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Dust Properties of Super-Nova Remnant (Crab Nebula)  
Using AKARI Survey

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ABSTRACT

We present the distribution of dust color temperature, Planck’s function, dust mass, and visual extinction in the far-infrared (140 µm and 90 µm) AKARI surveys of the Crab Nebula using Sky View Virtual Observatory. With a systematic search of a supernova remnants, we found Crab Nebula at R. A. (J2000) / Decl. (J2000) = 05h 34' 31.94"/+22° 00' 52.20". The maximum flux is found to be 145.94 MJy sr⁻¹ at 140 µm and 177.01 MJy sr⁻¹ at 90 µm wavelength. The total dust mass of the Supernova remnant is estimated to be 6.11 × 10⁻²⁹ kg (3.07 × 10⁹ M☉) and the dust color temperature is found in the range between 31.16 K to 47.11 K with mean value of temperature of 38.07 K. Similarly we obtained the value of Planck’s function in the range of 3.96 × 10⁻¹⁵ W m⁻² sr⁻¹ Hz⁻¹ to 1.96 × 10⁻¹⁴ W m⁻² sr⁻¹ Hz⁻¹ with average value 9.59 × 10⁻¹⁵ W m⁻² sr⁻¹ Hz⁻¹. The value of visual extinction ranges from 9.21 × 10⁻¹⁴ mag to 2.70 × 10⁻¹³ mag with mean value of 1.57 × 10⁻¹³ mag. The distribution trend of flux, dust color temperature, and Planck’s function are nearly similar, whereas dust mass and visual extinction follow an inverse relationship with the previous three parameters.

Keywords: AKARI; Crab Nebula; Dust Color Temperature; Dust mass; Visual Extinction.

1. INTRODUCTION

A supernova is the result of a star ending by a powerful explosion leaving behind an expanding gaseous remnant. The origin of interstellar medium, black holes, X-ray binaries, etc. are connected to super-nova explosion [1-3]. Supernovae is the main cause of efficient dust in the galaxies. Using 100 µm and 60 µm IRAS maps, Kiss et al. (2004) and Koenyves et al. (2007) investigated 462 far-infrared loops, studied their luminosity distributions and concluded that these structures are formed and governed by supernovae and young stellar winds at the low Galactic latitude [4, 5]. The dust in the universe is mostly from the explosion that may be from star formation or star explosion or maybe a collision between meteoroids, maybe others things which can’t be discovered yet [6-9]. Matsuura et al. had also studied that the dust in the universe is from SN eject [10]. Dust plays an important role in our earth, our solar system and also the whole universe. The radiation in the galaxies in the space is also due to the dust evolved from the supernova explosion [11]. Matsura et al., (2015) confirmed large mass of dust in the eject of supernova SNe 1987A is about 0.4 to 0.7 M☉ and according to them core collapse supernova (CCSNe) is the main source of interstellar dust [12]. Supernova remnants (SNRs) play an important key role in understanding supernovae explosion mechanism, star formation, the phenomenon of dust formation mechanism, exploring the likely sources of Galactic cosmic rays, and the chemical enrichment of interstellar medium (ISM) [13-15]. Supernova remnants are very important because it gives the structure of the galaxies. They are also the source of heating of the interstellar gas by the means of magnetic turbulence and violent shocks. It is important for our evolution because it forms the heaviest elements like iron, magnesium, copper, gold, uranium etc. The Milky Way Galaxy contains over 200 supernova remnants which
make our galaxy beautiful. It is the source of energy and heavy elements [13-15]. Green et al. (2004) suggest that 77% of the remnants are closed as shell, 12% are composite and remaining 4% have not observed clearly [16]. These facts suggest that interstellar dust plays an important role in shaping mechanism of ISM. Several authors studied about dust environment around Nebula, Pulsars, AGB stars and white dwarfs using IRAS, IRIS AKARI band and survey they found two digit and very low kelvin dust color temperature [17-26]. So, we studied the physical properties interstellar dust like dust temperature, distribution of Planck's function, dust mass, and visual extinction, etc. near the supernova remnant crab nebula.

