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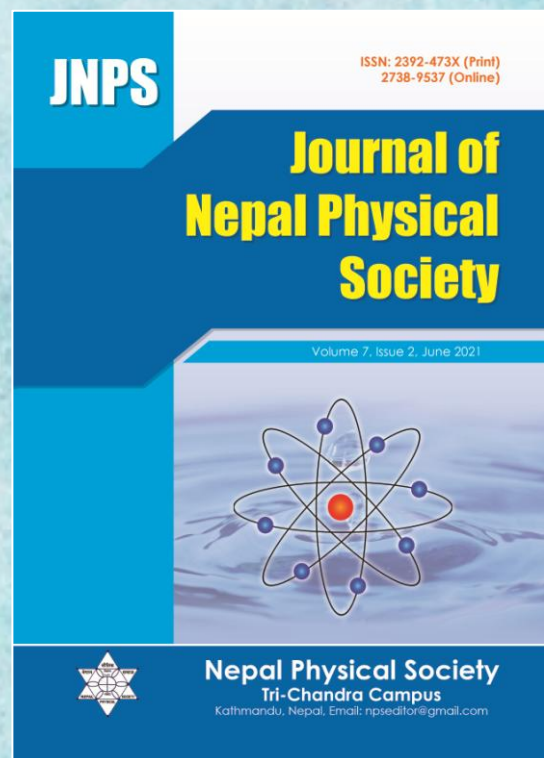
Study of Dust Cavity around the White Dwarf WD 0352-049 in Infrared Astronomical Satellite Map

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ABSTRACT

In this work, we have studied the far-infrared images of the dust cavity around the White Dwarf WD 0352–049 available in Infrared Astronomical Satellite Map from Sky View Observatory. The size of the cavity is 24.48 pc × 8.10 pc. We have studied the relative infrared flux density and calculated the dust color temperature and dust mass. The temperature of the whole cavity structure lies between a maximum value 24.09 ± 0.50 K to a minimum 21.87 ± 0.61 K with fluctuation of 2.22 K and an average value of 23.09 ± 1.11 K. The small fluctuation of dust color temperature suggests that the dust in cavity structure is evolving independently and less disturbed from background radiation sources. The color map shows the identical distribution of flux at 60 μm and 100 μm and the inverse distribution of dust color temperature and dust mass. There is a Gaussian-like distribution of relative flux density, dust color temperature and dust mass. The Gaussian distribution of temperature suggests that the dusts in cavity are in local thermodynamic equilibrium. The study of relative flux density and dust color temperature along the major and minor axis shows there is a sinusoidal fluctuation of flux and temperature, which might be due to the wind generated by White Dwarf located nearby the center of the cavity structure. The total dust mass of the dust is found to be 0.07 $M_\odot$ and that of gas is 13.66 $M_\odot$. The Jeans mass of the structure is less than the total mass of gas in the structure, suggesting the possibility of star formation activity by gravitational collapse in the future. Also, the study of inclination angle suggests that the three-dimensional shape of the structure is uniform and regularly shaped.

Keywords: White Dwarf, Infrared, Dust Cavity, Dust Color Temperature, Dust Mass.

1. INTRODUCTION

Infrared astronomy is the branch of astronomy that studies the infrared source in the galaxy utilizing the properties of infrared bands of electromagnetic radiation. The infrared band covers the range of wavelength from 0.7 μm to 1000 μm in the electromagnetic spectrum. The ubiquitous source of infrared light in the galaxy is the dust which blends almost uniformly within the interstellar medium (ISM). Dust absorbs the ultraviolet radiation emitted from nearby sources and reradiates it in the infrared band. Dust is an important component of ISM because it controls the chemistry and thermal process in ISM. Also, the possibility of the formation of the earth like the planetary system is possible due to the presence of dust in ISM.

Interstellar dust forms during the post-main sequence evolution phase of the star. Most of the ejected mass from stars due to stellar wind remains as dust in ISM. However, this mechanism contributes a very less fraction of interstellar dust. The majority of dust are formed by accretion and coagulation of grains in the cold region of ISM and many processes are still unknown.

In the late phase of the post main sequence evolution of an intermediate-mass star, the compressed core remains as a White Dwarf with an envelope of dust surrounding it, called a planetary nebula. The study of dust around White Dwarf can reveal important archeological information about the White Dwarf and parent star from which it is formed.

Infrared Astronomical Satellite (IRAS) (https://www.jpl.nasa.gov) is the first-ever space-based telescope that studies infrared astronomical sources. It has many groundbreaking discoveries and many sources are still waiting for identification [1]. The study of dust emission can decode the prehistoric information of stellar evolution. Recently, a study of huge dust emission regions around the evolved planetary nebula NGC 1514 and its bipolar dust jets concluded that the study of dust emission regions can reveal the prehistoric information of all phases of mass loss in intermediate-mass star [2]. The study of dust structure around White Dwarf WD 0253+209 using IRAS 60 μm and 100 μm images concluded that the dust structure is formed due to the interaction between the post AGB winds of the White Dwarf [3].

