2D Monte-Carlo Radiative transfer modeling of the disk shaped secondary of Epsilon Aurigae

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Abstract

We present two dimensional Monte-Carlo radiative transfer models for the disk of the eclipsing binary $\epsilon$ Aur by fitting its spectral energy distribution from optical to the far-IR wavelengths. We also report new observations of $\epsilon$ Aur made by AKARI in its five mid and far-IR photometric bands and were used to construct our SED. The disk is optically thick and has flared disk geometry containing gas and dust with a gas to dust mass ratio of 100. We have taken the primary of the binary to be a F0Iae-type post-AGB star and the disk is heated by a B5V hot star with a temperature of 15,000 K at the center of the disk. We take the radius of the disk to be 3.8 AU for our models as constrained from the IR interferometric imaging observations of the eclipsing disk.
Our models imply that the disk contains grains which are much bigger than the ISM grains (grain sizes 10\(\mu\) to 100\(\mu\)). The grain chemistry of the disk 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 disk shaped secondary in \(\epsilon\) Aur system could be the result of accretion of matter and or mass transfer from the primary which is now a F0Iae post-AGB star. It is not a proto-planetary disk. The disk is seen nearly edge on with an inclination angle larger than 85\(^o\). We propose from our radiative transfer modeling that the disk is not solid and have a void of 2AU radius at the center within which no grains are present making the region nearly transparent. The disk is not massive, its mass is derived to be less than 0.005M\(_{\odot}\).

1. Introduction

Epsilon Aurigae (HD 31964; \(\epsilon\) Aur hereafter) is an eclipsing binary with an orbital period of 27.1 years showing 0.75 mag depth in optical during eclipse and the primary is occulted by the disk shaped secondary causing two year long eclipse (Guinan & De-Warf 2002, Carroll et al. 1991, and Parthasarathy & Frueh 1986). The eclipse depth is independent of wavelength, but the depth, 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 parellal to the binary orbit. IR observations made by Woolf (1973) revealed an excess emission in the infrared. The observations carried out during the previous eclipises and particulary the 1982 - 1984
eclipse and the recent 2009 - 2011 eclipse reveal the presence of a dusty plus gaseous disk in ϵ Aur, which is the body causing a two year long eclipse. The presence of neutral gas in and around the disk 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 K I 7699Å 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$M_\odot$ and the other one is the low mass star model with the primary having a mass of 4$M_\odot$. The optical spectra of ϵ Aur near the end of 1954-1956 eclipse was used to hypothesize the presence of a Be like hot star at the center of a large disk, from deducing the electron density at the disk (Hack 1961). Later, the IUE UV observations during the 1982 - 1984 eclipse implied the presence of a hot source inside the disk which can be fitted by a B5V star (Parthasarathy & Lambert (1983b), Ake & Simon (1984), Boehm, Ferluga & Hack (1984), Chapman, Kondo & Stencel (1983), Alter et al. (1986), Hoard et al. (2010)).

The mass ratio of the primary to the secondary obtained from binary solution is 0.62 (Kloppenborg et al., 2010) which constrains a lower mass for the primary of ϵ Aur. Accurate distance measurement by Hipparcos (650pc, Perryman et al. 1997) and in turn an estimate on intrinsic luminosity of the primary also does not favour for a high mass star model.

Enhancement of N, Na and s-process elements were found in the atmosphere of the
primary by Sadakane et al. (2010) in their high resolution optical spectroscopy. This may indicate the occurrence of third dredge-up and s-process nucleosynthesis in the primary of $\epsilon$ Aur, suggesting again a post-AGB primary for $\epsilon$ Aur. It is now fairly established that the $\epsilon$ Aur system consists a post-AGB star, a B5 type main sequence secondary and a disk of gas and dust.