2. METHODS AND MATERIALS

2.1 Database

We used SkyView virtual Observatory (https://skyview.gsfc.nasa.gov) in order to search an isolated nebular structure at different AKARI wavelength bands nearby the supernova remnant i.e., Crab Nebula for our observation of dust abundance. We followed the method used by Jha and Aryal, (2017) during the search of best candidate [24, 26]. We found an isolated nebular structure at R. A. (J2000): 05\(^h\) 34\(^m\) 94.00\(^s\), Decl. (J2000): +22\(^\circ\) 00\('\) 52.20, and downloaded the FITS images in two different bands of AKARI (90 \(\mu\)m and 140 \(\mu\)m) for our datasets.

The FITS images were downloaded and processed using software Aladin v11.0.

2.2 Dust Color Temperature

For the estimation of dust color temperature. The flux density emitted at a wavelength \(\lambda_i\) is given by [27-29]

\[
F = \left[\frac{2\pi c}{\lambda_i^2} N_d \alpha \lambda_i^{-\beta} \Omega_i \right] \frac{hc}{kT_{\lambda_i}}
\]

where, \(N_d\) is the dust grains column density, \(\alpha\) is a constant which depend on the flux and optical depth of the dust, \(\beta\) is emissivity index varies with wavelength, \(\lambda_i\) and \(\Omega_i\) is the solid angle made by the detector.

To obtain the dust color temperature equations let us consider \(T_d \ll T\) and \(\Omega_{90} = \Omega_{140}\) and also \(\lambda_{140} = \frac{hc}{kT_{140}}\) and \(\lambda_{90} = \frac{hc}{kT_{90}}\), the ratio of flux densities at 90 \(\mu\)m, \(F(90 \mu\m)\) and 140 \(\mu\m,\) \(\frac{F(140 \mu\m)}{F(140 \mu\m)}\) gives the value of \(R\) as:

\[
R = \left[\frac{\frac{hc}{e^{\lambda_{140}RT_d} - 1}}{\frac{hc}{e^{\lambda_{90}RT_d} - 1}}\right] 0.64^{-\beta} \quad (2)
\]

By substituting the value of \(T_{140} = 103\) K and \(T_{90} = 160\) K in equation (2)

\[
R = \left[\frac{\frac{103}{e^{\lambda_{140}RT_d} - 1}}{\frac{160}{e^{\lambda_{90}RT_d} - 1}}\right] 0.64^{-\beta} \quad (3)
\]

The value of \(\beta\) depends upon the properties of dust grains such as size, composition, compactness etc.
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For the pure black body $\beta = 0$, for amorphous layer-lattice matter $\beta = 1$ and for metal and crystalline dielectrics $\beta = 2$. For smaller value of $T_d$, 1 can be dropped from both numerator and denominator of above equation (3) and it takes the form

$$ R = 0.64^{-(3+\beta)} \left( \frac{T_d^{103}}{T_d^{100}} \right) $$

Taking natural logarithm on both sides of equation (4) we get

$$ \ln(R) = \ln\left(0.64^{-(3+\beta)} \right) \left( \frac{T_d^{103}}{T_d^{100}} \right) $$

$$ T_d = \frac{-57}{\ln(R \times 0.64^{-(3+\beta)})} $$

Which is the required Dust color temperature of the supernova remnant using AKARI 90 and 140 µm wavelength.

Where, $R = \frac{F(90)}{F(140)}$

Equation (6) is used for the determination of the dust grain temperature in the remnant of the Supernova [24, 26].

