Resolve partially the inner disk for Epsilon Eridani

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Abstract. We present mid-infrared imaging observations of the debris disk around one of the main sequence star Epsilon Eridani in the Q-band at (20.5 µm) and (17.6 µm). The dust that produces emission in debris disk is spatially resolved in the inner region of the debris disk of Epsilon Eridani at distance approximately between 1.4 - 4 AU.

Method: The target has been observed Epsilon Eridani using the GTC (Gran Telescope Canaria) with CanariaCam instrument, which performs imaging in mid-IR (Q-band). To detect the disk around Epsilon Eridani star, we observed a standard star and the target star, consequently. We then measured the PSF (Point Spread Function) of our standard star to limit the radial flux profile of our target star. The images were centred to the center images before subtracted the radial flux of the standard star from the radial profile of science target to get the residual flux which is produced by the debris disk. The first important step is removing the background effect from images with contribution flux of star. For this, we calculated the standard deviation of background as well as the seeing variation during the observation to estimate the value of stellar flux residuals.

Result: The dust emission around the debris disk is spatially resolved and the size of the emission is determined. The dust detected around Epsilon Eridani is located in the same distance from the star where a giant planet has confirmed. The photometry measurements are achieved for emission 0.268 Jy and the flux of the star is 2.18 Jy.

1. Introduction

Epsilon Eridani (HD 22049, HIP 16537) is a main-sequence star has as spectral type K2V and its age between 0.5 - 1 Gyr. Its mass is 0.8 Mʘ and distance is 3.2 pc. It is coordinate in the sky α=03:32:55.84, δ= 09:27:29. It is one of the first four stars that debris disk is detected IRAS in 1983 and it is one of the so-called Fabulous four (Aumann et al., 1985; Gillett et al., 1986).

Greaves et al. (1998, 2005) resolved the disk and measured the size of the dust ring around the star between 30-60 AU and he estimate its mass to be 0.04-0.3 Earth mass. He found inhomogeneity in the ring that suggests the presence of a large orbiting body either within the ring or just inside in.
In addition to that, some studies confirmed the two giant planets in the inner region of the debris disk which are observed using the radial velocity method Hatzes et al. (2000), Moran et al. (2004), Benedict et al. (2006).

Backman et al. (2009), observed Epsilon Eridani using the Spitzer and Caltech Sub-millimeter telescope at wavelengths. He noticed that the more than 95 % of the Infrared emission between 20 µm - 30 µm at T = 100 K - 150 K comes from two inner belts. These two inner belts consist of astronomical silicate grains with a size of the grains of 3 µm for both belts.

Greaves et al. (2014) suggest that could be detected outer warm belt at distance 12 - 16 AU using Herschel far-infrared images of the system. Recently, Kate Y. L. Su et al. (2017) resolved the debris disk around Epsilon Eridani by using SOFIA observatory and confirmed the dust emission at distance 25 AU.

In the last ten years, there are many of the debris disk have been detect using ground telescopes at infrared wavelength. Therefore, this motivates us to investigate the exozodiacal dust of inner debris disk for Epsilon Eridani by using a high angular resolution technique at Mid-Infrared wavelength.

2. Observations

The observations were obtained with Canaricam/GTC in the Q4 filter with \( \lambda c = 20.5 \) µm and \( \Delta \lambda = 1 \) µm. The log of the observations is given in Table 1. We reduced the data using the IDL package iDealCam designed for Canaricam (Li et al., 2013). We implemented frame selection on our data in order to discard the frames which image quality is significantly degraded by to pointing or chopping errors etc...

We first performed this selection by visual inspection for each save-set or nodeset, then combined the dataset to the final image after recentering each image using a Lorentzian fit to the PSF. As Eridani is a sufficiently bright source, we could perform this operation on the individual save-sets. For Gamma Eridani the selection was made among the nodeset frames, which are obtained by stacking several save-sets. This is due to Epsilon Eridani being significantly fainter than the PSF reference and hardly observable in the individual frames/save-sets.

As the reduced frames may suffer from horizontal stripping, an additional background subtraction operation was included to mitigate this effect by subtracting averaged columns.

