# Practice session I Interferometry basics with RSPRO

Corrections

#### 2 Our first model : the uniform disk

It is now time to play with a first model. The one already loaded in the *Example1.asprox* file is a uniform disk. It is the grounding of almost all interferometric-data analysis, and it is very often used, not only to perform stellar diameters fits, but also first-order interpretations of any extended objects.

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### Question : Give the same expression with the stellar diameter and wavelength expressed in mas and $\mu {\rm m},$ respectively.

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 $\theta = 4 \text{ mas}$ 

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### Practice session I: Interferometry basics with ASPRO

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#### File Edentify WLTI School of Interferometry Practice Session I: Interferometry basics 🕼 Targets Main settings Configuration(s) Q V Simbad Interferometer DEMO S0 S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12 S13 S14 S15 Night restriction S0 S7 Date 2010/09/21 ♦ 00:00:00.000 89:00:00.000 -Instrument DEMO SPATIAL Editor Min. Elevation 30 Wind 0 Status: 1 Information Sky Map Observability UV coverage OlFits viewer Notebook plot data DEMO - DEMO [0.460 µm - 0.460 µm] - S0-S1-S2-S3-S4-S5-S6-S7-S8-S9-S10-S11-S12-S13-S14-S15-S16 Day: 2010-09-21 - Source: 00:00:00.000 89:00:00.000 1.1 1.0 0.9 0.8 0.7 **Positive Visibility Negative Visibility Positive Visibility dWF** 0.6 0.5 0.4 Negative Visibility Phase = $0^{\circ}$ Phase = $180^{\circ}$ Phase = $0^{\circ}$ Phase = $180^{\circ}$ 0.3 0.2 0.1 0.0 OIFitsExplorer/JMM -0.1 150 100 $V(\rho) = 2^{J_{1}(\pi\rho\theta)}$ **NISPHI (deg)** Centro-symmetric object 🗇 Real Fourier Transform Phase=0° (positive number) Phase=180° (negative number) -100 -150 -200 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 0 105 RADIUS (m) [21.161, 0.638] Infos: 136 / 136 points Data: X[1.000, 100.986] Y[2.484E-4, 0.998] Data+Err: X[1.000, 100.986] Y[2.484E-4, 0.998] A D F Show VISAMP, VISPHI vs RADIUS ▼ Color by effective wav... ▼ □ Skip Flagged □ Draw lines ▼ 🗌 log 🖌 inc. 0 🔾 auto 🖲 default 🔾 fixed x Axis RADIUS ▼ 🗌 log 🔲 inc. 0 ○ auto 🖲 default 🔾 fixed VISAMP y Axes 💌 📃 log 📃 inc. 0 🔘 auto 🖲 default 🔾 fixed VISPHI

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The object is centro-symmetric ⇔

Its Fourier Transform is Real The phase is 0 (positive number) or 180° (negative)

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> B(V=0) ≈ 29m Amplitude ≈ 0.132

# 3. Few other 1D distributions

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### Practice session I: Interferometry basics Cith ASPRO

#### 3.1 Limb darkened disk

Question : Note the baseline length corresponding to the first zero of visibility and the secondlobe amplitude.

Now imagine you would estimate the size of this 4mas limb-darkened star by measuring the position of the first zero of visibility and using the formula determined for a uniform disk in the previous section.

Question : Does the star appears bigger or small than its real size? Explain why.

Question : How can you discriminate between the uniform disk and the limb darkened disk?

#### 3.2 Gaussian distribution

Change the model to a "gaussian" (remove previous), and click on Add. Look at the new set of parameters shown in the bottom part of the window. This model has also four parameters, i.e. *flux\_weight1*, x1, y1 like for all models, and *fwhm1*, the full width at half maximum of the Gaussian distribution. Let's set this value to 4 mas and then click on **Ok** to close the window.

Question : What is the Fourier transform of a Gaussian distribution?

Question : Compare the phase signal to that of the uniform disk.

**Question : What is the baseline length corresponding to a visibility of 0?** 

#### 3.3 Ring

Open the **Target editor** again, **Remove** the Gaussian model and **Add** a Ring model instead. This time the model has 5 parameters :  $flux\_weight1, x1, y1$ , a diameter like the uniform disk, and also a width. Let's consider the case of a 4 mas infinitely-thin ring : diameter1=4, and width1=0.

Question : What are the baseline length corresponding to the first zero of visibility and the amplitude of the second lobe?



#### File Edenness the VLTI School of Interferometry

#### Practice session I: Interferometry basics with ASPRC



#### File Edition and the VLTI School of Interferometry

### Practice session I: Interferometry basics with BSPRO

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### Practice session I: Interferometry basics Dith ASPRC

#### 3.1 Limb darkened disk

Question : Note the baseline length corresponding to the first zero of visibility and the secondlobe amplitude.

Now imagine you would estimate the size of this 4mas limb-darkened star by measuring the position of the first zero of visibility and using the formula determined for a uniform disk in the previous section.

Question : Does the star appears bigger or small than its real size? Explain why.

Question : How can you discriminate between the uniform disk and the limb darkened disk?

#### 3.2 Gaussian distribution

Change the model to a "gaussian" (remove previous), and click on Add. Look at the new set of parameters shown in the bottom part of the window. This model has also four parameters, i.e. *flux\_weight1*, x1, y1 like for all models, and *fwhm1*, the full width at half maximum of the Gaussian distribution. Let's set this value to 4 mas and then click on **Ok** to close the window.

