Two-dimensional Monte Carlo radiative transfer modelling of the disc-shaped secondary of Epsilon Aurigae

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ABSTRACT

We present two-dimensional Monte Carlo radiative transfer models for the disc of the eclipsing binary Epsilon Aurigae by fitting its spectral energy distribution (SED) from optical to far-infrared (IR) wavelengths. We also report new observations of Epsilon Aurigae made by AKARI in its five mid- and far-IR photometric bands and which were used to construct our SED. The disc is optically thick and has a flared disc geometry containing gas and dust with a gas to dust mass ratio of 100. We have taken the primary of the binary to be an F0Iae-type post-asymptotic giant branch (post-AGB) star and the disc is heated by a B5V hot star with a temperature of 15 000 K at the centre of the disc. We take the radius of the disc to be 3.8 au for our models as constrained from the IR interferometric imaging observations of the eclipsing disc. Our models imply that the disc contains grains which are much bigger than the interstellar medium (ISM) grains (grain sizes 10 to 100 μm). The grain chemistry of the disc is carbonaceous and our models show that silicate and ISM dust chemistry do not reproduce the slope of the observed SED in the mid-IR to far-IR regions. This implies that the formation of the disc-shaped secondary in the Epsilon Aurigae system could be the result of accretion of matter and/or mass transfer from the primary which is now an F0Iae post-AGB star. It is not a protoplanetary disc. The disc is seen nearly edge-on with an inclination angle larger than 85°. We propose from our radiative transfer modelling that the disc is not solid and has a void of 2 au radius at the centre within which no grains are present making the region nearly transparent. The disc is not massive; its mass is derived to be less than 0.005 M⊙.

Key words: radiative transfer – stars: AGB and post-AGB – binaries: eclipsing – circumstellar matter – stars: individual: ϵ Aurigae.

1 INTRODUCTION

Epsilon Aurigae (HD 31964; ϵ Aur hereafter) is an eclipsing binary with an orbital period of 27.1 yr showing 0.75 mag depth in the optical during eclipse; the primary is occulted by the disc-shaped secondary causing a two-year-long eclipse (Parthasarathy & Fruch 1986; Carroll et al. 1991; Guinan & DeWarf 2002). The eclipse depth is independent of wavelength, but the depth, the duration of the eclipse and the masses of the components imply that the components should be almost equally bright; however, no secondary eclipse was observed. Eclipse characteristics indicate that the occulting object is very elongated with a dimension of 5–10 au parallel to the binary orbit. Infrared (IR) observations made by Woolf (1973) revealed an excess emission in the IR. The observations carried out during the previous eclipses and particularly the 1982–1984 eclipse and the recent 2009–2011 eclipse reveal the presence of a dusty plus gaseous disc in ϵ Aur, which is the body causing the two-year-long eclipse. The presence of neutral gas in and around the disc-shaped secondary was for the first time discovered by Parthasarathy (1982, see Stencel 1982) and Parthasarathy & Lambert (1983a) from the systematic increase in the strength of the KI 7699 Å line during the 1982–1984 eclipse.

Orbital characteristics and spectral properties of the primary are consistent with two different models for the system: one is a high-mass star model with the primary having a mass of 15 M⊙ and the other one is a low-mass star model with the primary having a mass of 4 M⊙. The optical spectra of ϵ Aur near the end of the 1954–1956 eclipse were used to hypothesize the presence of a Be-like hot star at the centre of a large disc, from deducing the electron density at the disc (Hack 1961). Later, International Ultraviolet Explorer (IUE) ultraviolet (UV) observations during the 1982–1984 eclipse implied the presence of a hot source inside the disc which can be fitted by a B5V star (Chapman, Kondo & Stencel 1983; Parthasarathy...
Discs are among the most common astrophysical systems, and a powerful technique for observing them is the stellar occultation method. $\epsilon$ Aur offers this opportunity for a new class of discs.