Recently Stefanik et al. (2010) reported an updated single-lined spectroscopic solution for the orbit of the F0Iae 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 strongest constraint on the ephemeris. From this they find a period of 9896 days (27.0938 years) 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 F0Iae primary star. Other notable recent results are the infrared images of the transiting disk by Kloppenborg et al. (2010) and interferometric studies by Stencel et al. (2008). More recently Stencel et al. (2011) made detailed infrared studies of $\epsilon$ Aur during the 2009 - 2011 eclipse. Disks are among most common astrophysical systems, and a powerful technique for observing them is stellar occultation method (Forrester & Lissauer 1982). $\epsilon$ Aurigae offers this opportunity to a new class of disks which are associated with post-AGB
stars. $\epsilon$ Aur disk was described variously as thick (Huang 1965) or thin, flat or twisted, opaque or semi transparent, fully solid or possessing a central hole. A wealth of data are now available in the literature from UV to the far-IR wavelengths, which can give an insight into the nature of the disk.

From the 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 a F0Iae post-AGB star and a B5V type main sequence star surrounded by a geometrically thin and partially transparent disk. They proposed a single-temperature black body model for the disk and constrained the disk to have a temperature of 550K, a size of 3.8 AU with a thickness of 0.95 AU and is viewed nearly edge on. Their model deals with average bulk properties of the disk with cylindrical volume and assumes an uniform mass distribution. However, the nature of the disk with more realistic characteristics such as radial density distribution and temperature profile, scale height and grain chemistry obtained through a 2D radiative transfer modeling and addressing its origin are not yet available.

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

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

2. SED of $\epsilon$ Aur

To construct the SED of $\epsilon$ Aur from far-UV to the 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 IRAS and MSX space missions. Mid-IR spectra from 9.89 to 37.14 $\mu$m were taken from Spitzer Heritage Archive. Photometric measurements of Herschel infrared 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$\mu$, 18.0$\mu$, 65.0$\mu$, 90.0$\mu$ and 140.0$\mu$, 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. Majority of these observations were ob-
tained prior to the onset of the 2009 eclipse but well after the end of the 1984 eclipse.

3. Radiative Transfer Modeling

To solve the radiative transfer problem in the disk 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 disks (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 well be applied to astrophysical systems having axial symmetry geometry with disk, envelope and outflow components which are illuminated by a central star. Physical properties of the star and physical and geometrical parameters of the disk with an appropriate dustmodel 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. $SRCDUST$ provides disk temperature structure and synthesized SED of the star and the disk at 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 accretion process and hence we use a standard flared accretion density structure (Lynden-Bell & Pringle 1974) described as

$$\rho = \rho_0(1 - (R_{\text{star}}/\omega)^{0.5})(R_{\text{star}}/\omega)^{3/2}e^{xp(-1/2(z/h(\omega))^2)}$$

Eqn. 1.
Where, $\omega$ is the radial coordinate of the disk midplane and the scale height increases with radius as $h = h_0(\omega/R_{\text{star}})^\beta$. For our models we adopt flaring parameter $\beta = 1.25$ 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, Vinkivic 2012, Thi, Woitke & Kamp 2011) and the value of $\alpha = 3(\beta - 0.5) = 2.25$ (Shakura & Sunyaev 1973). We take $h_0 = 0.05R_{\text{star}}$ such that the disk will have a thickness of 0.76AU at its outer edge of radius 3.8AU 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 were 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, differs from MSX measurement obtained at phase 0.5 which are systematically brighter in the 3-5 $\mu$ region. Photometric flux at IRAC 4.47$\mu$ band is 52.9 Jy and at 4.35 $\mu$ 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 (Hoard et al 2010, Taranova et al 2001). 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 is given more important for modeling. 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 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 MRN size distribution but having sizes much larger than the ISM grains (10$\mu$ to 100 $\mu$) and 3) grains with large grain sizes following 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, the mass absorption coefficient and the cosine asymmetry parameter (g factor) for a wavelength range of 0.005 $\mu$ to 900 $\mu$ is computed using a mie code. Grains are taken to be spherically symmetric and we have used Henyey-Greenstein phase function (Henyey & Greenstein 1941) characterised by the g factor. This dustmodel file is called as an input by the $SRCDUST$ radiative transfer code.