Question : What is the Fourier transform of a Gaussian distribution?

Question : Compare the phase signal to that of the uniform disk.

**Question : What is the baseline length corresponding to a visibility of 0?** 

#### 3.3 Ring

Open the **Target editor** again, **Remove** the Gaussian model and **Add** a Ring model instead. This time the model has 5 parameters :  $flux_weight1, x1, y1$ , a diameter like the uniform disk, and also a width. Let's consider the case of a 4 mas infinitely-thin ring : diameter1=4, and width1=0.

Question : What are the baseline length corresponding to the first zero of visibility and the amplitude of the second lobe?

B ≈ 32 m Aplitude ≈ 0.092



Limb Darkened disk

### Practice session I: Interferometry basics Gith RSPRC

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The star appears smaller although it has exactly the same size as before. The light emission is more "concentrated" in the center due to the limb darkening.

#### Uniform disk

Limb Darkened disk

### Practice session I: Interferometry basics Gith RSPRC

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### Practice session I: Interferometry basics City ASPRC

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Question : What are the baseline length corresponding to the first zero of visibility and the amplitude of the second lobe?

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The star appears smaller although it has exactly the same size as before. The light emission is more "concentrated" in the center due to the limb darkening.

#### By measuring the 2<sup>nd</sup> lobe amplitude



#### File Education of Interferometry Practice session I: Interferometry basics 🕻 ŔΠ Constraints Targets Main settings Configuration(s) INTE Q V Simbad Interferometer DEMO S0 S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12 S13 S14 S15 Night restriction -S0 S7 Date 2010/09/21 ♦ 00:00:00.000 89:00:00.000 -Instrument DEMO SPATIAL Editor Min. Elevation 30 Wind • Status: 1 Information Sky • • Map Observability UV coverage OlFits viewer Notebook plot data DEMO - DEMO [0.460 µm - 0.460 µm] - S0-S1-S2-S3-S4-S5-S6-S7-S8-S9-S10-S11-S12-S13-S14-S15-S16 Day: 2010-09-21 - Source: 00:00:00.000 89:00:00.000 1.1 1.0 0.9 0.8 0.7 FT of a Gaussian is a Gaussian **dWB3** 0.5 0.4 Phase is 0° and V = 0 $\Leftrightarrow$ B = $\infty$ 0.3 0.2 0.1 0.0 Made by OIFitsExplorer/JMM -0.1 200 150 100 **NISPHI (deg)** -20

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### Practice session I: Interferometry basics Cith ASPRC

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**Question : What is the Fourier transform of a Gaussian distribution?** 

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**Question : What is the baseline length corresponding to a visibility of 0?** 

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Question : What are the baseline length corresponding to the first zero of visibility and the amplitude of the second lobe?

B ≈ 32 m Aplitude ≈ 0.092

The star appears smaller although it has exactly the same size as before. The light emission is more "concentrated" in the center due to the limb darkening.

By measuring the 2<sup>nd</sup> lobe amplitude

A Gaussian distribution

The phase is always 0

#### The zero is at the infinity

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### Practice session I: Interferometry basics with ASPRO

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#### File Education of Interferometry

#### Practice session I: Interferometry basics 📿



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### Practice session I: Interferometry basics Cith ASPRC

#### 3.1 Limb darkened disk

Question : Note the baseline length corresponding to the first zero of visibility and the secondlobe amplitude.

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**Question : What is the Fourier transform of a Gaussian distribution?** 

Question : Compare the phase signal to that of the uniform disk.

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#### 3.3 Ring

Open the **Target editor** again, **Remove** the Gaussian model and **Add** a Ring model instead. This time the model has 5 parameters :  $flux\_weight1, x1, y1$ , a diameter like the uniform disk, and also a width. Let's consider the case of a 4 mas infinitely-thin ring : diameter1=4, and width1=0.

Question : What are the baseline length corresponding to the first zero of visibility and the amplitude of the second lobe?

B ≈ 32 m Aplitude ≈ 0.092

The star appears smaller although it has exactly the same size as before. The light emission is more "concentrated" in the center due to the limb darkening.

By measuring the 2<sup>nd</sup> lobe amplitude

A Gaussian distribution

The phase is always 0

The zero is at the infinity

B ≈ 39m Aplitude ≈ 0.4

### Practice session I: Interferometry basics City ASPRC

#### 3.4 Comparison of these models

In the previous sections you have build four models (uniform disk, Gaussian distribution, ring, and limb darkened disk) with a characteristic size of 4 mas. Their main difference is the smoothness/sharpness of their intensity distribution.

Question : First, classify the models in term of sharpness/smoothness

Question : What is the relation between the distribution sharpness and the  $2^{nd}$  lobe amplitude ?

#### 3.5 Model confusion

If the interferometer largest spatial frequency (the ratio baseline length over wavelength) is not of the order of the typical size of your source, this may cause problems when you try to interpret your data.

Question : Compare the visibility obtained at 100m for a 0.9 mas uniform disk and a 0.5 mas Gaussian distribution.

Now switch to the K band using the UV-Coverage tab and changing the Instrument mode.