Recently, Stefaniak et al. (2010) reported an updated single-lined spectroscopic solution for the orbit of the FOIae primary star based on 20 years of monitoring at the CfA, combined with historical velocity observations dating back to 1897. They presented two solutions. One uses the velocities outside the eclipse phases together with mid-times of previous eclipses, from photometry dating back to 1842, which provide the strongest constraint on the ephemeris. From this they find a period of 9896 d (27.0938 yr) and an orbital eccentricity of 0.227. By using only radial velocities they find that the predicted middle of the current eclipse is nine months earlier, implying that the gravitating companion is not the same as the eclipsing object. They conclude that the purely spectroscopic solution may be biased by perturbations in the velocities due to the short-period oscillations of the FOIae primary star. Other notable recent results are the IR images of the transiting disc by Kloppenborg et al. (2010) and interferometric studies by Stencel et al. (2008). More recently Stencel, Kloppenborg & Wall (2011) made detailed IR studies of $\epsilon$ Aur during the 2009–2011 eclipse.

Discs are among the most common astrophysical systems, and a powerful technique for observing them is the stellar occultation method. $\epsilon$ Aur offers this opportunity for a new class of discs which are associated with post-AGB stars. The $\epsilon$ Aur disc was described variously as thick (Huang 1965) or thin, flat or twisted, opaque or semitransparent, fully solid or possessing a central hole. A wealth of data are now available in the literature from UV to far-IR wavelengths, which can give an insight into the nature of the disc.

From the spectral energy distribution (SED) constructed by their new Spitzer Space Telescope observations and the archival far-UV to mid-IR data, Hoard et al. (2010) proposed a three-component model for the $\epsilon$ Aur system which consists of an FOIae post-AGB star and a B5V-type main-sequence star surrounded by a geometrically thin and partially transparent disc. They proposed a single-temperature blackbody model for the disc and constrained the disc to have a temperature of 550 K, a size of 3.8 au with a thickness of 0.95 au and to be viewed nearly edge-on. Their model deals with the average bulk properties of the disc with cylindrical volume and assumes a uniform mass distribution. However, the nature of the disc with more realistic characteristics such as radial density distribution and temperature profile, scale height and grain chemistry obtained through two-dimensional radiative transfer modelling and consideration of its origin is not yet available.

Near-IR interferometric imaging of $\epsilon$ Aur in the H band was made in 2009 November and December by Kloppenborg et al. (2010) which showed that the eclipsing body is a tilted opaque disc which is moving in front of the F star. Their study reveals the compactness of the obscuring disc across the two epochs and provides the first direct evidence for the presence of a geometrically thin and optically thick disc. With the estimated Hipparcos distance of 625 pc the maximum thickness of the disc obtained by them is 0.76 au and the radius of the disc is 3.81 au. Kloppenborg et al. (2010) also estimated the mass of the F star to be 3.69 $M_\odot$. They estimate a disc mass of $4.45 \times 10^{-5} M_\odot$ [with interstellar medium (ISM) gas–dust ratio].

Results obtained by Kloppenborg et al. (2010) from their interferometric imaging observations can greatly help to make possible a detailed disc model of $\epsilon$ Aur, describing its nature with density and temperature profiles and disc grain chemistry. Here we attempt to make such a model for the disc from fitting of the SED of $\epsilon$ Aur from far-UV to far-IR wavelengths obtained from archival data and by solving the radiative transfer problem of the disc in a two-dimensional case.

