy & Astrophysics Journal, vol. 574, no. A41, pp. 1-18, February 2015.

[15] F. Eupen, "Interferometric Observations of the Circumstellar Disk Environments in Close Binary Stars," in Take a Closer Look, Köln, November 2018, p. 72, https://doi.org/10.5281/zenodo.1488912.

[16] K. D. Kanagawa, J. Hashimoto, T. Muto and et al., "ALMA Observation of the Protoplanetary Disk around WW Cha: Faint Double-peaked Ring and Asymmetric Structure," *The Astrophysical Journal*, vol. 909, p. 212, March 2021. [Online]. https://doi.org/10.3847/1538-4357/abdfc5

[17] S. W. Stahler and F. Palla, The Formation of Stars, 1st ed. Federal Republic of Germany: WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2004.

[18] F. Malbet, R. Lachaume, J.-P. Berger, and et al, "New insights on the AU-scale circumstellar structure of FU Orionis," *Astronomy & Astrophysics Journal*, vol. 437, pp. 627 - 636, July 2005.

[19]] 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.

[20] A. G. A. Brown, A. Vallenari, T. Prusti and et al., "Gaia Data Release 2 - Summary of the contents and survey properties," A&A, vol. 616, no. A1, pp. 1- 22, August 2018. [Online]. https://doi.org/10.1051/0004-6361/201833051

[21] 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.

[22] A. Schegerer, S. Wolf, N. V. Voshchinnikov and et al., "Analysis of the dust evolution in the circumstellar disks of T Tauri stars," Astronomy & Astrophysics Journal, vol. 456, pp. 535–548, May 2006.