#### Question : Do the same comparison.

Typical uncertainties on the visibility measurements are of the order of a few percent.

 $\label{eq:Question:In which band(s) can you discriminate between these models and determine the object size?$ 

Go back to the B band, and compare the visibility at 100m from the 0.9 mas uniform disk and a 0.61 mas Gaussian distribution.

Question : How can we discriminate between these two intensity distributions?

#### 3.6 Point source and flat field

There is two additional intensity distributions that are widely used for modelling :

- the point source used to model a source too small to be resolved whatever by the interferometer
- the flat field used to represent the exact opposite, a fully resolved object.

Note that these models are useless on their own and are only used to build multi-component models described further down.

#### Question : What are the point source and flat field visibility functions?

In ASPRO2 point sources are modelled using the *punct* function. Flat field are not included, but can be modelled easily using a very extended uniform disk, for example with  $D \ge 250$  mas.



### Practice session I: Interferometry basics Gith ASPRO

Ring

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From the sharpest to the smoothest: Ring, Uniform disk, Limb-Darkened disk, Gaussian

Gaussian

LDD

### Practice session I: Interferometry basics City ASPRO

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## 2<sup>nd</sup> Lobe Amplitudes 0.13 0.09

LDD

UD

0.4

Ring

Gaussian

### Practice session I: Interferometry basics City, ASPRO

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Go back to the B band, and compare the visibility at 100m from the 0.9 mas uniform disk and a 0.61 mas Gaussian distribution.

Question : How can we discriminate between these two intensity distributions?

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From the sharpest to the smoothest: Ring, Uniform disk, Limb-Darkened disk, Gaussian

2<sup>nd</sup> Lobe Amplitudes

0.09

LDD

Gaussian

0.13

UD

0.4

Ring

#### Sharpness in image ⇔ higher lobes in FT Ring = 0.4 UD = 0.13 LDD = 0.09 Gauss. = 0

### Practice session I: Interferometry basics City ASPRC

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#### Rid Edentify VLTI School of Interferometry Practice session I: Interferometry basics Targets Main settings Configuration(s) Constraints <u>EUCIE</u> QT Interferometer DEMO S0 S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12 S13 S14 S15 Night restriction S0 S7 Date 2010/09/21 ♦ 00:00:00.000 89:00:00.000 Instrument DEMO SPATIAL -Editor Min. Elevation 30 Wind 8 Status: 1 Information Sky 4 • Map Observability UV coverage **OIFits viewer** Notebook plot data DEMO - DEMO [0.460 µm - 0.460 µm] - S0-S1-S2-S3-S4-S5-S6-S7-S8-S9-S10-S11-S12-S13-S14-S15-S16 Day: 2010-09-21 - Source: 00:00:00.000 89:00:00.000 1.1 1.0 0.9 0.8 0.7 0.6 0.5 0.5 0.4 0.3 Measurements at different baselines 0.2 0.1 0.0 -0.1 150 Longer baselines for 2nd lobe 100 VISPHI (deg) -100 -150 -200 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 0 105 RADIUS (m) Infos A D F Show VISAMP, VISPHI vs RADIUS ▼ Color by effective wav... ▼ □ Skip Flagged □ Draw lines x Axis RADIUS ✓ ☐ log ☑ inc. 0 ○ auto ● default ○ fixed ✓ ☐ log ☐ inc. 0 ○ auto ● default ○ fixed VISAMP v Axes ▼ 🗌 log 🔲 inc. 0 ○ auto 🖲 default ○ fixed VISPHI

OIFits done.

# Practice session I: Interferometry basics City ASPRC

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## FT(Point Source) : V = 1 FT(flat field) : V = 1 if (B=0) and V = 0 otherwise

# Practice session I: Interferometry basics City ASPRO

# 4. Going 2D with flattened models

## Practice session I: Interferometry basics City ASPRC

## 4 Going 2D with flattened models

In the previous sections you learned about 1D functions to model interferometric measurements. Now it is time to take a look at two-dimensional intensity distributions.

#### 4.1 Elliptical distributions

Question : Compare its visibility function to the one obtained for the 4 mas uniform disk.

Now modify the model so that the major-axis is oriented East-West.

Question : Where is the first zero of the visibility function?

Question : What uniform disk diameter does this correspond to?

Finally, put the disk major-axis at 45°.

Question : Can you conclude on the extension measured by an interferometer?

Now, let's use a new set of baselines. Load the configuration file *Example2.asprox*. Look at the UV plan in the UV coverage tab. The baselines in the new set all have the same length, i.e. 42m, but they have different position angles, and cover all directions.

Go to the **OIFits viewer** tab and plot the Visibility (VISAMP and VISPHI) as a function of the position angle (POS\_ANGLE).

Question : Without looking at the model can you determine the major-axis position angle?

Question : Assuming an elliptical Gaussian model what are the major and minor axes FWHMs?

#### 4.2 Application to geometrically thin disk

Elliptical intensity distributions are widely used to model geometrically-thin circumstellar disks. In this case the flattening is due to the projection of the disk on the sky-plane, i.e., perpendicular to the observer line of sight. At an inclination angle of  $0^{\circ}$ , i.e. pole-on, the disk is not flattened, and the elongation ratio (i.e. major-axis/minor-axis) grows with the inclination angle.