### 2 SED of $\epsilon$ Aur

To construct the SED of $\epsilon$ Aur from far-UV to far-IR wavelengths we have used the archival data from ground-based and space-based observing facilities. UV data were obtained from HST GHRS, optical and near-IR photometric data were taken from SIMBAD and mid-IR to far-IR photometric measurements were obtained from the IRAS and MSX space missions. Mid-IR spectra from 9.89 to 37.14 $\mu$m were taken from the Spitzer Heritage Archive. Photometric measurements of Herschel IR bandpasses were taken from recently published results of Hoard et al. (2012). We have also obtained new mid-IR and far-IR fluxes at five photometric bands of AKARI, viz. at 9.0, 18.0, 65.0, 90.0 and 140.0 $\mu$m, see Table 1. Wherever magnitude measurements were available, they were converted into fluxes using appropriate zero-magnitude fluxes at the respective photometric bands. All the observations were made outside the eclipse phases of $\epsilon$ Aur. The majority of these observations were obtained prior to the onset of the 2009 eclipse but well after the end of the 1984 eclipse.

### 3 Radiative Transfer Modelling

To solve the radiative transfer problem in the disc of $\epsilon$ Aur in two dimensions, we have used a Monte Carlo radiative transfer code SRCDUST. It is based on the Monte Carlo radiative equilibrium and temperature-correction techniques developed by Bjorkman & Wood (2001) and was adopted to simulate ellipsoidal envelopes and T Tauri discs (Wood et al. 2002; Whitney et al. 2003). This code was tested by comparing to a set of benchmark calculations for spherically symmetric codes by Bjorkman & Wood (2001). This code can solve the radiative transfer problem in three-dimensional cases and can be well applied to astrophysical systems having axial symmetry geometry with disc, envelope and outflow components.

<table>
<thead>
<tr>
<th>Wavelength ($\mu$m)</th>
<th>Flux (Jy)</th>
<th>Flux quality</th>
<th>Error (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.0</td>
<td>21.4143</td>
<td>3</td>
<td>0.128 868</td>
</tr>
<tr>
<td>18.0</td>
<td>5.44896</td>
<td>3</td>
<td>0.057 6079</td>
</tr>
<tr>
<td>65.0</td>
<td>0.509413</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>90.0</td>
<td>0.44311</td>
<td>3</td>
<td>0.061 5824</td>
</tr>
<tr>
<td>140.0</td>
<td>2.11441</td>
<td>1</td>
<td>1.019 68</td>
</tr>
</tbody>
</table>

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which are illuminated by a central star. Physical properties of the star and physical and geometrical parameters of the disk with an appropriate dust model are provided as the input for the code. We have chosen the code to consider only the disk component illuminated by a star at the center. \( \text{SRCDUST} \) provides the disk temperature structure and synthesized SED of the star and the disk at the required angle of view in the output. More details on the code can be seen in Whitney et al. (2003). The disk is considered here as to have formed by the accretion process and hence we use a standard flared accretion density structure (Lynden-Bell & Pringle 1974) described as

\[
\rho = \rho_0 [1 - (R_{\text{disk}}/\alpha)^{0.5}] [R_{\text{disk}}/\alpha]^\beta \exp[-1/2(z/h(\omega)^{2.0})],
\]

where \( \omega \) is the radial coordinate of the disk mid-plane and the scale height increases with radius as \( h = h_0(\alpha R_{\text{disk}})^{\beta/2} \). For our models we adopt a flaring parameter \( \beta = 1.25 \) which was based on the accretion disk models at hydrostatic equilibrium (D’Alessio et al. 1999) and was used to describe the structure of the accretion disk (Wood et al. 2001; Thi, Woitke & Kamp 2011; Vinkovic 2012) and the value of \( \alpha = 3(\beta - 0.5) \) (Shakura & Sunyaev 1973). We take \( h_0 = 0.05 R_{\text{disk}} \) such that the disk will have a thickness of 0.76 au at its outer edge of radius 3.8 au as constrained by the IR interferometric observations of Kloppenborg et al. (2010). The inner radius is constrained by dust sublimation temperature. The angle of inclination and the mass of the disk are varied to match the synthesized SED with the observations. For this specific case, the primary of \( \epsilon \) Aur can also heat the disk, and evidence for an increase in temperature in the F star heated portions was observed in the IR spectra during the post-mid-eclipse recently by Stencel et al. (2011), and the effect of irradiation was studied by Takeuchi (2011), Spitzer data of Hoard et al. (2010), obtained when the orbital phase is 0.8, differ from the MSX measurement obtained at phase 0.5 which is systematically brighter in the 3–5 \( \mu \)m region. The photometric flux at the IRAC 4.47 \( \mu \)m band is 52.9 Jy and at the 4.35 \( \mu \)m MSX-B2 band it is 72.1 Jy. This can be attributed to viewing the hotter side of the disk irradiated mostly by the F star (Taranova et al. 2001; Hoard et al. 2010). The systematic difference suggests an actual difference in the characteristics of the cool component between these two observations and no time variability on this has been established. However, disk heating by the primary is not considered in our models as overall disk heating is dominated by the hard UV photons from the hot central star, and recently taken Spitzer data where the differential heating is minimum are given more importance for modelling. This is adequate to study the disk physical and chemical properties.