In this work, we have studied the dust cavity like structure around the White Dwarf WD 0352−049, located at Galactic Longitude; 194.33^o and Galactic Latitude; − 40.92^o, using 60 μm and 100 μm IRAS images. This WD 0352−049 is also recognized as SDSS J035514.53−044930.2 (http://simbad.u-strasbg.fr/simbad/). The relative flux, dust color temperature, dust mass, and their analysis within the dust cavity like structure are presented in this work.

2. METHODOLOGY

2.1. Estimation of Dust Color Temperature and Dust Mass

The dust color temperature is estimated by knowing the ratio of the relative flux density at 60 μm and 100 μm, R, using the following formula [4],

$$T = \frac{-96}{\ln[R \times 0.6^{(3+\beta)}]} \; ... (1)$$

Where, β is called spectral index, which values varies from 0 to 3, 0 for perfect blackbody, 1 for amorphous layer−lattice and 2 for metals and dielectric crystals. In this work we have used the value 2 assuming the dust grain as the dielectric crystal [5].

The inverse relation between dust color temperature and spectral index describes the by the hyperbolic function given as [5],

$$\beta = \frac{1}{\delta + \omega T} \; ... (2)$$

Where, δ and ω are the free parameters, having values 0.40 ± 0.02 and 0.00079 ± 0.0005 K^{-1} [5].

Once we know the dust color temperature and distance to the structure we can calculate the mass of dust using the formula given by [6, 7],

$$M_{dust} = \frac{4a\rho}{3Q_v}\left[\frac{S_v D^2}{B(v,T)}\right] = 0.4\left[\frac{S_v D^2}{B(v,T)}\right] \; ... (3)$$

Here, a = weighted grain size = 0.01 μm [7] , ρ = grain density = 3000 kg/m^3 [7] , Q$_v$ = grain emissivity at 100 μm = 0.001 [7], S_v= absolute flux = F(100 μm) × MJy/Str × 5.288 × 10^{-9} and 1 MJy/Str = 1 × 10^{-20} kg/s^2 in SI unit [7], D = distance, $B(v, T)$ = Planck's function of blackbody radiation.

2.2. Inclination Angle

The inclination angle is the angle between the line of slight and the normal vector of the plane of the cavity structure. This is estimated by using the Holmberg (1946) [8] formula given by,

$$\cos^2 i = \frac{\left(\frac{b}{a}\right)^2 - (q^*)^2}{1 - (q^*)^2} \; ... (4)$$

Here, $\frac{b}{a}$ is the ratio of the minor and major axis of the dust cavity, called axial ratio, and q^* is intrinsic flatness.

2.3. Jeans Mass and Jeans Criteria

Jeans mass gives the limiting value of the mass of the clouds for the cloud to collapse due to its gravity. If the mass of the cloud is more than the limiting mass or Jeans mass then the cloud might be collapsed due to its own gravity. The Jeans mass can be calculated as [9],

$$M_J = \left(\frac{kT}{m_H G}\right)^{3/2}\frac{1}{\rho^{1/2}} \; ... (5)$$

Where, k is the Boltzmann constant, m_H is the mean molecular weight of Hydrogen, G is the universal gravitational constant and ρ is the density of the dust.

To calculate the density of our dust cavity structure, we use the formula given as [9],

$$\rho = \left(\frac{3}{4\pi}\right)^{2/3}\frac{kT}{m_H G R^2} \; ... (6)$$

Where, R is the average size of the cavity structure.

3. RESULTS AND DISCUSSION

3.1. Structure: Contour Map and Scatter Plot

IRAS images of moderate resolution at Galactic Longitude: 190.22^0 & Galactic Latitude: -40.50^0 are extracted from the IRAS server in Groningen [10] and the FITS image at 60 μm and 100 μm taken from Sky View Observatory (http://skyview.gsfc.nasa.gov). The FITS images are processed in ALADIN 2.5 [11] software. We draw two contours with levels 47 and 20. There are

793 pixels inside contour Outer–47, all pixels are included for study.