Question : Find the formula of the elongation ratio for this simple geometrically thin disk model Question : Conclude on the inclination angle of our object.



#### FILL ENCLOSE STREET School of Interferometry Practice session I: Interferometry basics 🚇 Stions Targets Main settings Configuration(s) Constraint Q V Simbad S0 S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12 S13 S14 S1 Interferometer DEMO Night restriction -S0 S7 2010/09/21 ÷ ♦ 00:00:00.000 89:00:00.000 Date Instrument DEMO SPATIAL -Editor Min. Elevation 30 Wind Status: 👔 Information • Sky • Map Observability UV coverage **OIFits viewer** Notebook plot data DEMO - DEMO [0.460 µm - 0.460 µm] - S0-S1-S2-S3-S4-S5-S6-S7-S8-S9-S10-S11-S12-S13-S14-S15-S16 Day: 2010-09-21 - Source: 00:00:00.000 89:00:00.000 1.1 1.0 0.9 0.8 0.7 Same Visibility curve as for the 4 mas uniform disk **UNEXTICATION** 0.6 0.5 0.4 0.3 0.2 0.1 0.0 -0.1 \_\_\_\_\_ North-South Baseline 150 100 And North South Elongation VISPHI (deg) 50 Elong = 2 D(minor\_axis) = 2mas -100 $D(Major_axis) = 2x2 = 4 mas$ -150 -200 20 5 10 25 30 35 45 50 55 60 65 70 75 80 85 90 95 100 0 40 105 RADIUS (m) ArrName: DEMO | InsName: DEMO\_SPATIAL 0.46-1ch | Date: 2010-09-21 | Baseline: 52-56 | Config: S0-51-52-53-54-55-56-57-58-59-510-511-512-513-516 | Target: 00:00:00.000 89:00:00.000 hide Wavelength: 0.460 µm | Spatial Freq: 63.03 MA | Radius: 29.00 m | Pos. angle: 0.00 deg | Hour angle: 0.01 h Table: OI VIS#3 | Row: 34 | Col: 0 | File: Aspro2 00 00 00 089 00 00 000 DEMO DEMO DEMO SPATIAL 0.46-1ch 80-81-52-53-54-55-56-57-58-59-510-511-512-513-514-515-516 2010-09-21.fits

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## Practice session I: Interferometry basics with ASPRC

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It is extacly the same! (V=0 ⇔ B=29m) The baseline is North-South oriented and so it ``sees'' The major-axis of the Elongated disk

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## Fill Edge 19th YLTI School of Interferometry

## Practice session I: Interferometry basics

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#### File Edentity VLTI School of Interferometry Practice session I: Interferometry basics 😡 ŘΠ stions Main settings Targets Configuration(s) Constraints Interferometer DEMO S0 S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12 S13 S14 S1 Night restriction -50 57 Date 2010/09/21 ♦ 00:00:00.000 89:00:00.000 Instrument DEMO SPATIAL -Editor Min. Elevation 30 Wind Status: 👔 Information • Sky • • Map Observability UV coverage OlFits viewer Notebook plot data DEMO - DEMO [0.460 µm - 0.460 µm] - S0-S1-S2-S3-S4-S5-S6-S7-S8-S9-S10-S11-S12-S13-S14-S15-S16 Day: 2010-09-21 - Source: 00:00:00.000 89:00:00.000 1.1 1.0 0.9 0.8 0.7 **dWBSIN** 0.6 0.5 4 mas \* • 3.2 mas 2 mas 0.3 0.2 0.1 ... \* \* \* \* \* 0.0 Made by OIFitsExplorer/JMM -0.1 . . . . . 150 100 VISPHI (deg) 50 -5 -100 -150 36.995 Made by OIFitsExplorer/JMN -200 5 10 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 0 15 105 RADIUS (m) ArrName: DEMO | InsName: DEMO SPATIAL\_0.46-lch | Date: 2010-09-21 | Baseline: 39-316 | Config: 30-31-52-53-54-55-36-37-38-59-310-511-512-513-514-515-516 | Target: 00:00:00.000 89:00:00.000 hide Wavelength: 0.460 µm | Spatial Freq: 80.42 MA | Radius: 37.00 m | Pos. angle: 0.00 deg | Hour angle: 0.01 h Table: OI VIS#3 | Row: 114 | Col: 0 | File: Aspro2\_00\_00\_00\_00\_09\_00\_00\_000\_DEMO\_DEMO\_DEMO\_SPATIAL\_0.46-1ch\_S0-S1-S2-38-S4-S5-S6-37-S8-S9-S10-S11-S12-S13-S14-S15-S16\_2010-09-21.fits Data: X[1.000, 100.986] Y[1.123E-4, 0.999] [13.874, 1.060] Infos: 136 / 136 points Data+Err: X[1.000, 100.986] Y[1.123E-4, 0.999] A D F Show VISAMP, VISPHI vs RADIUS ▼ Color by effective wav... ▼ □ Skip Flagged □ Draw lines x Axis RADIUS ▼ 🗌 log 🖌 inc. 0 🔾 auto 🖲 default 🔾 fixed ▼ □ log □ inc. 0 ○ auto ● default ○ fixed VISAMP y Axes 💌 📃 log 📃 inc. 0 🔘 auto 🖲 default 🔾 fixed VISPHI A.7.