### 4 RESULTS

We have computed model SEDs of the disk with the central star with different physical and chemical properties of dust in the disk. The central star has a spectral type of B5V with \( T_{\text{eff}} \) of 15 000 K and having a mass of 5.9 M\(_{\odot}\) and a surface gravity log \( g \) of 4.0 (Hoard et al. 2010). Models for the disk were computed with (1) grains with the ISM size distribution and having amorphous carbon chemistry, (2) grains with ISM chemical composition following the MRN size distribution but having sizes much larger than the ISM grains (10 to 100 \( \mu \)m), and (3) grains with large grain sizes following the MRN distribution function but having silicate alone and amorphous carbon alone dust chemistry.

For a given dust chemistry and for a given grain size distribution function, a dust model with absorption and scattering cross-sections, mass absorption coefficient and cosine asymmetry parameter

<table>
<thead>
<tr>
<th>Models</th>
<th>Grain chemistry</th>
<th>Grain size distribution</th>
<th>( T_{\text{disk}} ) at ( R_{\text{out}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>Amorphous carbon</td>
<td>( a_{\text{min}} = 0.05 )</td>
<td>261 K</td>
</tr>
<tr>
<td>Model 2</td>
<td>Amorphous carbon</td>
<td>( a_{\text{min}} = 10 )</td>
<td>252 K</td>
</tr>
<tr>
<td>Model 3</td>
<td>Amorphous silicate 60 per cent</td>
<td>( a_{\text{min}} = 10 )</td>
<td>292 K</td>
</tr>
<tr>
<td></td>
<td>Amorphous carbon 40 per cent</td>
<td>( a_{\text{min}} = 100 )</td>
<td>–</td>
</tr>
<tr>
<td>Model 4</td>
<td>Amorphous silicate</td>
<td>( a_{\text{min}} = 10 )</td>
<td>293 K</td>
</tr>
</tbody>
</table>

\( (g \) factor) for a wavelength range of 0.005 to 900 \( \mu \)m is computed using a MIE code. Grains are taken to be spherically symmetric and we have used the Henyey–Greenstein phase function (Henyey & Greenstein 1941) characterized by the g factor. This dust model file is called as an input by the \( \text{SRCDUST} \) radiative transfer code.

The wavelength-dependent optical constants for the astrophysical silicates and amorphous carbon required to calculate the dust model file were taken from Draine (2003) and Zubko et al. (1996), respectively, for all our models. The outer radius of the disk \( R_{\text{out}} \) is adapted from Kloppenborg et al. (2010), and is 3.8 au, and the inner radius \( R_{\text{in}} \) is decided by the dust sublimation temperature at the disc which is taken as 1500 K. Each model was taken from the best out of about 10 models computed. The flux output from the radiative transfer code is then added to the Kurucz model flux at each wavelength of an F0Iae post-AGB star with \( T_{\text{eff}} \) = 7700, log \( g \) \approx 1 (Castelli, Hoëst & Kondo 1982) and mass of 2.2 M\(_{\odot}\) with solar abundance (Castelli & Kurucz 2003) to obtain the final SED of \( \epsilon \) Aur. The model SED derived by this method is then subjected to interstellar extinction with a value of \( A_V = 1.1 \) found in the literature (Mozurkewich et al. 2003), which can be directly compared with the observations. The interstellar extinction curve needed for calculating the ISM contribution was computed empirically for all wavelengths using the method given by Fitzpatrick & Massa (2007).