### 2.3 Dust Mass Estimation

Dust mass can be estimated by the method of Hilderbrand (1983) and Young et al. (1983). According to them the dust mass can be calculated from infrared flux densities [30, 31] as:

$$ M_{dust} = \frac{4 \alpha a \rho}{3 Q_v} \frac{S_v D^2}{B(v, T_d)} $$

where,
- $a$ = weighted grain size
- $\rho$ = grain density
- $D$ = Distance of the Structure
- $S_v$ = grain emissivity
- $Q_v$ = grain emissivity

For 140 µm wavelength, the expression for the dust mass reduces to,

$$ M_{dust} = 0.40 \left( \frac{S_v D^2}{B(v, T_d)} \right) $$

The value of Planck’s function $B(v, T_d)$ varies with frequency, and temperature. The Planck’s function is a well-known function, given by

$$ B(v, T) = \frac{2h\nu^3}{c^2} \exp \left( \frac{h\nu}{kT} \right) $$

where,
- $h$ = Planck’s constant
- $c$ = velocity of light
- $\nu$ = frequency at which the emission is observed
- $T_d$ = Dust color temperature of each pixel

### 2.4 Visual Extinction

For estimation of visual extinction optical depth can be written as [26, 27]

$$ \tau_{140} = 1 - \frac{F_{140\mu m}}{B(v, T_d)_{140}} $$

Here $F_{140\mu m}$ in $\text{kg s}^{-2}$ and $B(v, T_d)_{140}$ in $\text{W m}^{-2} \text{sr}^{-1} \text{Hz}^{-1}$ at 140 µm flux in AKARI as suggested by Wood et al. [26] for IRAS survey. For IRIS and AKARI survey, following empirical equation is used to estimate the visual extinction [26, 27]

$$ A_{\nu} = 15.078 \left( 1 - e^{-\tau_{140}} \right) $$

### 3. RESULTS AND DISCUSSION

#### 3.1 Projection Map

![Projection Map](image)

Fig. 2: The projection map of our candidate.
The selected nebular structure centered at R.A. (J2000) / Decl. (J2000) = 05\textsuperscript{h} 34\textquoteleft 31.94\textquoteleft\textquoteright +22\textdegree 00\arcmin 52.20\arcsec is shown in projection map with blue color in Figure 2. From this map it is seen that our structure lies near to the equatorial region.

Figure 3 shows the plot of 90µm flux versus 140µm AKARI flux density scattered plot. The equation of best fitted line is given by,

\[ F(90) = 1.28 F(140) - 44.63 \]  

(13)

with the slope of value 1.28 and correlation coefficient \( R^2 = 0.94 \). The slope 1.28 explains that for every additional unit MJysr\(^{-1}\) in flux density at 140 µm the flux density at 90µm increase by an average of 1.28 MJysr\(^{-1}\). This shows the strongest linear relationship occurred between these two parameters.

### 3.2 Contour maps

Figure 4(a), (b) shows the contour map of the flux density at 90 µm and 140 µm MJysr\(^{-1}\). For these contour plot we had plotted the R.A. (J2000) in x-axis and Decl. (J2000) in y-axis and flux as color map. Figure 4(a), (b) represents a two-dimensional contour plot with the projection of fluxes in the XY plane. We obtained that the range of flux density at 90 µm 23.89 MJysr\(^{-1}\) to 177.01 MJysr\(^{-1}\) with average 72.55 MJysr\(^{-1}\) where as for 140 µm band 55.01 MJysr\(^{-1}\) to 145.94 MJysr\(^{-1}\) with average 91.47 MJysr\(^{-1}\). It indicates that there is more deviation in case of 90 µm emission.

Fig. 4: The contour maps of (a) F(90 µm) and (b) F(140 µm) along with their color scale.

Fig. 5: Contour maps of (a) dust color temperature and (b) Planck’s function along with their color scale.
Figure 5 (a) and (b) shows the contour map of the dust color temperature \( (T_d) \) in Kelvin and Planck’s function \( (B(\nu, T_d)) \) in Wm\(^{-2}\)sr\(^{-1}\)Hz\(^{-1}\).