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282 M Provided by JMMC

## Practice Session I: Interferometry basics with ASPRC

#### 4 Going 2D with flattened models

In the previous sections you learned about 1D functions to model interferometric measurements. Now it is time to take a look at two-dimensional intensity distributions.

#### 4.1 Elliptical distributions

Question : Compare its visibility function to the one obtained for the 4 mas uniform disk.

Now modify the model so that the major-axis is oriented East-West.

Question : Where is the first zero of the visibility function?

Question : What uniform disk diameter does this correspond to?

Finally, put the disk major-axis at 45°.

Question : Can you conclude on the extension measured by an interferometer?

Now, let's use a new set of baselines. Load the configuration file *Example2.asprox*. Look at the UV plan in the UV coverage tab. The baselines in the new set all have the same length, i.e. 42m, but they have different position angles, and cover all directions.

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It is extacly the same! (V=0 ⇔ B=29m) The baseline is North-South oriented and so it ``sees'' The major-axis of the Elongated disk

Twice as far, i.e., B=58m Now the baseline is oriented along the minor-axis

#### 2mas

At 45° we found 3.1 mas, an intermediate value between the major and minor axes. The interferometer only measures extension along the baseline orientation

#### File Edition of Interferometry Practice Session I: Interferometry basics 🔂 ŘΠ CTIONS Targets Main settings Configuration(s) Constraint Q Simbad Interferometer DEMO S0 S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12 S13 S14 S1 Night restriction -S0 S7 Date 2013/09/06 ♦ 00:00:00.000 89:00:00.000 Instrument DEMO SPATIAL -Editor Min. Elevation 30 Wind Status: 👘 Information 8 Sky • • Map Observability UV coverage OlFits viewer Notebook plot data DEMO - DEMO [0.460 µm - 0.460 µm] - S0-S7 Day: 2013-09-06 - Source: 00:00:00.000 89:00:00.000 1.1 1.0 0.9 0.8 0.7 **UISAMP** 0.6 0.5 0.4 0.498 0.3 All baselines have the same Length! 0.2 0.1 0.0 49.648 Made by OIFitsExplorer/JMN -0.1 200 150 100 Lower Visibility 🗇 Larger extension VISPHI (deg) 50 Major-axis at 50° 0 -50 -100 -150 49.648 -200 -200 -190 -180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 POS\_ANGLE (deg) ArrName: DEMO | InsName: DEMO\_SPATIAL\_0.46-lch | Date: 2013-09-06 | Baseline: S0-S7 | Config: S0-S7 | Target: 00:00:00.000 89:00:00.000 hide Wavelength: 0.460 µm | Spatial Freq: 91.30 MA | Radius: 42.00 m | Pos. angle: 49.65 deg | Hour angle: -3.30 h Table: OI\_VIS#3 | Row: 13 | Col: 0 | File: Aspro2\_00\_00\_00\_00\_00\_00\_00\_00DEMO\_DEMO\_SPATIAL\_0.46-1ch\_S0-57\_2013-09-06.fits Infos A D F Show VISAMP, VISPHI vs POS\_ANGLE ▼ Color by effective wav... ▼ □ Skip Flagged □ Draw lines ▼ 🗌 log 🖌 inc. 0 🔾 auto 🖲 default 🔾 fixed x Axis POS ANGLE 🔻 🗌 log 🔄 inc. 0 🔾 auto 🖲 default 🔾 fixed VISAMP y Axes ▼ □ log □ inc. 0 ○ auto ● default ○ fixed VISPHI

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352 M Provided by JMMC

## Practice session I: Interferometry basics Lith ASPRC

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yes, as there is some modulation, minimum is at 50°, which mean the longest dimension (the major axis) has a PA of 50°

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# Practice session I: Interferometry basics City ASPRO

# 5 Composed models

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#### 5 Composed models

Imagine that your model is a weighted sum of N components :

$$I_{tot}(x,y) = \sum_{i=1}^{N} f_i I_i(x,y)$$
(1)

where  $I_i(x, y)$  is the intensity distribution of the i<sup>th</sup> component and  $f_i$  its relative flux with  $\Sigma f_i=1$ . Question : What is the visibility function (i.e. normalized Fourier Transform) for this model?

#### 5.1 Star + circumstellar disk model

Let's look at a simple star + circumstellar disk example. First, load a new observation file : *Example3.asprox*. Go to the UV coverage tab and look at it (again remove the annoying Plot rise/set uv tracks option). It is composed two perpendicular strips of baselines : one North-South and one East-West. It will allow us to probe our object along these two perpendicular orientations.

Now, open the **Target Editor** and create a two components model composed of a 0.5 uniform disk (for the star) and an elliptical Gaussian distribution (for the circumstellar disk), with a 8 mas major-axis oriented North-South and a 4 mas minor-axis. Put the flux contribution of each component to 50%.

Plot the visibility amplitude and phase as a function of the baselines lengths.

#### Question : Describe the visibility function.

Change the flux ratio between the two components and look at the visibility function.

#### Question : What has been modified? Can you explain why?

Now imagine that you want to constrain the circumstellar environment extension and flattening.

Question : What baseline lengths and orientations will you choose?

Question : Will these set of baselines give information on the stellar surface?