The wavelength dependent optical constants for the astronomical silicates and amorphous carbon required to calculate the dustmodel 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 Kloppenbourg et al. (2010), which is 3.8 AU and the inner radius $R_{\text{in}}$ is decided by the dust sublimination temperature at the disk which is taken as 1500 K. Each model was taken from 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 a F0Iae post-AGB star with $T_{\text{eff}} = 7700$, log $g \sim 1$ (Castelli, Hoekstra & 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 was then subjected to the 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 ISM contribution was computed empirically for all wavelengths using the method given by Fitzpatrick & Massa (2007).

In the following sections we discuss individual models of the disk in detail and compare them against the mutiwave length observations to constrain the nature of the grains in the disk and disk geometry and discuss the origin of the disk.

4.1 Larger grains in the disk

As noted earlier by Kopal (1971) the eclipse of $\epsilon$ Aur in the optical and near-IR wavelengths was observed to be approximately gray, indicating a larger grain population in the disk. 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 a grain sizes larger than 10 \( \mu \). Lack of solid state features were also noticed 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 large grain size and further propose here the expected grain sizes in the disk of \( \epsilon \) Aur. We have calculated dust models in the disk following MRN grain size distribution and one having ISM grain sizes with \( a_{\text{min}} = 0.05\mu \) and \( a_{\text{max}} = 0.2\mu \) (model 1) and another having larger grain sizes with \( a_{\text{min}} = 10\mu \) and \( a_{\text{max}} = 100\mu \) (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 disk was calculated with 10 million photons from the central star, to minimize ripples seen in the SED at longer wavelength region. Models with different inclination angles of the disk were calculated, and the disk model corresponds to nearly edge-on viewing fits the observations better than others. The model SED of the \( \epsilon \) Aur system viewed at 87\( ^{\circ} \) and at 60\( ^{\circ} \) are shown against observations in Fig 2. The thermal images of the disk viewed at these two inclination angles and at three different wavebands (K band, SPITZER IRAC 8\( \mu \)m and SPITZER MIPS 70 \( \mu \) bands) are shown in Fig 5. The grain sizes for model 2 were arrived by gradually increasing the lower and upper limits of grain sizes form model 1. The minimum size is fixed at 10\( \mu \) by the disappearance of the IR features and the maximum size could be even larger as no notable changes are seen at longer
wavelength side of the considered range. Sub-mm fluxes will say more on it.

The computed model SEDs using \textit{SRCDUST}, after subjecting to the ISM extinction, were compared with the observations in Fig 1. It can be seen that model 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 model 2, the disk is sufficiently hot to show the features in emission if the grains are small in sizes, the minimum temperature observed at the outer edge of the disk is 252 K for the model 2.

The radial temperature profile at the disk midplane is shown in Fig. 3. We conclude from our study that the grains in the disk of \( \epsilon \) Aur are much larger in size than the ISM grains. This may indicate a possibility of grain growth in the disk of \( \epsilon \) Aur. Mass of the disk 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 depended opacity at UV region as noted by Hoard et al. (2010).

4.2. Grain Chemistry and the origin of the disk

4.2.1 Disk with ISM grain chemistry
An important test which will give an idea on the origin of the disk is the grain chemistry in the disk. If the disk is a protoplanetary disk then we expect the grain chemistry in the disk 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 with 60% of astronomical silicate and 40% of amorphous carbon in mass. As we have seen that the grains in $\epsilon$ Aur disk are larger in size, we have taken a grain size distribution with $a_{\text{min}} = 10.0 \mu$ and $a_{\text{max}} = 100 \mu$ following standard MRN power law with an exponent of $q = -3.5$ (model 3) to compute the dustmodel file required for the radiative transfer simulation.

Monte Carlo radiative transfer through the disk was calculated for this dustmodel with 10 million photons from the central star to get the model SED. After subjecting to the ISM extinction, the best fit SED to the observation implies that the disk is inclined to the line-of sight with an angle larger than 85 degrees. The disk mass was estimated to be $0.005 \, M_\odot$ assuming a gas to dust mass ratio of 100. The computed SEDs corresponding to this model is plotted against the observed data points in Fig 3. As seen in the figure, the model fit is not good enough. It shows a shallower slope in the far-IR region when compared with the observations. This implies that the grain chemistry in the disk of $\epsilon$ Aur does not resemble with the ISM grain chemistry. The radial temperature profile in the disk midplane for this model is shown in Fig 3. The minimum temperature at the outer edge of the disk for this model is 292 K.