The contour map of the dust cavity structure with contour level is shown in Fig. 3.1 (left). The map also explores the position of White Dwarf WD 0352–049, center of cavity structure, major and minor axis. The scatter diagram of the dust cavity structure is shown in Fig. 3.1(right). Each points represent a single pixels under study. The shape of the scatter plot resembles the shape of the Outer–47 contour in the contour map.
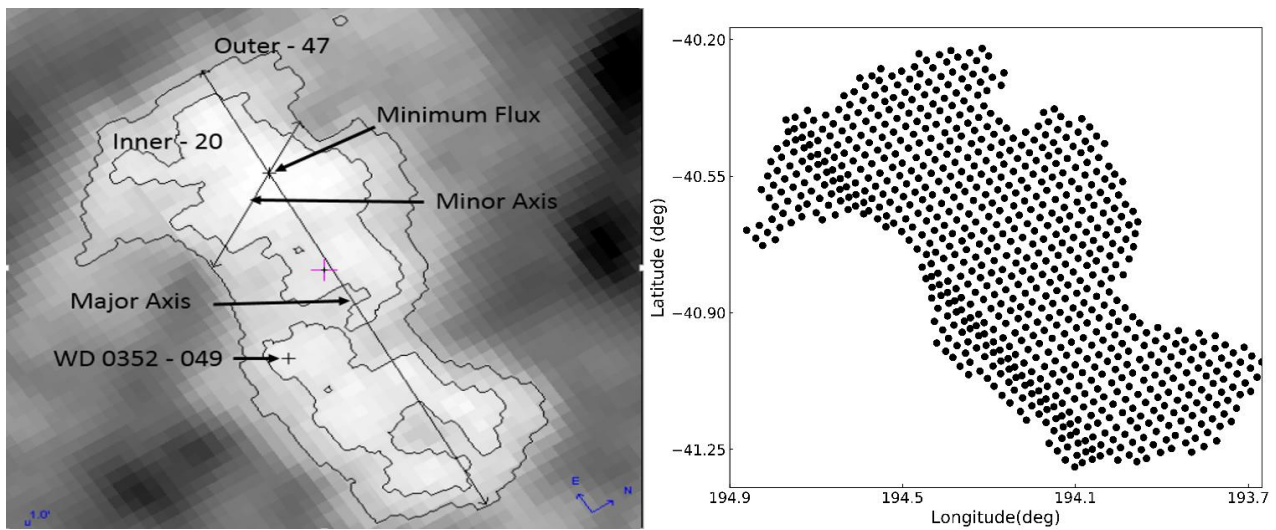
Fig. 3.1: Left: The image of the dust cavity structure with contours drawn on it in ALADIN 2.5. Right: The data points inside the Outer–47 contour with Galactic Longitude and Latitude along X and Y–axis respectively. There are 793 points, each represents single pixel.

3.2: Dust Color Temperature and Dust Mass

The dust color temperature and dust mass of each 793 pixels have been calculated by using equations (1) and (3) respectively. The maximum and minimum temperature within the cavity structure is found 24.09 ± 0.50 K and 21.87 ± 0.61 K respectively, with a range of 2.22 K and an average value of 23.09 ±1.11 K. The average temperature suggests that the dust cloud is not cirrus type cloud and the range of temperature less than 5 K suggests that the dust in cavity structure is evolving independently and less disturbed from external radiation sources.

For the calculation of dust mass, we use the distance to the structure 1219 pc using SIMBAD (http://simbad.u-strasbg.fr/simbad/). The total dust mass of all pixels with the structure is 1.36×10^{29} kg (0.07 M$_\circ$). The mass of the gas in ISM is nearly 200 times the mass of the dust [12]. Using this

concept, the mass of gas is calculated 2.72×10^{31} kg (13.66 M$_\circ$).

3.3: Infrared Flux, Temperature and Spectral Index

A linear relationship between two infrared fluxes, at 60 μm and 100 μm, can give the average temperature of the cavity structure. The relative infrared flux taken from IRAS image are plotted taking flux at 100 μm along X–axis and flux at 60 μm along Y–axis. The data are fitted for the straight line passing through the origin, as shown in Fig. 3.2 (a). The value of regression coefficient, R, for the best fit straight line is 0.50 indicating a good relationship between the data points.

The slope of the straight line represents the average ratio of relative flux at 60 μm and 100 μm. The equation representing the linear relation between 60 μm and 100 μm flux is,

$$F(60) = 0.20\, F(100) \dots (7)$$

Using the slope of the straight line 0.20 to get the average dust color temperature of the cavity structure, we get dust color temperature 23.12 K. The average value of temperature from both methods is almost equal to each other.

We have also analyzed the relation between dust color temperature, T, and spectral index, β. By taking the value of spectral index from 0 to 3 [5], in the difference of 0.1. We have calculated the corresponding dust color temperature using equation (1). We wanted to check the hyperbolic relation between T and β as given by equation (2).

