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ARTICLE

A New Far Infrared Cavity Near White Dwarf WD0245+541

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Abstract: A new far infrared dusty cavity of size 17.4' x 8.6' at 100 μm IRAS (Infrared Astronomical Satellite) map located 0.15^o northwest of white dwarf WD0245+541 is investigated. We present dust color temperature, dust mass, and the Planck function distributions in and around the cavity (FIC0248+542). The dust color temperature has been determined to fall within the range of 23.0 to 27.3 (±1.9) K, while the dust mass is found to be 0.8 x 10^{26} kg. The Planck function distribution along the white dwarf is observed to be non-uniform.

Keywords: White Dwarf, Far infrared cavity, Dust color temperature, Planck function, Gaussian distribution.

1. Introduction

Far infrared cavity (FIC hereafter) is the region in the interstellar medium (ISM) where flux density is found to be much lower than that of the background. Interstellar dust (mostly carbon and silicon compounds) absorbs the radiation and emits it in longer wavelengths [1]. Interstellar dust records the region's history and drives ISM's evolutions in the recycling process of stellar evolution. A white dwarf (WD hereafter) emits wind and is believed to be responsible for the formation of a far infrared cavity (FIC). A dusty ring surrounding the white dwarf WD2226-210 has been observed at the core of the Helix nebula [2] and it has been identified as a source of UV radiation emission. Aryal *et al*. [3] studied planetary nebula NGC 1514 on 100 μm IRAS maps and found an extended dust emission of size ~ 2.6 pc. They noticed bipolar dust emission centered on the planetary nebula. Sapkota *et al.* [4] identified two FICs near WDs WD0038Z+730 and WD0531-022.

Our objective is to identify the region where dust (FIC) and wind (WD) interact. In addition, we intend to find out dust color temperature, dust mass, and their respective distributions.

2. Region of Interest and Methods

A systematic search is performed at 100 and 60 μm of IRAS maps [5] around nearby (distance < 20 pc) WDs [6]. The Infrared Astronomical Satellite (IRAS) was the first mission to put a telescope in space to survey the sky in infrared. This was a joint project involving the US, the UK, and the Netherlands. The survey encompassed the entire sky at wavelengths of 12, 25, 60, and 100 μm [5]. This project yielded a number of unexpected discoveries, including the identification of six new comets, providing images of the core of our galaxy, and the detection of solid material around the stars Vega and Fomalhaut, which strongly suggests the existence of planetary systems around other stars. Our objective is to find an FIC satisfying the following selection criteria: (a) diameter of the cavity > 15’, (b) WD should be located within 15’ of the cavity, (c)

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IRAS data at longer wavelength should be available, and (d) galactic latitude < ±10°.

We noticed a cavity around the WD0245+541 and downloaded its IRIS images, a new generation of IRAS images that benefits from better zodiacal light subtraction, calibration, and zero levels [3]. We employed ALADIN2.5 software to extract the flux densities of each pixel in 100 and 60 μm IRIS images. Aladin Desktop is the main application of the Aladin Sky Atlas suite, developed in Java. Aladin Desktop is able to run on any configuration (Windows, Mac, Linux, etc.) even on small machines (>128MB RAM). Background and foreground corrections have been made using this software and the method used by Aryal *et al.* [3]. We use [7, 8] to determine the values of dust color temperature:

$$T_d = -96 \frac{1}{ln\{R \times 0.6^{(8+\beta)}\}} \quad (1)$$

Here, R and β represent the ratios of flux densities and spectral index, respectively. The color denotes the temperature of dust due to its particular wavelength of light. To calculate the temperature of dust, Wood *et al.* first computed the flux densities at each pixel. Subsequently, they determined the ratio and then applied the black-body radiation law [7]. The values of the spectral index depend upon the composition of dust materials, their size, and compactness. The spectral index values for the perfect black body, amorphous matter, and metallic crystalline are 0, 1, and 2, respectively [8]. FIC is surrounded by dust. Therefore, it contains materials of high metallicity. In accordance with the recommendation in Ref. [3], we have chosen a value of β = 2. Interstellar dust is typically on average about 0.2 μm in size, some can be as large as 50 μm, and some as small as just a dozen or so atoms! Dust is produced in the interstellar medium during the late stage of stellar evolution. To calculate dust mass, we adopt the formula given by Young *et al.* [9]:

$$M_d = 0.40 \left[\frac{F_v D^2}{B(v,T)}\right] \quad (2)$$

Here F_v is the flux density at 100 μm and D is the distance. The distance to the WD is taken from the catalog [10]. We calculate the values of the Planck function $B(v,T)$ for each pixel using [1]:

$$B(v,T) = \frac{2hv^8}{c^2}\left[\frac{1}{e^{\frac{hv}{kT}}-1}\right] \quad (3)$$

The Planck function rises very sharply at short wavelengths (due to the exponential), reaches a peak at some wavelength, then falls gradually at longer wavelengths. Microsoft Excel and ORIGIN8.0 software are used for the calculation and plotting.