In the following sections, we discuss the individual models of the disc in detail and compare them against the multiwavelength observations to constrain the nature of the grains in the disc and disc geometry and discuss the origin of the disc. The parameters of the models are listed in Table 2.

#### 4.1 Larger grains in the disc

As noted earlier by Kopal (1971) the eclipse of \( \epsilon \) Aur in the optical and near-IR wavelengths was observed to be approximately grey, indicating a larger grain population in the disc. Broad dust features are expected in the spectra if the grain sizes are much smaller than the central wavelength of the emission feature. When \( 2\pi a \) (\( a \) is the size of the grain) is smaller than \( \lambda \), constant emissivity will be seen for strongly absorbing materials and no spectral features will be found. As it was seen, the far-IR spectra of \( \epsilon \) Aur obtained with Spitzer IRS are smooth without any notable dust features (Hoard et al. 2010), suggesting grain sizes larger than 10 \( \mu \)m. Lack of solid-state features was also noted by Stencel et al. (2011) in their IR spectra. We examine here using radiative transfer models the absence of such broad dust features in the spectra of \( \epsilon \) Aur by taking a large grain size, and further propose here the expected
We have calculated dust models in the disc following the MRN grain size distribution; one having ISM grain sizes with \( a_{\text{min}} = 0.05 \) and \( a_{\text{max}} = 0.2 \) \( \mu \text{m} \) (model 1) and another having larger grain sizes with \( a_{\text{min}} = 10 \) and \( a_{\text{max}} = 100 \) \( \mu \text{m} \) (model 2). Both the dust models have amorphous carbon grain chemistry. These dust models are used for our radiative transfer simulation.

Monte Carlo radiative transfer in the disc was calculated with 10 million photons from the central star, to minimize ripples seen in the SED at a longer wavelength region. Models with different inclination angles of the disc were calculated, and the disc model corresponding to nearly edge-on viewing fits the observations better than others. The model SEDs of the \( \epsilon \) Aur system viewed at 87° and 60° are shown against observations in Fig. 2. The thermal images of the disc viewed at these two inclination angles and at three different wavebands (\( K \) band, \textit{Spitzer} IRAC 8 \( \mu \text{m} \) and \textit{Spitzer} MIPS 70 \( \mu \text{m} \) bands) are shown in Fig. 5. The grain sizes for model 2 were arrived at by gradually increasing the lower and upper limits of grain sizes from model 1. The minimum size is fixed at 10 \( \mu \text{m} \) by the disappearance of the IR features and the maximum size could be even larger as no notable changes are seen at the longer wavelength side of the considered range. Submillimetre fluxes will provide more insight.

The computed model SEDs using SEDDUST, after subjecting to the ISM extinction, were compared with the observations in Fig. 1. It can be seen that models with smaller grain sizes produce broad dust emission features in the far-IR region of the SED and the overall match to the observation is not good, whereas the model SED corresponding to the large grain population is nearly smooth at all wavelengths. The plot of computed dust opacity against wavelength for the ISM grain size distribution is also shown in the lower panel of Fig. 1. As seen in the radial temperature profile of model 2, the disc is sufficiently hot to show the features in emission if the grains are small in size; the minimum temperature observed at the outer edge of the disc is 252 K for model 2.