We have fitted the hyperbolic function as well as parabolic function for our data set (T, β). The best fit lines for two function is shown in Fig. 3.2 (b). The correlation coefficient, R, for hyperbolic fit and parabolic fit, are 0.89 and 1.0 respectively. Our data set (T, β) fit perfectly in parabolic function as well as a very good fit for hyperbolic function. The value of free parameters δ and ω in our case have been calculated −2.04 and 0.11 respectively. This result supports the inverse relation between dust color temperature and spectral index as suggested by equation (2).
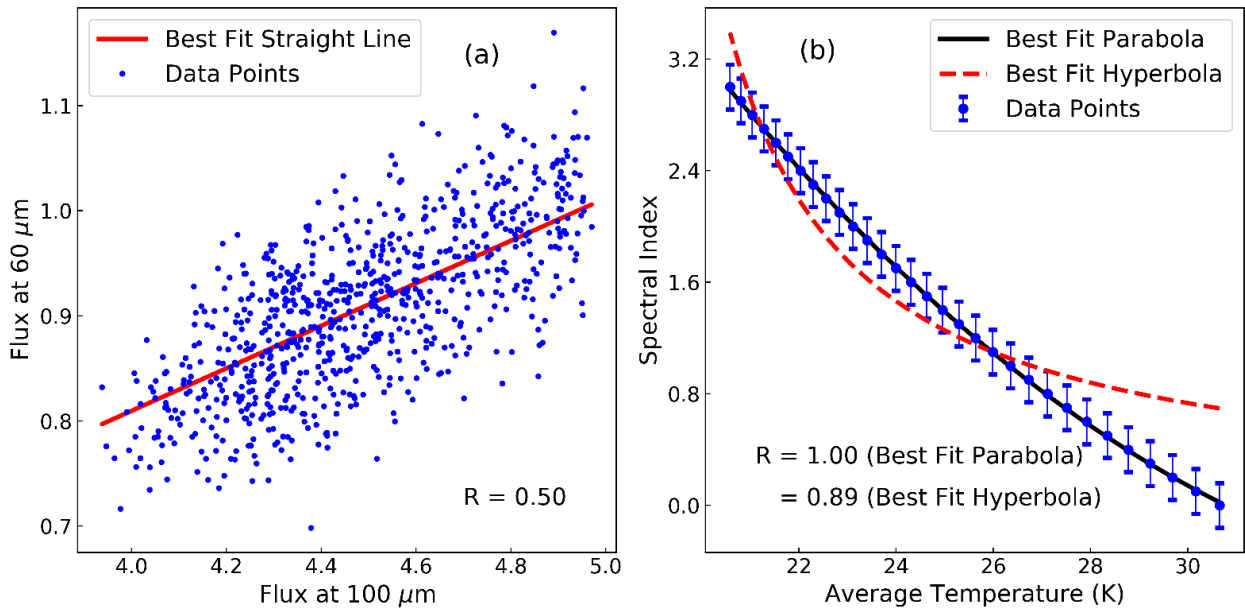
Fig. 3.2: Left (a)**:** Best fitted straight between the relative flux density at 60 μm and 100 μm. Relative flux at 100 μm is taken along X–axis and relative flux at 60 μm is taken along Y–axis. Right (b): Showing the inverse relationship between temperature (along X–axis) and spectral index (along Y–axis). The dashed red curve represents the best fit hyperbola and solid black curve represents the best fit parabola. The error bar represents the standard error on β. In both graph, R represents the correlation coefficient.