3. Results

We introduce FIC0248+542 located near white dwarf WD0245+541 and discuss dust color temperature, dust mass, and the Planck function distributions with the help of contour maps and histograms. Figure 1(a) shows 3.0° x 3.0° field of a FIC at 100 μm, near a white dwarf WD0245+541 (symbol '+') located at R.A. (J2000) = $02^h48^m37.2^s$ (galactic longitude, l = 139.54°), Dec. (J2000) = +54°23'29" (galactic latitude, b = -4.66°). The location of flux minima at 100 μm is represented by the symbol 'X'. The DSS (Digitized Sky Survey) 1.6' field centered at the WD can be seen in Fig. 1(b). This WD is of DAZ9.7 spectral type [11], showing Balmer lines only and hence possesses ~ 25,000 K surface temperature [12]. This WD is hot and emits non-degenerate materials in the form of wind. These materials interact with ambient ISM and sweep it away to form a dust cavity.

This WD is at a distance of 10.35 pc [10]. Its proper motion is 0.537 mas yr^{-1} [13]. The size of the cavity is found to be 17.4' x 8.6' and the WD is located 12.4' south-west from the flux minima (symbol 'X') of the cavity. Figure 1(c) shows the flux density contour map at 100 μm wavelengths, where the minimum flux region is represented by red color. The contour levels are at 1.6, 1.7, 1.9, 2.0, 2.2, 2.3, 2.5, and 2.6 MJy/sr.

Using ALADIN2.5 software, we obtained flux densities of 66 pixels on 60 and 100 μm images of the region of interest. Next, these values were corrected for the background. Finally, we studied the dust color map and distribution, as shown in Figs. 1(c) and 2(a), after determining its value for each pixel using Eq. (1). In a similar manner, using Eq. (2), we calculated the dust mass of each pixel and studied the distribution of the obtained values. The dust color temperatures are found to lie in the range from (23.0 ± 0.9) K to (27.3 ± 2.9) K. The offset temperature is found to be ~ 4 K, indicating the cavity is not stable. Figures 1(d) and 1(e) show dust color temperature and dust mass maps. The minimum flux (northeast) region showed relatively high dust color temperature. Interestingly, the cooler region is found to be less massive. Gaussian distribution is a continuous probability distribution with symmetrical sides around its center with equal mean, median, and mode. Therefore, any physical quantity that is a sum of many independent processes is assumed to follow Gaussian. The cumulative effect of all such forms is likely to follow normal distribution. Therefore, we use Gaussian fit to check any deviation from the natural process in the interstellar medium.