The radial temperature profile at the disc mid-plane is shown in Fig. 3. We conclude from our study that the grains in the disc of \( \epsilon \) Aur are much larger in size than the ISM grains. This may indicate a possibility of grain growth in the disc of \( \epsilon \) Aur. The mass of the disc is found to be low, 0.005 \( M_\odot \), for the assumed gas to dust mass ratio of 100. The SEDs do not fit with the observations in the shorter wavelength region (see Fig. 2), which may indicate an additional grain population with very small grains and having a wavelength-dependent opacity at the UV region as noted by Hoard et al. (2010).

### 4.2 Grain chemistry and the origin of the disc

#### 4.2.1 Disc with ISM grain chemistry

An important test which will give an idea on the origin of the disc is the grain chemistry in the disc. If the disc is a protoplanetary disc, then we expect the grain chemistry in the disc to be a mixture of amorphous silicates and amorphous carbon grains with mass proportion as seen in the ISM. We have run a radiative transfer model to investigate if the SED shows ISM dust chemistry. For the ISM dust model we have used bare spherical grains composed of 60 per cent of astronomical silicate and 40 per cent of amorphous carbon. The computed model SEDs using SEDDUST, after subjecting to the ISM extinction, were compared with the observations in Fig. 1.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Top: model SEDs of the disc with large size carbonaceous grains (solid line) and carbonaceous grains with ISM grain size distribution (dotted line). New AKARI fluxes are indicated as filled squares, Herschel measurements are shown squares with caps, Spitzer IRS spectra are shown as filled triangles and other photometric measurements are filled pentagons. Bottom: mass absorption coefficient of amorphous carbon (per gram of gas and dust) with ISM grain size distribution calculated using optical constants taken from Zubko et al. (1996).
Modelling the disc-shaped secondary of ϵ Aur

4.2.2 Disc with post-AGB envelope dust chemistry

To investigate if the disc originated from the mass transfer and/or accretion from the post-AGB primary on to its secondary, we have computed SEDs for disc models with silicate alone and amorphous carbon alone grain chemistry. If the primary were an evolved AGB star transferring mass through the Lagrangian point by Roche lobe overflow to its companion, then the dust grains in the disc should have pure silicate or pure amorphous carbon chemistry, depending on the mass and the evolutionary stage of the AGB primary at the time of mass transfer and/or accretion. We have made two dust model files separately with amorphous silicate and amorphous carbon grains, both following an MRN grain size distribution with sizes varying from $a_{\text{min}} = 10$ to $a_{\text{max}} = 100$ μm with a power-law exponent of $-3.5$. Monte Carlo radiation transfer through the disc was computed for these two dust models with 100 million photons from the central star to get a smooth SED at longer wavelengths. The SED obtained from the simulation was subjected to the interstellar extinction and then compared with the observations (see Fig. 3).

Our results imply that the disc model with amorphous carbon dust chemistry fits the observations better than the amorphous silicate dust chemistry which shows a steeper slope in the far-IR region. We suggest from our study that the grains in the disc of ϵ Aur are basically amorphous carbon, and it is quite unlikely that silicate dust is present in the disc. Hence, we conclude that the disc was formed from mass transfer and/or accretion from the C-rich post-AGB star (during a superwind mass-loss phase on the AGB) to its main-sequence companion. We took a gas to dust mass ratio of 100 which resulted in a disc mass less than 0.005 M$_\odot$. The radial temperature structure of the disc corresponding to these two models is shown in Fig. 4. The minimum grain temperature seen at the outer edge of the disc has a value of 293 K for the amorphous silicate model (model 4) and 252 K for the amorphous carbon model (model 2).
4.3 Does the disc have a central void?