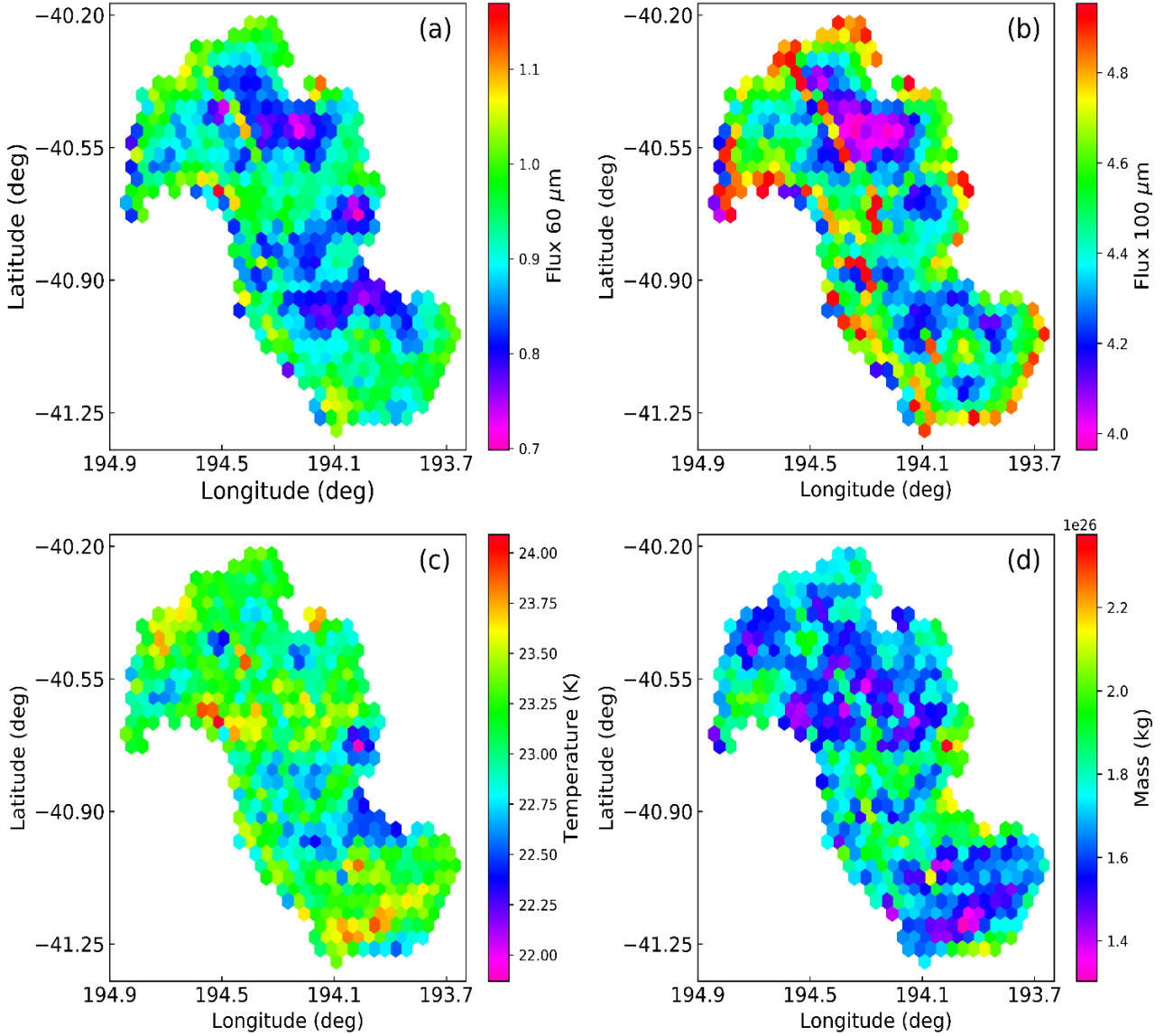### 3.4: Color Map: Relative Flux Density, Dust Color Temperature and Dust Mass

The data of relative infrared flux density at 60 μm and 100 μm extracted using ALADIN 2.5 [11], dust color temperature and dust mass within 793 pixels in cavity structure are studied using the color map. The color map for relative flux at 60 μm and 100 μm, dust color temperature and dust mass are shown in Fig. 3.3.

The color map clearly shows the identical distribution for relative flux at 60 μm and 100 μm however, the magnitude of flux is different, less in 60 μm and more in 100 μm. In general, the IRAS

images at 60 μm have less flux density than in 100 μm images. The identical distribution of these two infrared fluxes indicates the similar chemical composition of dust within the cavity structure, probably produced from WD 352–049 during the AGB phase.