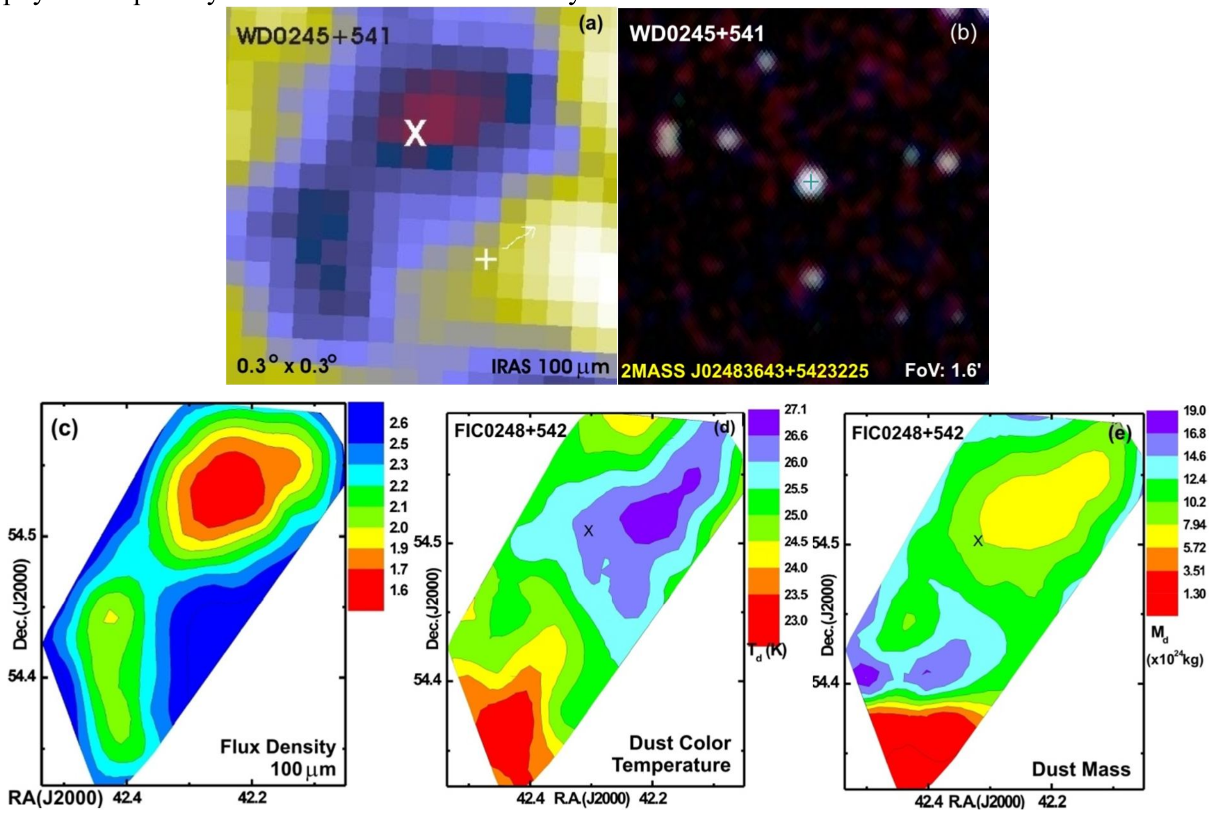

FIG. 1. (a) 0.30° x 0.30° field of FIC surrounded by dust at 100 μm, located near (b) white dwarf WD0245+541 centered at R.A. (J2000) = $02^h48^m37.2^s$ (galactic longitude, l =139.54°), Dec. (J2000) = +54°23'29" (galactic latitude, b = -4.66°). The symbols `+' and `x' represent the position of the WD and minimum flux region of the cavity. respectively. (c) Flux density. (d) Dust color temperature. (e) Dust mass contour maps. The contour levels are shown in the units MJy/sr (c), K (d), and kg (e).

The Gaussian fit can be seen in Fig. 2(a). The Gaussian distribution is:

$$y = y_0 + \frac{Ae^{\frac{-4ln2(x-x_c)^2}{\omega^2}}}{\omega\sqrt{\frac{\pi}{4ln2}}} \quad (4)$$

Here, y_0, A, x, and x_c represent Gaussian offset, area, width, and center, respectively. In our case, the Gaussian distribution of dust color temperature is found to be:

$$n_T = 0.30 + 31.7e^{-0.70(T_d-25.40)^2} \quad (5)$$

The Gaussian distribution of dust mass, as seen in Fig. 2(b) is:

$$n_M = 3.25 + 14.29e^{-9.81\times10^{-48}(M_d-10.80\times10^{23})^2} \quad (6)$$

A positive skewness is observed in the dust mass distributions. In the Eqs. (5) and (6) the values of mean, median, and the modes are found to be different. Gaussian distributions are self-conjugate, meaning that when you have a Gaussian likelihood function, selecting a Gaussian prior will yield a Gaussian posterior. We found that the dust color temperature [Fig. 2(a)] and dust mass [Fig. 2(b)] distributions deviate from the Gaussian, suggesting that the FIC near WD0245+541 is not stable. The northern part of the cavity is the coolest region.

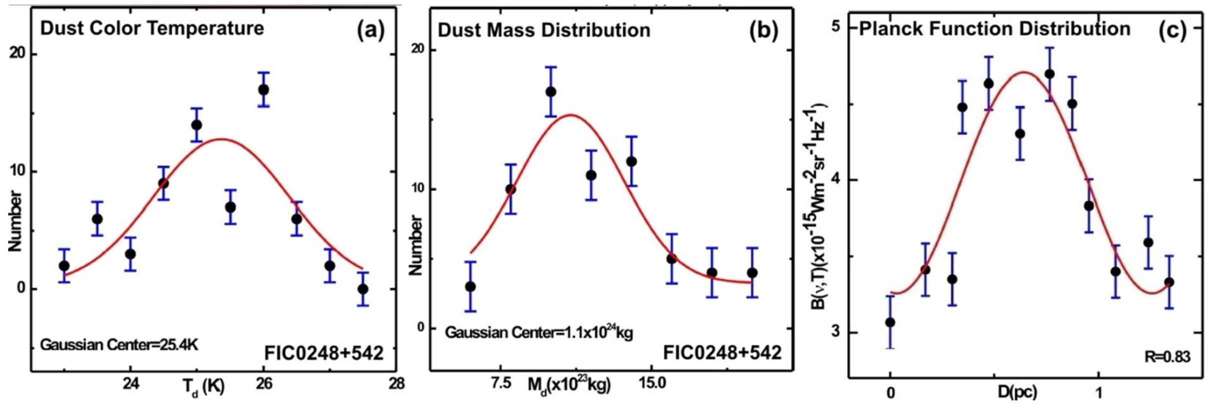

FIG. 2. Histograms showing (a) dust color temperature (T_d), (b) dust mass (M_d), and (c) the Planck function ($B(\nu,T)$) distributions. The D represents the distance between the flux minima and the WD. The Gaussian fit is represented by the solid curves in (a) and (b). The solid curve in (c) is the sinusoidal fit. The statistical ±1σ error bars are shown.