## Practice session I: Interferometry basics City ASPRC

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The Fourier transform of a weighted sum of functions is the weighted sum of their respective Fourier transforms.

## Practice session I: Interferometry basics with ASPRC

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## Practice session I: Interferometry basics City, ASPRO

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## Practice session I: Interferometry basics Lith ASPRC

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## File Editemetry

## Practice session I: Interferometry basics City, ASPRO

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## Practice session I: Interferometry basics with ASPRC

#### 5 Composed models

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Provided by JMMC

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Baselines shorter than the plateau : B < 20 m Disk elongated ⇔ Baselines in many orientations.

No. The star start to be significantly resolved for baselines larger than 60 m.

# Practice session I: Interferometry basics City ASPRO

#### 5.2 Binaries

A second kind of very useful two components model is the binary model. We will use a single strip of North-South aligned baselines to exlpore this model. So, load the *Example1.asprox* file.

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Question : Describe and explain the visibility function.

Write down the amplitude of the sinusoidal modulation. Set the flux ratio to 0.1/0.9 and then to 0.5/0.5.

#### Question : What is the link between the flux ratio and the amplitude of the binary modulation?

Write down the modulation period in meter, and express it in  $B/\lambda$  units (cycles/rad). Then set the binary separation, i.e. *sep2*, to 10 mas. and do this again.

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Do the same but with *theta2* equal to  $30^{\circ}$ ,  $45^{\circ}$ , and  $60^{\circ}$ .

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## Practice session I: Interferometry basics City, ASPR0

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## Practice Session I: Interferometry basics with ASPR



#### File Edition of Interferometry Practice session I: Interferometry basics 🔂 TIONS Targets Main settings Configuration(s) Constraint Interferometer DEMO S0 S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12 S13 S14 S1 Night restriction S0 S7 2010/09/21 ÷ ♦ 00:00:00.000 89:00:00.000 Date Instrument DEMO SPATIAL Editor Min. Elevation 30 Wind • Status: 👘 Information Sky Observability UV coverage **OIFits viewer** Notebook Map plot data DEMO - DEMO [0.460 µm - 0.460 µm] - S0-S1-S2-S3-S4-S5-S6-S7-S8-S9-S10-S11-S12-S13-S14-S15-S16 Day: 2010-09-21 - Source: 00:00:00.000 89:00:00.000 1.1 1.0 0.9 0.8 0.7 0.6 0.5 0.4 $T = 9.5 \text{ m} \Leftrightarrow 2.06e7 \text{ cycles/rad}$ 0.3 10 mas binary 0.2 0.1 0.0 Made by OIFitsE: -0.1 150 100 $\Rightarrow 1/10$ mas = 2:06e7 cycles/rad 1 mas = 4.84 e-9 radVISPHI (deg) 50 -50 -100 -150 18.997 -200 10 15 20 25 30 35 40 50 55 60 65 70 75 80 85 95 5 45 90 100 105 RADIUS (m) ArrName: DEMO | InsName: DEMO\_SPATIAL\_0.46-1ch | Date: 2010-09-21 | Baseline: S1-S5 | Config: S0-S1-S2-S3-S4-S5-S6-S7-S8-S9-S10-S11-S12-S13-S14-S15-S16 | Target: 00:00:00.000 89:00:00.000 hide Wavelength: 0.460 µm | Spatial Freq: 41.30 MA | Radius: 19.00 m | Pos. angle: 0.00 deg | Hour angle: 0.01 h Table: OI VIS#3 | Row: 19 | Col: 0 | File: Aspro2 00 00 00 00 89 00 00 000 DEMO DEMO DEMO SPATIAL 0.46-1ch 80-81-82-83-84-85-86-87-88-89-810-811-812-813-814-815-816 2010-09-21.fits A D F Show VISAMP, VISPHI vs RADIUS ▼ Color by effective wav... ▼ □ Skip Flagged □ Draw lines x Axis RADIUS ▼ 🗌 log 🖌 inc. 0 🔘 auto 🖲 default 🔾 fixed VISAMP ▼ □ log □ inc. 0 ○ auto ④ default ○ fixed y Axes ▼ □ log □ inc. 0 ○ auto ● default ○ fixed VISPHI

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## Practice session I: Interferometry basics Cith RSP

#### Binaries 5.2

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- 5mas => 19m => 4.13<sup>e-7</sup> cycles/rad
- 10mas => 9.5m => 2.06<sup>e-7</sup> cycles/rad The modulation period is equal to the inverse of the binary separation.

 $1 \text{ mas} = 4.84^{e-9} \text{ rad}$  $4.13^{e-7} = 1/5$  mas  $2.06^{e-7} = 1/10$  mas

## Practice session I: Interferometry basics City, ASPR0

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## File Editemetry Practice session I: Interferometry basics with BSPRO

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## Practice session I: Interferometry basics City, ASPR0

#### 5.2 Binaries

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Then, open the **Target Editor** and create a model consisting of two point sources. Set their flux to 0.2 and 0.8. Look at the second component, the *x*2 and *y*2 parameters have been replaced by *sep*2 and *pos\_angle2*, i.e. polar coordinates. Choose *sep*2=5 and *pos\_angle2*=0. This simulates two unresolved stars separated by 5 mas in the North-South orientation, i.e. aligned with our baselines.

Question : Describe and explain the visibility function.