The color plot of temperature and mass clearly exhibits the inverse relation, i.e., the mass density for cold dust is high and vice versa. This result represents that around the White Dwarf WD 0352–049 the cold dusts are heavier than the hot dust, generally observed around low–pressure regions in ISM.
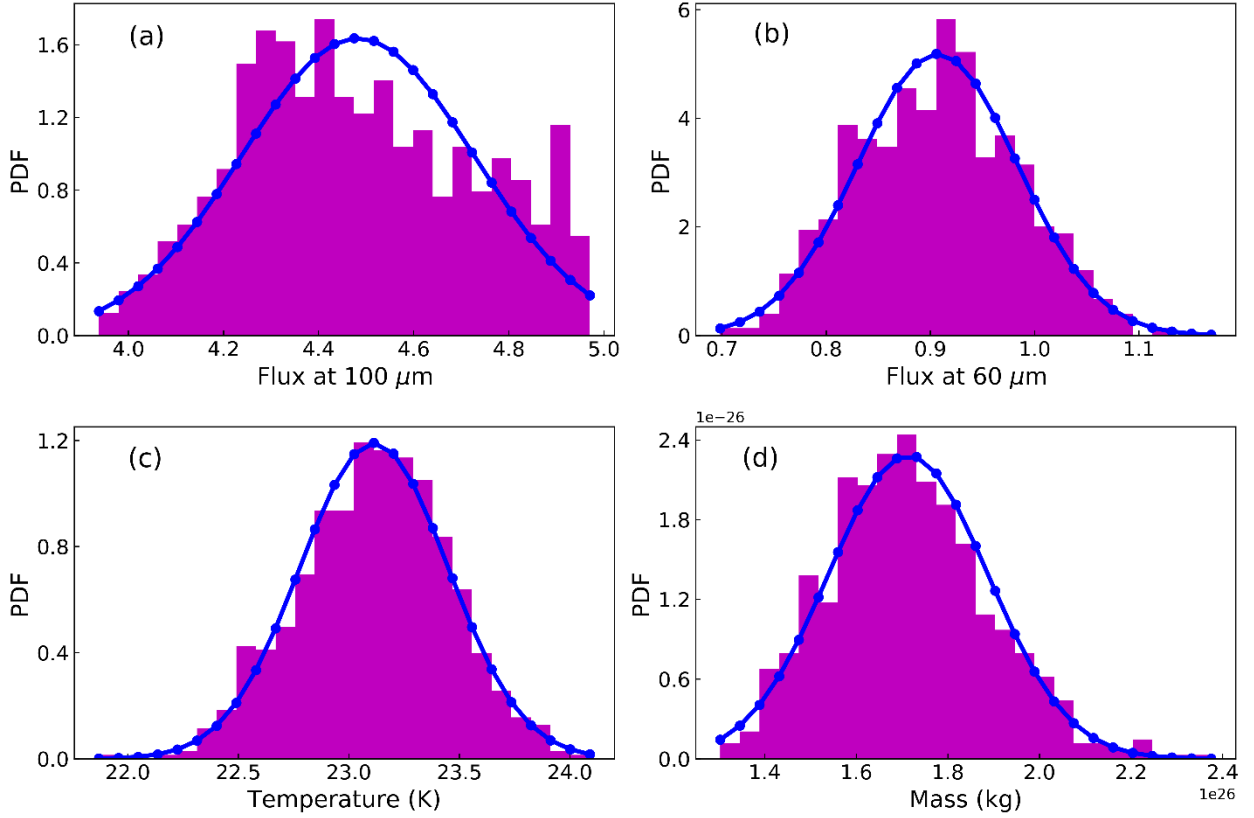
Fig. 3.3: Color map of the relative flux density at 60 μm (a) and 100 μm (b), dust color temperature (c) and dust mass (d). In all color map, Galactic Longitude is taken along X–axis Galactic Latitude is along Y–axis and the other variables (flux, temperature, mass) are taken in the color bar.

3.5. Gaussian Plot of Flux, Dust Color Temperature, and Dust Mass

The data of relative infrared fluxes, temperature, and mass of each pixel are binned with bin size 25 to study the Gaussian distribution of data with a histogram. The Gaussian distribution for each data is shown in Fig. 3.4. The distribution of flux at 60 μm and temperature are fit well with Gaussian nature, whereas the distribution of flux at 100 μm and dust mass slightly deviates from Gaussian nature.

The Gaussian distribution of relative flux at 60 μm and 100 μm indicates that the emitters of short wavelength infrared light are more symmetrically distributed than the emitters for long wavelength infrared light. From this, it can be inferred that the small size dust grains are more symmetrically distributed than the large dust grains around the White Dwarf WD 0352–049. From Gaussian distribution of temperature, we can conclude that the temperature distribution is symmetric and the dusts within the cavity structure are in local thermodynamic equilibrium. Also, it might be due to similar chemical composition of dust within the cavity structure.

Fig.3.4: Gaussian distribution with histogram for the relative flux density at 100 μm (a) and 60 μm (b), dust color temperature (c) and dust mass (d). In all plot the data (fluxes, temperature, mass) are taken along X−axis and probability density function (PDF) is taken along Y−axis. The graph for flux density at 60 μm and dust color temperature are close to Gaussian distribution.

3.6. Variation of Flux and Temperature along Major and Minor Axis

The minimum relative flux density in 100 μm FITS image is located at Galactic Longitude: 194.35° and Galactic Latitude; – 40.50°. Considering this location as a center of the cavity structure, we draw major and minor axis towards the elongated and contracted sides. The size of the major and minor axis are 69.0 arcmin and 22.84 arcmin respectively. The variation of fluxes and dust color temperature are studied along the major and minor axis. The variation of fluxes and temperature are fitted using polynomial and sine wave function as shown in Fig. 3.5.

Along the major axis, the flux at 60 μm and 100 μm both are fitted for a five-degree polynomial, as shown in Fig. 3.5 (a) and (b) respectively. The polynomial fit nearly overlaps with sine wave fit indicating the sinusoidal fluctuation of flux density along major axis. The correlation coefficient, R, for five−degree polynomial fit is 0.51 and sine wave fit is 0.42, which indicates that the five−degree polynomial is fitted better than the sine wave

because the correlation coefficient for five−degree polynomial fit is more than sine wave fit.