4. Discussion: Dust Oscillation

Interstellar dust particles act as an efficient radiator in the infrared. They are non-degenerate, non-interacting, and light (10^{-16} to 10^{-6} kg) in nature [6]. Therefore, these particles obey Maxwellian velocity distributions unless they are being driven by wind. We know that the Planck function rises very sharply at short wavelengths (due to exponential term), reaches a peak at some wavelengths, and then falls gradually at longer wavelengths. At longer wavelengths, it is believed to be uniform in the stable cavity. The variation of the Planck function along the direction of WD from the flux minima of the cavity can be seen in Fig. 2(c). It is found to be non-uniform. We consider that the dust oscillates sinusoidal as:

$$y = y_0 + A \sin \frac{\pi(X - X_c)}{\omega} \tag{7}$$

Here, the parameters y_0, A, X_c, and ω are offset, amplitude, phase shift, and period of oscillation, respectively. We found sinusoidal distribution as:

$$B(\nu, T) = 4.00 + 0.72 \sin\left[\frac{\pi(D - 0.34)}{0.61}\right] \times 10^{-15} \tag{8}$$

Here, the period of oscillation (0.61) is found to be smaller by 26% than the amplitude (0.72) of oscillation. This result advocates the interstellar dust in FIC0248+542 oscillates sinusoidally in the direction of the WD. Dust absorbs and scatters not only stellar photons but also the radiation from dust and gas. Light scattering by dust is a process in which an incident electromagnetic field is scattered into a new direction after interaction with a dust particle. The directions of the propagation of the incident wave and the scattered wave define the so-called scattering plane. Therefore, the wind emitted from the progenitor of the white dwarf WD0245+541 might be responsible for the formation of FIC0248+542 in the process of evolution.

4.1 Comparison with Other Works

The dust color temperature (T_d) of interstellar cirrus cloud is found to lie in the range of 20-27 K [14, 15]. Reach *et al.* [16] observed the white dwarf G29-38 using Spitzer data and found a cloud of small grains of size ~$10R_{sun}$ away from the white dwarf. Aryal & Weinberger [17] studied 100 μm IRAS maps around white dwarf WD1003-44 and determined T_d in the range 20.7 (± 0.6) K to 21.6 (± 0.2) K. Jha *et al.* [18, 19] measured T_d for four far infrared loops namely G007+18, G143+07, G214-01, and G323-02 which are located near pulsars showed the values of T_d 19.4 (±1.2) K to 25.3 (±1.7) K. Gautam and Aryal [20] calculated T_d in four far infrared cavities (FIC01+55, FIC05+28, FIC06-05, and FIC06-01 near AGB stars) and found 18.3 (±1.2) K to 20.5 (±1.3) K dust color temperatures. Sapkota *et al.* [4] studied the physical properties of two dusty far infrared cavities at 100 μm located near white dwarfs WD0038+730 and WD0531-022. They used similar methods and calculated T_d values as 19.5-30.3 (±2.6) K. In both cavities, the period of oscillation is found to be 2-16 times larger than that of the amplitude of the oscillation. They noticed oscillation of the interstellar dust in the direction of the white dwarf. These findings corroborate the results of our study.

5. Conclusion

We investigate a far infrared dusty cavity FIC0248+542 in IRAS maps at 100 µm wavelengths, located near white dwarf WD0245+541. The dust color temperature and dust mass distributions are studied. Additionally, we study the variation of the Planck function in the direction of WD0245+541. In conclusion, our findings can be summarized as follows:

(1) The dust color temperatures of a far infrared cavity (size ~17.4' x 8.6') near white dwarf WD0245+541 are measured to be within the range of 27.3 (±1.9) K to 23.0 (±0.9) K. The total mass of the dust in FIC0248+542 is 0.8 x 10^{26} kg.

(2) The distribution of the Planck function towards the WD0245+541 is found to be non-uniform, displaying a preference for a sinusoidal pattern. The amplitude of this sinusoidal pattern is slightly greater than the period of oscillation.

Our future plans include conducting spectroscopy of the dust cavity at radio wavelengths.

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