Write down the amplitude of the sinusoidal modulation. Set the flux ratio to 0.1/0.9 and then to 0.5/0.5.

Question : What is the link between the flux ratio and the amplitude of the binary modulation?

Write down the modulation period in meter, and express it in  $B/\lambda$  units (cycles/rad). Then set the binary separation, i.e. *sep2*, to 10 mas. and do this again.

Question : Give the relation between the binary separation (in rad) and the modulation period (in cycles/rad).

Now change theta2 to 90°: binary in the East-West orientation.

Question : Describe and explain the visibility function.

Do the same but with *theta2* equal to  $30^\circ$ ,  $45^\circ$ , and  $60^\circ$ .

Question : How does this affect the visibility function? Why?

Finally replace the components by uniform disks and try various diameters between 0 and 2 mas, for each component, separately.

Question : What is the effect of resolving one component on the visibility function?

The visibility function corresponding to a binary is a weighted cosine function.

If r is the flux ratio between the components (r<1), the amplitude A of the modulation is given by :

 $A = \frac{2r}{1+r}$ 

• 5mas => 19m => 4.13<sup>e-7</sup> cycles/rad

10mas => 9.5m => 2.06<sup>e-7</sup> cycles/rad
 The modulation period is equal to the inverse of the binary separation.

1 mas =  $4.84^{e-9}$  rad  $4.13^{e-7} = 1/5$  mas  $2.06^{e-7} = 1/10$  mas

There is no modulation anymore as the baseline samples perpendicular to the binary direction. V = 1 as the interferometer ``sees" an unresolved object in the baselines orientation.



OlFits done.

330 M Provided by JMMC



OlFits done.

311 M Provided by JMMC



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The interferometer samples the projected separation of the binary along the baseline orientation



OlFits done.

## Practice session I: Interferometry basics City, ASPR0

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There is no modulation anymore as the baseline samples perpendicular to the binary direction. V = 1 as the interferometer ``sees" an unresolved object in the baselines orientation.

The interferometer samples the projected separation of the binary along the baseline orientation

It is a convolution of two distributions in the image plane, so in the Fourier plane it amounts to a mutiplication of the binary pattern with the FT of a disk, i.e., a Bessel function

## Practice session I: Interferometry basics City ASPRO

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Question : what is the field of view (the size) of this image?

Play with the zooming and the color scale.

Question : Can you explain the shape of the intensity distribution?

Close the **Target Editor** window, and go to the UV Coverage tab to select the N band. Look at the 2D Fourier transform of the image overplotted on the UV Coverage plot.

Finally, go back to the **OiFits viewer** tab to see North-South and East-West cuts of the 2D-visibility function. As before, plot VISAMP & VISPHI as a function of RADIUS.

Question : Is the visibility function closer to that of a Gaussian distribution or uniform disk?

Question : What are the values of the visibility in the two orientations for a 20 m baseline?

Question : Using these values estimate the objects extension in the North-South and East-West orientations.

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## Practice session I: Interferometry basics City ASPRC

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#### 227 mas

We see the inner rim of the dusty disk, the disk emission in N band, and some central emission which correspond to the central star. The disk is flattened which is a hint that it is not seen pole-on.



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## Practice Session I: Interferometry basics City, ASPRO



## Practice session I: Interferometry basics City, ASPRC

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## Practice session I: Interferometry basics Gith ASPRC

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> V= 0.755 V= 0.618

## Practice session I: Interferometry basics City ASPRC

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V= 0.755

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fwhm ≈ 34.7 mas fwhm ≈ 45.4 mas

## Practice session I: Interferometry basics Gith ASPRC

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 $B = 20m \lambda = 12\mu m$ 

fwhm ≈ 34.7 mas fwhm ≈ 45.4 mas

Elong = 1 / cos (incl.) Elong = 45.4/34.7 = 1.31Incl  $\approx 40^{\circ}$ 

## Practice session I: Interferometry basics City ASPRO

# 6 Effect of the Wavelength

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## Practice session I: Interferometry basics City ASPRC

## 6 Effect of the observed wavelength

#### 6.1 Achromatic objects observed at various wavelengths

The spatial resolution of an inteferometer strongly depends on the observing wavelength. Imagine that our North-Pole interferometer is able to observe in any photometric band between  $0.46\mu m$  (B) and  $12\mu m$  (N).

#### Question : Which band will give the highest resolution?

To change the observing wavelength go to the UV Coverage tab. You can select a photometric band between B and N in the Instrument mode list.

#### Question : Give the ratio between the resolutions in N and B bands

Let's assume a 0.05 uncertainty on our visibility measurement and three baselines of 50, 70 and 100 m.

#### Question : In which band should we observe a 1 mas star?

#### Question : Should we observe a 5 mas star with the same configuration?

Now, let's do a multi-wavelength observation. First load the *Example4.asprox* file. It contains a 3 telescopes (S0-S5-S16) configuration of baselines. Unlike for the other exercices the observing wavelength is not fixed to one band but ranges between  $0.1\mu$ m to  $10\mu$ m, the "Wide" (and fake) instrument mode of the UV Coverage panel.

Note that for this observation we use a 1 mas uniform disk model.

First plot the visibility and phase as a function of the baseline length to see the visibility of the three baselines.