It was discussed earlier in the literature if the disc of ϵ Aur has a central void or not. Hoard et al. (2010) argued on the presence of a void at the centre of the disc which was originally proposed by Wilson (1971) and Wilson & Van Hamme (1986) to explain the mid-eclipse brightening observed during the 1982–1984 eclipse (see also Budaj 2011). Our radiative transfer models also comply with this suggestion. For the given parameters of the central star and the disc, the radial temperature structure of the disc computed by the code for all models is shown in Fig. 4. As seen in the figure, the dust sublimation temperature of 1500 K determines the inner edge of the disc which is starting at around 2.0 au from the central star for all the models considered. If the central star is hot, as observed in the UV data (Parthasarathy & Lambert 1983b), a void near the star is expected and our study gives a quantitative estimate for the size of this void. Within this radius of 2 au the matter in the disc is dust free and hence it is more transparent. It is hence proposed that the mass distribution in the disc follows equation (1), from the outer edge of the disc (3.8 au) to the inner edge (2.0 au), and the relation breaks below this radius. It is possible that gaseous matter may be present in the void in neutral or ionized form which is free from dust. This void could cause the mid-eclipse brightening. Fig. 5 shows the thermal images of the disc simulated for the IRAC and MIPS bands from our code for inclinations of 87° and 60°.

We propose that the clearing of dust in the central hole of the ϵ Aur disc is due to the photo-evaporation processes (Clarke, Gendrin & Sotomayor 2001) as the inner edge of the disc is produced by the dust sublimation temperature. The transition region of the inner edge of the disc to the central hole is hence expected to be smooth, unlike for the case of the disc observed with LkHα330, where the dust clearing in the hole could be caused by gravitational perturbation (Brown et al. 2008). The inner edge of the ϵ Aur disc in our study is like the fixed structure model considered by Thi et al. (2011) which differs from their soft edge models with rounded inner rims showing enhanced near-IR continuum emission when viewed face on. For the case of ϵ Aur, where there is no enhanced near-IR emission observed and the disc is viewed edge-on, it is difficult to constrain the existence of a puffed-up inner edge from its SED.

5 CONCLUSIONS AND DISCUSSION

From solving the radiative transfer problem of the disc of ϵ Aur in the two-dimensional case, we conclude that the disc is less massive (0.005 M⊙) and is seen nearly edge-on. The dust grains in the disc are much larger than the ISM grains having sizes of 10 to 100 μm and they have carbonaceous dust chemistry. Silicate is not expected to be present. This shows a C-rich post-AGB as the primary of ϵ Aur. New AKARI data presented here fit well with the proposed model SED of ϵ Aur; however at 140 μm the deviation is significant, even after taking into account the error in the measurement. This may show the existence of more cool dust in the outer rim on the disc which is not considered by the model. More data in the far-IR region (near 140 μm) are needed to confirm this. The temperature structure of the disc for the computed models shows that the disc has a central void of radius 2 au. This void causes a mid-eclipsing brightening. Recently, Stencel et al. (2011), from IR studies of ϵ Aur during the recent eclipse, have concluded that the disc is dominated by...
Figure 4. Radial dust temperature profile of the disc mid-plane. Model 1 (top-left), model 2 (top-right), model 3 (bottom-left) and model 4 (bottom-right).

Figure 5. Thermal images of the $\epsilon$ Aur disc at the $K$ band and the IRAC 8 $\mu$m and MIPS 70 $\mu$m bands obtained from our models at inclination angles 60$^\circ$ (top, showing the central void) and 87$^\circ$ (bottom).
large grains. Bipolar dusty and gaseous discs have been detected around young and evolved stars from follow-up high-resolution imaging surveys of IRAS sources (Chesneau 2010). Among the post-AGB stars there are several objects with bipolar dust discs and some of them were found to be single-lined spectroscopic binaries (Chesneau 2010). A circumstellar dust disc has been found around the evolved binary Upsilon Sagittarii (Netolicky et al. 2009). Also, a large Hα forming region has been found around Beta Lyrae and Upsilon Sagittarii (Bonneau et al. 2011). The Hα profile in the outside eclipse spectra of ε Aur suggests the presence of a similar large Hα envelope or ring around the FOaе star. Shell spectra produced from our study can be taken only as the lower limit as it is the mass of an annular disc with inner radius 2 au and outer radius 3.8 au.

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