For these contour plot we had plotted the R.A. (J2000) in X-axis and Decl. (J2000) in Y-axis and dust color temperature and Planck’s function as third parameter along with color bar. In figure violet to red indicates increasing sequence of physical parameters. In this case we obtained the range of dust color temperature from 31.16 K to 47.11 K and whose, average value 38.07 K. Similarly values of Planck’s function varies from \( 3.96 \times 10^{-15} \) Wm\(^{-2}\)sr\(^{-1}\)Hz\(^{-1}\) to \( 1.96 \times 10^{-14} \) Wm\(^{-2}\)sr\(^{-1}\)Hz\(^{-1}\) and its mean value found to be \( 9.59 \times 10^{-15} \) Wm\(^{-2}\)sr\(^{-1}\)Hz\(^{-1}\). The central part of the structure was found to be hotter than outer region as a consequence the Planck’s function higher at the core region than outer region.

Figure 6(a) and (b) shows the contour map of the visual extinction \( (A_v) \) in mag and dust mass \( (M_d) \) in kilogram.

For these contour plot we had plotted the R.A. (J2000) in X-axis and Decl. (J2000) in Y-axis and visual extinction and dust mass in as color map. In figure violet to red indicates increasing sequence of physical quantities. In this case we obtained the range of visual extinction from \( 9.21 \times 10^{-14} \) mag to \( 2.70 \times 10^{-13} \) mag and average value \( 1.57 \times 10^{-13} \) mag. The values of dust mass lies between \( 4.14 \times 10^{34} \) kg to \( 3.37 \times 10^{36} \) kg and its mean value found to be \( 7.98 \times 10^{35} \) kg. Here, we observed the core region of the structure to be less dense than the outer region as a result of the lower extinction in the central part. The mass of dust estimated by Jha et. al, (2017) in cavity is lesser than our calculated dust mass by using AKARI maps at 90 µm and 140 µm [19].

### 3.3 Normal Fit

Figure 7 (a) and (b) represents the normal distribution plot for dust color temperature and dust mass. In these plots we have tested Gaussian distribution. In figure 7 (a) dust color temperature fitted normal distribution. But in figure 7(b) left skewness was observed.
These two plots give the phenomena of inverse trend between dust mass and dust color temperature.

3.4 Visual Extinction

$$T_d = -0.57 \ A_v + 47.05$$  \hspace{1cm} (15)

Here, we obtained the negative correlation between them which yield the correlation coefficient value as $R^2 = -0.59$. It shows the inverse relation between temperature and extinction.

Figure 8 represents the correlation between the dust color temperature and visual extinction around remnant structure. In this case we obtained the best fitted line as:

$$T_d = -0.57 \ A_v + 47.05$$

4. CONCLUSIONS

We have studied the dust distribution around the supernova remnant using FITS from the Sky View Virtual Observatory of AKARI map with the data reduction software Aladin v11.0 and other supporting programs. We conclude our results as follows:

- The flux density is higher around the middle part of the selected structure. The minimum and maximum flux densities at 90 µm are 23.89 MJysr$^{-1}$ and 177.01 MJysr$^{-1}$ where as at 140 µm its value are 55.01 MJysr$^{-1}$ to 145.94 MJysr$^{-1}$.

- The dust color temperature lies in the range 31.16 K to 47.11 K with average value 38.07 K. Similarly values of Planck’s function lies between $3.96 \times 10^{-15}$ Wm$^{-2}$sr$^{-1}$Hz$^{-1}$ to $1.96 \times 10^{-14}$ Wm$^{-2}$sr$^{-1}$Hz$^{-1}$ with mean value $9.59 \times 10^{-15}$ Wm$^{-2}$sr$^{-1}$Hz$^{-1}$.

- The value of visual extinction varies from $9.21 \times 10^{-14}$ mag to $2.70 \times 10^{-13}$ mag.

- The dust mass lies in the range $4.12 \times 10^{24}$ kg and $3.37 \times 10^{36}$ kg, its mean value found to be $7.98 \times 10^{35}$ kg with total dust mass of the nebular structure is found to be $6.11 \times 10^{39}$ kg ($3.07 \times 10^{9}$ M$_\odot$).

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