Along the minor axis the flux at 60 μm and 100 μm both are fitted for three−degree polynomial and sine wave, as shown in Fig. 3.5 (d) & (e) respectively. The polynomial plot almost overlap with sine wave indicating the sinusoidal fluctuation of flux density along the minor axis also. The correlation coefficient, R, for three-degree polynomial fit is 0.88 and sine wave fit is 0.85, which indicates that the three – degree polynomial is fitted better than the sine wave because the correlation coefficient for three−degree polynomial fit is more than sine wave fit however, there is no significant difference.

For the dust color temperature, the polynomial curve (fifth−degree for major axis and three−degrees for minor axis) and sine wave curve are almost overlapping each other. Along the major axis, the correlation coefficient, R, for the fifth−degree polynomial fit is 0.29 and sine wave fit is 0.31. Along the minor axis, the correlation coefficient, R, for three−degree polynomial fit is

0.62 and the sine wave fit is 0.60. These results indicate that there is also the sinusoidal fluctuation of temperature along the major and minor axis within the dust cavity.

These all results suggest the presence of thermal wind in the dust cavity possibility generated by the White Dwarf WD 0352−049 located nearby the center of the dust cavity.
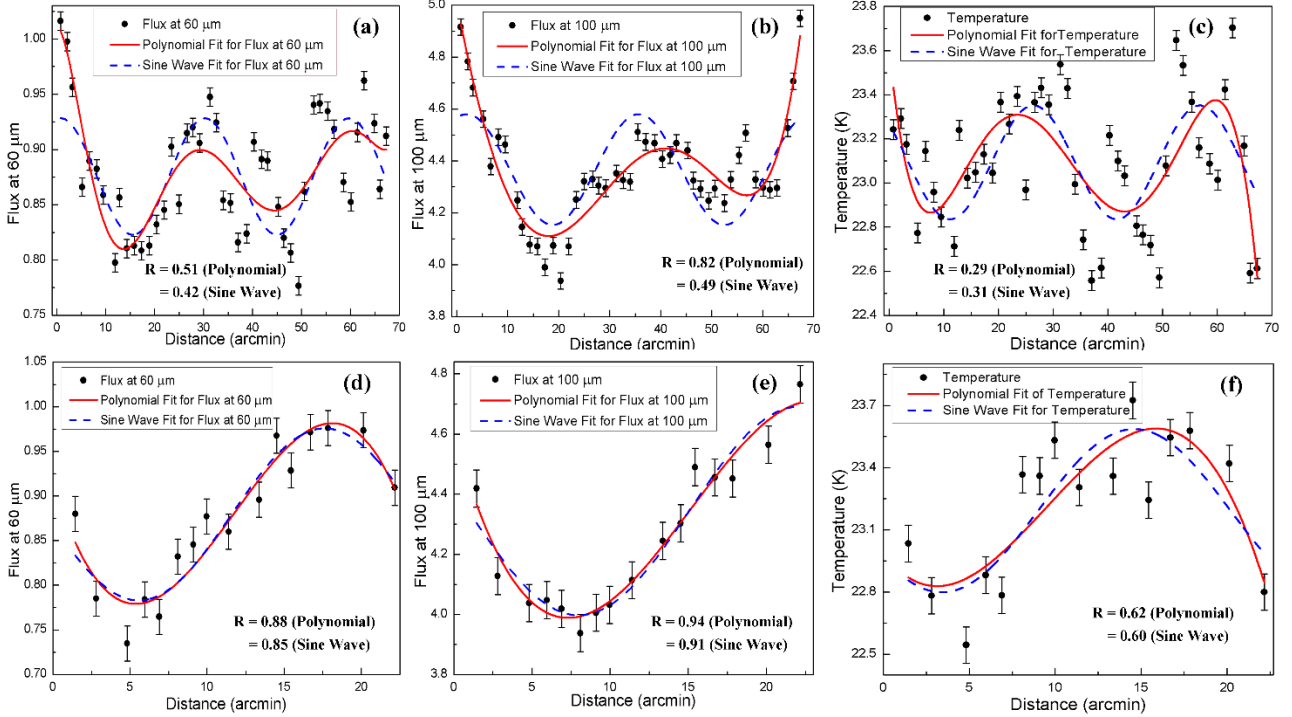
Fig. 3.5: Top panel showing the variation of relative flux density at 60 μm (a), 100 μm (b) and dust color temperature (c) along major diameter. Bottom panel showing the variation of relative flux density at 60 μm (d), 100 μm (e) and dust color temperature (f) along minor diameter. In all figures, the solid red line represents the polynomial fit and the dashed blue line represents sine wave fit. The value of the correlation coefficient is represented by R in all graphs.

