Practical Session "Stellar Atmospheres"

M. Wittkowski (ES0)

Material (/home/linux/data/Stellar_Atmospheres)

I. Model Atmosphere examples:

/home/linux/data/Stellar_Atmospheres/Models/PHOENIX:

- Tabulated intensity profiles from the PHOENIX model atmosphere code (Hauschildt & Baron 1999, J. Comp. Appl. Math., 109, 41; Hauschildt et al. 1999, ApJ, 525, 871),
- Version 16 of the PHOENIX code.
- Subset of a large grid that was calculated for Wittkowski et al. (2012, A&A, 540, L12) and Arroyo-Torres et al. (2013, A&A, 554, A76)
- Examples for the practical session: $M=1M_{sun}$, Teff: 3000K…4900K, log g: 0..+3. All models use solar chemical composition.
- Filename: lte<Teff/100><-logg>-0.0.reduced.
- Wavelengths between 1 μm and 2.5 μm with a spectral resolution that is optimized for the AMBER MR mode.
- Corrections from 0% intensity radii (corresponding to the outermost model layer) and Rosseland radii (corresponding to the layer where the Rosseland-mean opacity is 2/3) are available here: /home/linux/data/Stellar_Atmospheres/Models/PHOENIX/factorRoss.dat

/home/linux/data/Stellar_Atmospheres/Models/CODEX:

- Tabulated intensity profiles of a series of dynamic model atmospheres from Ireland et al. (2011, MNRAS).
- Here, a subset of series 'o54' (designed to match o Cet) covering one cycle (phases -0.3 … 1.00).
- Wavelengths between 1.4 μm and 2.5 μm with s spectral resolution that is optimized for the AMBER MR mode. (calculated for Wittkowski et al.,2011, A&A, 532, L7).
- Details on the model parameters available here: /home/linux/data/Stellar_Atmospheres/Models/CODEX/modelparameters.dat

II. Data example

/home/linux/data/Stellar_Atmospheres/Data/XHya:

- One example data file, taken with the AMBER MR 2.3 μm mode on 2008-12-29 in visitor mode.
- Mira variable X Hya
- From Wittkowski et al. (2011, A&A, 532, L7)

III. IDL-Scripts

- Command-line IDL routines to handle the models and the data
- Basics based on Wittkowski et al. (2004, A&A, 413, 711).
- For the use with the present PHOENIX model atmospheres, see Wittkowski et al. (2012, A&A, 540, L12) and Arroyo-Torres et al. (2013, A&A, 554, A67).
- For the use with the CODEX model atmospheres, see Wittkowski et al. (2011, A&A, 532, L7).
- See also other papers of a series based on interferometric data and PHOENIX model atmospheres: Wittkowski et al. (2006, A&A, 460, 843 and A&A, 460, 855).
- Usage described below.

1. Intensity profiles predicted by PHOENIX models

Start an idl session by typing

```
idl
```

Define an angular diameter, and a range of baselines and wavelength intervals:

```
diam=15.e-3 ; in mas
baseline=findgen(100)+1. ; in m
T=3000. ; in K
wavelength=baseline*0.+2.2e-6 ; in m  'continuum band'
width=baseline*0.+0.1e-6 ; in m
```

Example1:
Define a PHOENIX model atmosphere, for example with T_{eff}=4900 K, log g = 1.50

```
phoenixfilename='/home/linux/data/Stellar_Atmospheres/
Models/PHOENIX/lte49-1.50-0.0.reduced'
```

Define the Rosseland correction for this model, which you find in the following table: /home/linux/data/Stellar_Atmospheres/Models/PHOENIX/factorRoss.dat

```
rross1=1./1.05241
```

Load the model atmosphere:

```
phoenix_vlti,phoenixfilename,1.,wavelength,width,clv1,
radii1,lambda1,flux1
```

Plot the intensity profile:

```
plot,radii1,clv1(0,*)
```

You see the intensity as a function of radius. Radius=1 corresponds to the outermost model layer.

Indicate the Rosseland radius for this model:

```
plots,[rross1,rross1],[0,max(clv1(0,*))],line=1
```

Repeat the steps for another example with different wavelength settings or a different model atmosphere.