Table 1. Summary of Epsilon Eridani observations in the Q4 filter on 6th of January 2013.

| Target   | UT               | Filter | On-source | Airmass | Seeing ["] | PWV [mm] | Flux standard       |
|----------|------------------|--------|-----------|---------|-------------|----------|--------------------|
| 80 Cet   | 19:55:04 - 19:58:36 | Q4     | 165       | 1.27    | 1.15 - 1.17 | 5.9      | photometric Cal.   |
| Gamma Eri | 20:35:54 - 20:39:27 | Q4     | 134       | 1.466   | 1.08 - 1.73 | 5.6      | PSF and phot. Cal. |
| Epsilon Eri. | 20:50:33 - 21:25:33 | Q4    | 1568      | 1.28    | 1.54 ± 0.05 | 5.4      | Science            |
| Gamma Eri | 21:45:42 - 21:49:14 | Q4     | 113       | 1.353   | 1.5        | 5.2      | PSF and phot. Cal. |
| Gamma Eri | 20:35:54 - 20:39:27 | Q4     | 108       | 1.351   | 1.4        | 5.2      | PSF and phot. Cal. |
| Epsilon Eri. | 20:50:33 - 21:25:33 | Q4     | 1568      | 1.306   | 1.20 ± 0.1 | 5.2      | Science            |
| Gamma Eri | 21:45:42 - 21:49:14 | Q4     | 139       | 1.39    | 1.27       | 6.0      | PSF and phot. Cal. |

80 Cet 23:00:50 - 23:04:21 Q4 165 1.55 1.32 - 1.15 5.9 Photometric Cal.
3. Data reduction
We reduced the data with iDealCam and performed shift-and add on individual savesets or nodsets to improve the Strehl ratio. The bad frames were detected visually and flagged to be discarded from data processing. These frames correspond to situations where strong elongations of the core is detected or when bright horizontal detector stripes pass through the PSF.
Figure (1) represents the values of the The Full-Width Half Maximum (FWHM) of the calibration star and the science stars after choosing good frames visually. The Full-Width Half Maximum (FWHM) values of good frames for Gamma Eridani are represented in the black open circles and the Full-Width Half Maximum (FWHM) values of good nodsets for Epsilon Eridani are represented in the red circles. The theoretical diffraction limit value of the GTC telescope (0.45\textdegree) in the Q4 filter is represented in the black dashed line.
We have performed a non linear least-square fits for every saveset of the calibration (Gamma Eridani) star and every node of the science star (Epsilon Eridani). For each saves, respectively nodes, we measured the ellipticity of the PSF and found a value of ±0.1 for the remaining frames.

![Figure 1](image.png)

**Figure 1.** Represent the values of the (FWHM) after selecting visually good and bad frames for two stars Gamma Eridani and Epsilon Eridani.

The bad frames have discarded visually according to the shape of the PSF (elongated PSF shape) and the values of the Full-Width Half Maximum (FWHM) are less than the value of the diffraction limit of the telescope (0.45\textdegree). The average values of the FWHM have extracted for the good frames of the reference and science stars as shown in table 2.
### Table 2. FWHM and the 3σ uncertainty on the mean. FWHM is the statistical measurement over many frames using the Lorentzian fit.

| Target   | Total Time[Sec] | FWHM[''] |
|----------|-----------------|----------|
| Gamma Eri. | 103             | 0.490±0.004 |
| Epsilon Eri. | 577.98          | 0.522±0.006 |
| Gamma Eri. | 103             | 0.499±0.005 |
| Gamma Eri. | 93              | 0.503±0.003 |
| Epsilon Eri. | 557.34          | 0.520±0.002 |
| Gamma Eri. | 124             | 0.491±0.003 |

4. **Full-Width-at-Half-Maximum**

We have used a statistical technique called (Student t-test) to resolve debris disk variances (Moerchen et al., 2010). Resolving the disk using this technique is by taking the difference between mean values of the FWHM for the science from the FWHM of the calibrator as defined in this equation:

\[
\text{FWHM}_{\text{sci}} - \text{FWHM}_{\text{cal}} \geq 3 \sigma_{\text{ext}}
\]  

(1)

where FWHM\(_{\text{sci}}\) is the mean of the FWHM measurements for the selected saveset of the science star and FWHM\(_{\text{cal}}\) is the mean of the FWHM measurements for the selected saveset of the calibration stars. \(\sigma_{\text{ext}}\) is the combined standard deviation of the mean and calculated as follows:

\[
\sigma_{\text{ext}} = \sqrt{\sigma_{\text{sci}}^2 + \sigma_{\text{cat}}^2}
\]  

(2)

where \(\sigma_{\text{sci}}^2\) is the standard deviation of the mean of the FWHM measurements of the science star and \(\sigma_{\text{cat}}^2\) is the standard deviation of the mean of the FWHM measurements of the calibration star.