3.7. Size, Inclination Angle

The angular dimension of the structure (69.0 arcmin × 22.84 arcmin) is converted into linear dimension by using the formula; $l = d \times \theta$, where, l is linear dimension and θ is angular size and d is the distance, 1219 pc, taken from SIMBAD (http://simbad.u-strasbg.fr/simbad/). The size of the cavity structure is 24.48 pc × 8.10 pc with an average size of 16.29 pc.

The inclination angle is calculated using Holmberg (1946) [9] formula. We draw two contours at level 47 (outer) and 20 (inner) using ALADIN2.5 [11]. There are three contours; Outer–47, Inner–20 (upper), and Inner 20 (down). To calculate the inclination angle we need the major axis, a, and minor axis, b, of each contour and the value of intrinsic flatness (q^*). The value of q^* is taken from 0.13 to 0.33 with a difference of 0.02 [13].

The major and minor axis of the Outer – 47 contour is 69 arcmin and 22.84 arcmin. The value of

inclination angle varies uniformly from 72.15° to 88.47° while varying the q^* from 0.13 to 0.33 respectively. The major and minor axis of the Inner – 20 (down) contour is 26.46 arcmin and 9.53 arcmin. The value of inclination angle varies uniformly from 70.23° to 81.24° while varying the q^* from 0.13 to 0.33 respectively. Similarly, the major and minor axis of the Inner – 20 (upper) contour is 34.76 arcmin and 13.11 arcmin. The value of inclination angle varies uniformly from 69.11° to 78.89° while varying the q^* from 0.13 to 0.33 respectively.

From the study of inclination angle, it is seen that the inclination angle increases while moving outwards. Also, uniform and small variations in inclination angle are observed while varying the intrinsic flatness q^*. From all these calculations, we can conclude that the dust cavity structure is distributed uniformly and regularly shaped.

3.8. Density and Jeans Mass

To calculate the Jeans mass, at first we need to

calculate the density of the cavity structure using equation (6). We use the average size of cavity 5.03 × 10^{17} m for the calculation of density. The density of the cavity structure is obtained 1.74 × 10^{-20} kg/m^3. The average density of ISM is less than the 10^{-15} kg/m^3, the value for density match with the theoretical value of density in ISM. The Jeans mass of the structure is calculated using equation (5) and it is found 1.04 × 10^{31} kg (5.25 M$_\odot$), which is less than the total mass of gas (13.66 M$_\odot$) within the cavity structure. This suggests the possibility of star formation activity in the future. However, the cavity structure is a bubble like structure. The possibility of star formation activity from Jean's criteria is the unlikely result. This might be due to the value of distance we used in our work.

4. CONCLUSIONS

A study of infrared images of cavity structure around White Dwarf WD 0352–049 located at Galactic Longitude: 194.33^o and Galactic Longitude: − 40.92^o is performed. The relative infrared flux density taken from 60 μm and 100 μm FITS images are used to calculate the dust color temperature and dust mass within the cavity structure. The color map, Gaussian distribution, polynomial and sine wave function are used for the analysis of the properties of dust within cavity structure.

Following are the conclusions of this research work;

- The study of the relative flux density at 60 μm and 100 μm FITS image suggests that the dust cavity structure consists of the large dust grains having similar blackbody features at both 60 μm and 100 μm wavelength.

- The maximum and minimum temperature within the cavity structure is found 24.09 ± 0.50 K and 21.87 ± 0.61 K, with a range of 2.22 K and an average value of 23.09 ±1.11 K. The average temperature suggests that the dust cloud is not cirrus type cloud and the range of temperature less than 5 K suggests that the dust in cavity structure is less disturbed from external radiation sources and evolving independently.

- The study of the color map indicates the identical distribution of flux at 60 μm and 100 μm and inverse distribution of temperature and mass within the cavity.

- The Gaussian distribution of infrared flux, dust color temperature and mass suggests that they

are more or less distributed uniformly within the cavity structure. Gaussian distribution of dust color temperature suggests that the dusts within the cavity structure are in local thermodynamic equilibrium. The range of temperature also supports this fact.

- The study of variation of flux and temperature along the major and minor axis indicates the presence of thermal wind due to the White Dwarf 0352–049 located nearby the center of the cavity structure.

- The study of Jean's criteria of the structure allowed the possibility of star formation activity within the structure. However, this result is unlikely for the cavity−like structure.

- The study of inclination angle suggests that the structure is uniformly shaped and regularly structured from the morphological point of view.

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