4.2.2 Disk with post-AGB envelope dust chemistry
To investigate if the disk was originated from the mass transfer and/or accretion from the post-AGB primary on to its secondary, we have computed SEDs for disk models with silicate alone and amorphous carbon alone grain chemistry. If the primary were to be an evolved AGB star transferring mass through the lagrangian point by Roche lobe overflow to its companion, then the dust grains in the disk 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 dustmodel files separately with amorphous silicate and amorphous carbon grains, both following a MRN grain size distribution with sizes varying from $a_{\min} = 10\mu$ and $a_{\max} = 100\mu$ with a power law exponent of -3.5. Monte Carlo radiation transfer through the disk was computed for these two dustmodels 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 disk 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 disk of $\epsilon$ Aur are basically amorphous carbon, and it is quite unlikely that silicate dust is present in the disk. Hence we conclude that the disk was formed from mass transfer and/or accretion from the C rich post-AGB star (during superwind mass-loss phase on AGB) to its main sequence companion. We took a gas to dust mass ratio of 100 which resulted a disk mass less than 0.005 $M_\odot$. The radial temperature structure of
the disk corresponding to these two models are shown in Fig. 4. The minimum grain temperature is seen at the outer edge of the disk has a value of 293 K for amorphous silicate model (model 4) and 252 K for amorphous carbon model (model 2).

4.3 Does the disk have a central void?

It was discussed earlier in the literature if the disk of ǫ Aur has a central void or not. Hoard et al. (2010) argued on the presence of a void at the center of the disk which was originally proposed by Wilson (1971) and Wilson & Van Hamme (1986) to explain the mid-eclipse brightening observed during 1982-1984 eclipse. Our radiative transfer models also comply with this suggestion. For the given parameters of the central star and the disk, the radial temperature structure of the disk computed by the code for all models are shown in Fig 4. As seen in the figure, the dust sublimation temperature of 1500K, which determines the inner edge of the disk 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 disk is dust free and hence it is more transparent. It is hence proposed that mass distribution in the disk follows Eq. 1, from the outer edge of the disk (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 disk simulated for IRAC and MIPS bands from our code for inclination of 87° and 60°.
We propose that the clearing of dust in the central hole of $\epsilon$ Aur disk is due to the photo evaporation processes (Clarke et al. 2001) as the inner edge of the disk is produced by the dust sublimation temperature. The transition region of the inner edge of the disk to the central hole is hence expected to be smooth, unlike for the case of the disk observed with LkHa330, where the dust clearing in the hole could be caused by gravitational perturbation (Brown, Black, Qi et al. 2008). The inner edge of $\epsilon$ Aur disk in our study is like the fixed structure model considered by Thi, Woitke & Kamp (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 $\epsilon$ Aur, where there is no enhanced near-IR emission observed and the disk 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 disk of $\epsilon$ Aur in 2D case, we conclude that the disk is less massive ($0.005 M_\odot$) and is seen nearly edge on. The dust grains in the disk are much larger than the ISM grains having sizes of 10 $\mu$ to 100 $\mu$ and have carbonaceous dust chemistry. Silicate is not expected to be present. This shows a C rich post-AGB as the primary of $\epsilon$ Aur. New AKARI data presented here fit well with the proposed model SED of $\epsilon$ Aur, however at 140 $\mu$ the deviation is significant, even after taking into account of the error in the measurement. This may show existence of more cool dust in the outer rim on the disk which is not considered by the model. More data in the far-IR region (near 140 $\mu$) is needed to
confirm this. The temperature structure of the disk for the computed models shows that the disk has a central void of radius 2 AU. This void causes a mid eclipsing brightening. Recently Stencel et al. (2011) from infrared studies of ε Aur during the recent eclipse conclude that the disk is dominated by large grains. Bipolar dusty and gaseous disks have been detected around young and evolved stars from followup high resolution imaging surveys of IRAS sources (Chesneau 2010). Among the post-AGB stars there are several objects with bipolar dust disks and some of them were found to be single lined spectroscopic binaries (Chesneau 2010). Circumbinary dust disk has been found around the evolved binary Upsilon Sagittarii (Netolicek et al. 2009). Also, large H-alpha forming region has been found around Beta Lyrae and Upsilon Sagittarii (Bonneau et al. 2011). The H-alpha profile in the out side eclipse spectra of ε Aur suggests presence of similar large H-alpha envelope or ring around the F0Iae star. Shell spectra produced by the gaseous envelope of the disk, as presented by Ferluga & Mangiacapra (1991) can constrain if the void is empty or filled with neutral and ionized gases. IR spectra will help as it is expected that the IR spectrum will be dominated by the nebular lines of the disk than the photosphere of the primary (Stencel 2007). The disk mass estimated from our study can be taken only as the lower limit as it is the mass of an annular disk with inner radius 2 AU and outer radius 3.8 AU.