#### Question : Explain why we obtain a large range of values for the visibility of each baseline.

Now plot the visibility as a function of the spatial frequency  $B/\lambda$  (SPATIAL\_FREQ). The different colors correspond to different wavelengths from purple for the smallest one  $(0.1\mu m)$  to red for the largest one  $(10\mu m)$ .

Question : For this achromatic model case, conclude on the effect of observing at multiple wavelengths.



## Practice session I: Interferometry basics Gith ASPRO

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## Resolution $\Leftrightarrow$ B/ $\lambda$ Smaller $\lambda$ higher resolution

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Resolution  $\Leftrightarrow$  B/ $\lambda$ Smaller  $\lambda$  higher resolution

12/0.46 = 26

## Practice session I: Interferometry basics City ASPRC

#### 6 Effect of the observed wavelength

#### 6.1 Achromatic objects observed at various wavelengths

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To change the observing wavelength go to the UV Coverage tab. You can select a photometric band between B and N in the Instrument mode list.

Question : Give the ratio between the resolutions in N and B bands

Let's assume a 0.05 uncertainty on our visibility measurement and three baselines of 50, 70 and 100 m.

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Now, let's do a multi-wavelength observation. First load the *Example4.asprox* file. It contains a 3 telescopes (S0-S5-S16) configuration of baselines. Unlike for the other exercices the observing wavelength is not fixed to one band but ranges between  $0.1\mu$ m to  $10\mu$ m, the "Wide" (and fake) instrument mode of the UV Coverage panel.

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## Practice session I: Interferometry basics



## Practice session I: Interferometry basics Cith ASPRC

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## Practice Session I: Interferometry basics with ASPRO



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Provided by JMMC 463 M

## Practice session I: Interferometry basics Cith ASPRC

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This that case it is strictly equivalent to observing with different baselines lengths. It helps a lot to enhance the UV coverage.
# Practice session I: Interferometry basics Gith ASPRO

#### 6.2 Examples of chromatic objects

Question : Assuming that a star and its circumstellar environment emit as black-bodies, can you conclude on their flux ratio dependence on the wavelength? Which component will dominate the visible flux? What about the mid-infrared?

#### Question : How does the model depend on the wavelength?

Before closing the **Target Editor** let's rotate our model by 90° so that our 3 North-South baselines will make measurements along the major-axis (i.e. the equator) of this object. Now, close the **Target Editor** and go to the **OiFits Viewer** tab.

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## Practice session I: Interferometry basics with ASPRC

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# Practice session I: Interferometry basics City ASPRO



DISCO model taken from the AMHRA website https://amhra.oca.eu/AMHRA/disco-gas/input.htm

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## Practice session I: Interferometry basics with ASPRO

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plot data			
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ArrName: DEMO   InsName: DEMO 2T_SPECTRAL_0.4763-9.99747-1886ch   Date: 2012-09-10   Bas           Ndee         Wavelength: 0.6379 µm   Spatial Freq: 158.30 MA   Radius: 100.99 m   Pos. angle: -0.00 d           Table: 0I_VIS\$3   Row: 1   Col: 32   File: Aspro2_00_00_00_00_00_00_00_000_DEMO_DEMO_DEMO_ST	eline: S0-S16   Config: S0-S6-S16   Target: 00:00:00.000 89:00:00.000 eg   Hour angle: 0.01 h _SPECTRAL_0.4762-9.99747-1886ch_S0-S6-S16_2013-09-10.fits		
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## Practice session I: Interferometry basics with ASPRC

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### Practice session I: Interferometry basics with RSPRO



## Practice session I: Interferometry basics with ASPRC

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#### V=0 for B/λ ≈ 158.3 ⇔ θ ≈ 1.58 mas

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V=0 for B/λ ≈ 158.3  $\Leftrightarrow$  θ ≈ 1.58 mas

1" = 1au at 1 pc. 1au ≈ 107 Dsol Rstar ≈ 0.107 × distance (in pc) × θ (in mas) Rstar ≈ 10 Rsol

# Practice session I: Interferometry basics City ASPRO

# 7 Bonus

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## Practice session I: Interferometry basics Cith ASPRC

#### 6.3 Bonus : play with the models from the AMHRA service

You can go to the AMHRA service web page, download models and load them on ASPRO2. Currently, AMHRA gives access to the following models:

- Kinematic Be Disk : Model of the geometry (size and shape) and kinematics (rotation and expansion) of circumstellar disks, especially of Be stars observed at high spectral resolution (R>1000). It is not adapted to our DEMO interferometer that does not have a high spectral resolution mode. But you might test it with GRAVITY (in Brγ line) or MATISSE (in Brα line)
- Disk and stellar Continuum DISCO : we already used it, but you might want to compute model with different paramters.
- Evolved stars (Red Supergiants and AGBs): Stellar surface maps of evolved stars computed from 3D hydrodynamical simulation with CO5BOLD-OPTIM3D
- **Binary spiral model** : Phenomenological model mimicking the shock caused by the collision between the winds from massive stars (e.g. the WR and OB stars)
- Supergiant B[e] stars with HDUST : Grid of models for B[e] supergiants, i.e. hot stars surrounded by gaseous and dusty circusmtellar disk.
- Limb-darkening with SAtlas : Grid of models providing realistic intensity maps for spherically symmetric stars, showing the limb darkening effect.