The seeing has a very strong influence on the Mid-Infrared observations which effect on the FWHM values for the calibration and science stars. Therefore, the Student t-test technique is very proper to examine the values of the FWHM for the reference and science stars during the observation. The disk resolved or unresolved for the two observations of the science star (Epsilon Eridani) with four observations of the reference star (Gamma Eridani) is presented in Table 3.
**Table 3.** Shows the results of disk resolved or not for both observations of Epsilon Eridani after implement Student t-test technique (Moerchen et al., 2010).

| Calibrator    | FWHM_{sci}-FWHM_{cal} | 3σ_{ex} | Disk Resolved |
|---------------|------------------------|---------|---------------|
| **Epsilon-1** |                        |         |               |
| Gamma Eri.-1  | 0.032                  | 0.020   | YES           |
| Gamma Eri.-2  | 0.023                  | 0.023   | NO            |
| Gamma Eri.-3  | 0.019                  | 0.020   | NO            |
| Gamma Eri.-4  | 0.031                  | 0.020   | YES           |
| **Epsilon-2** |                        |         |               |
| Gamma Eri.-1  | 0.030                  | 0.013   | YES           |
| Gamma Eri.-2  | 0.030                  | 0.016   | YES           |
| Gamma Eri.-3  | 0.017                  | 0.010   | YES           |
| Gamma Eri.-4  | 0.029                  | 0.011   | YES           |

The results of the average of the FWHM with one sigma uncertainty for reference and science stars are plotted in Figure 2.

![Figure 2](image.png)

**Figure 2.** The average of the FWHM with 1 sigma uncertainty for Gamma Eridani (reference star) is shown in the black circles. The average of the FWHM with 1 sigma uncertainty for the Epsilon Eridani (science star) is shown in the red circles

5. **Radial Profiles**
We have plotted the radial profile of the point spread function (PSF) distribution in one dimension for the final images of Epsilon and Gamma Eridani after sub-pixel re-centering. The subfigure (3-a) and subfigure (3-b) show the radial profile of the two observations of Epsilon Eridani (red dotted line) compared with the radial profile of the four observations of Gamma Eridani (blue dotted line).
6. Results

1. The impact of the seeing is remarked on the first observation of the Epsilon Eridani. The value of the optical seeing is larger than 1.5 arcsecond. Due to that, the PSF of the science star was unstable during the observation. The emission of the disk around Epsilon Eridani is unresolved for Epsilon Eridani-1 observation with Gamma Eridani-2 and 3 observations, but resolved with Gamma Eridani-1 and 4 observations.
2. The emission of dust around the Epsilon Eridani star is resolved with 3 sigma uncertainty and radius of the emission is estimated to be 0.3 AU, the results are summarized in Table 3. In spite of the science star (Epsilon Eridani) is a very faint object and a bad optical seeing during the observation, the disk is partially resolved with 3 sigma significance after applying the different techniques to examine the point spread function (PSF).

3. The photometry measurements are archived using iDealCam software. We have extracted the average of the flux value for science star Epsilon Eridani in Q4 filter and is 2.49 Jy.

4. The uncertainty of the flux measurements for the two observations of Epsilon Eridani is 7 %. The value of the flux is equivalent to other measurements from Spitzer space telescope which is 2.48 Jy at wavelength 20.5 µm (Backman et al., 2009).

Acknowledgments
This work is supported by the University of Baghdad, College of Science. We are thankful to the Sky Team of the IAC for providing us with the seeing data. We would also like to express our gratitude to Prof. Lucas Labadie at University of Cologne for assistance and comments during the work.

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