6. Acknowledgements

We are thankful to Prof. Yoshifusa Ita for providing us the AKARI infrared fluxes of Epsilon Aurigae. MP is thankful to Prof. Shoken Miyama and Prof. Yoichi Takeda.
for their kind support, encouragement and hospitality. We are thankful to the referee for valuable comments which have improved the paper significantly.

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| Wavelength ($\mu$) | Flux (Jy) | Flux quality | Error (Jy) |
|-------------------|-----------|--------------|------------|
| 9.0               | 21.4143   | 3            | 0.128868   |
| 18.0              | 5.44896   | 3            | 0.0576079  |
| 65.0              | 0.509413  | 1            | –          |
| 90.0              | 0.44311   | 3            | 0.0615824  |
| 140.0             | 2.11441   | 1            | 1.01968    |

Table 1: New AKARI data obtained in its mid and far-IR bands.
Figure 1: Top: Model SEDs of the disk with large size carbonaceous grains (solid line) and carbonaceous grains with ISM grain size distribution (dashed line). New AKARI fluxes are indicated in filled squares, Herschel measurements are shown in square with caps, SPITZER IRS spectra is shown in filled triangles and other photometric measurements are in filled pentagon; Bottom: mass absorption coefficient of amorphous carbon (for unit gram of gas and dust) with ISM grain size distribution calculated using optical constants taken from Zubko et al.(1996).
Figure 2: Model SED fit to the observations from UV to far-IR wavelengths; solid line shows SED of disk at an inclination of 87° (model 2) and dashed line shows SED at 60° inclination. GHRS data are shown in circular points and data description for other measurements are as in Fig 1. Dotted line indicate the stellar photospheric flux without IR excess.
Figure 3: Model SEDs of the disk with a) amorphous carbon grains (solid line) b) amorphous silicate grains (dashed line) c) grains having ISM dust chemistry (dotted line). Data description is as in Fig 2.
Figure 4: Radial dust temperature profile of disk midplane. Model 1 (top left), model 2 (top right), model 3 (bottom left) and model 4 (bottom right).
Figure 5: Thermal images of $\epsilon$ Aur disk at K band, IRAC $8\mu$ and MIPS $70\mu$ bands obtained from our models at inclination angles $60^\circ$ (top, showing the central void) and $87^\circ$ (bottom).
| Models       | Grain Chemistry                        | Grain Size distribution | $T_{dust}$ at $R_{out}$ |
|--------------|----------------------------------------|--------------------------|-------------------------|
| Model 1      | amorp. carbon                          | $a_{min} = 0.05\mu$      | 261 K                   |
|              |                                        | $a_{max} = 0.2 \mu$      |                         |
| Model 2      | amorp. carbon                          | $a_{min} = 10\mu$        | 252 K                   |
|              |                                        | $a_{max} = 100\mu$       |                         |
| Model 3      | amorp. silicate 60%                    | $a_{min} = 10\mu$        | 292 K                   |
|              | amorp. carbon 40%                      | $a_{max} = 100\mu$       |                         |
| Model 4      | amorp. silicate                        | $a_{min} = 10\mu$        | 293 K                   |
|              |                                        | $a_{max} = 100\mu$       |                         |

Table 2: Parameters of the radiative transfer models discussed in the text.