Example2:

For example, use the same model atmosphere, but a different wavelength interval:

```
Wavelength=baseline*0.+2.29e-6 ; in m CO band
width=baseline*0.+0.02e-6 ; in m

phoenix_vlti,phoenixfilename,1.,wavelength,width,clv2,
radii2,lambda2,flux2
```

Overplot the intensity profile of example 2, for the same model but a different bandpass

```
oplot,radii2,clv2(0,*),line=2
```

Example 3:

For example, use the first wavelength interval, but a different model atmosphere with T_{eff}=3000 K, and logg=0.00.

```
wavelength=baseline*0.+2.2e-6 ; in m  'continuum band'
width=baseline*0.+0.1e-6 ; in m
phoenixfilename='/home/linux/data/Stellar_Atmospheres/
Models/PHOENIX/lte30-0.00-0.0.reduced'
phoenix_vlti,phoenixfilename,1.,wavelength,width,clv3,
radii3,lambda3,flux3
rross3=1./1.17151
```

Overplot the intensity profile of example 3:

```
oplot,radii3,clv3(0,*),line=3
```

Indicate the Rosseland radius for this new model:

```
plots,[rross3,rross3],[0,max(clv1(0,*))],line=1
```

If you like, try other wavelength intervals and/or models.

Which models and wavelength intervals show a stronger limb-darkening effect, and which show a weaker limb-darkening effect ? Which model-predicted features could be probed by interferometric observations?

2. Visibility functions predicted by PHOENIX model atmospheres

Do the steps of Section 1 to load the examples.

Open a new idl window:

```
window,1
```

Calculate the visibility function for Example 1:

```
visphoenix1=vis_phoenix(diam./rross1,baseline,waveleng
th,radii1,lambda1,clv1)
```

Plot the visibility modulus for example 1 as a function of baseline

```
plot,baseline,abs(visphoenix1)
```

Compute and overplot the visibility function for Example 2:

```
visphoenix2=vis_phoenix(diam/rross1,baseline,wavelengt
h,radii2,lambda2,clv2)
oplot,baseline,abs(visphoenix2)
```

And for Example 3:

```
visphoenix3=vis_phoenix(diam/rross3,baseline,wavelengt
h,radii3,lambda3,clv3)
oplot,baseline,abs(visphoenix3)
```

Do you see a different strength of the limb darkening effect? Where? For which examples?

3. Intensity profiles predicted by CODEX models

Repeat the steps of Section 1 for the example of CODEX model atmospheres:

```
diam=15.e-3 ; in mas
baseline=findgen(100)+1. ; in m
T=3000. ; in K
wavelength=baseline*0.+2.2e-6 ; in m  'continuum band'
width=baseline*0.+0.1e-6 ; in m
```

Set a new window:

```
window,2
```

Example 4: Series ‘o54’, model ‘248480’ (maximum phase, continuum band)

```
codexseries='o54'
codexmodel='249240' ; maximum phase
codex_vlti,codexseries,codexmodel,wavelength,width,clv
4,radii4,lambda4,flux4

plot,radii4,clv4(0,*)
```

Note that CODEX models reach to 5 'parent star’ radii.

Example 5: (maximum phase, i.e. the same model, but in a CO band:

```
wavelength=baseline*0.+2.29e-6 ; in m CO band
width=baseline*0.+0.02e-6 ; in m
codex_vlti,codexseries,codexmodel,wavelength,width,clv
5,radii5,lambda5,flux5

oplot,radii5,clv5(0,*)
```

Example 6: Continuum band with another model example (minimum phase)

Choose the first bandpass but another model (for example for minimum phase)

```
wavelength=baseline*0.+2.2e-6 ; in m  'continuum band'
width=baseline*0.+0.1e-6 ; in m
codexseries='o54'
codexmodel='250440' ; minimum phase
codex_vlti,codexseries,codexmodel,wavelength,width,clv
6,radii6,lambda6,flux6

oplot,radii6,clv6(0,*)
```

Example 7: (minimum phase and CO band)

```
wavelength=baseline*0.+2.29e-6 ; in m CO band
width=baseline*0.+0.02e-6 ; in m
codexseries='o54'
codexmodel='250440' ; minumum phase
codex_vlti,codexseries,codexmodel,wavelength,width,clv
7,radii7,lambda7,flux7

oplot,radii7,clv7(0,*)
```

Try other models and bandpasses.
For example, trace a certain feature with phase.
Which model phases and which bandpasses show compact intensity profiles and which show more extended intensity profiles?
How do the dynamic model atmosphere predictions (CODEX) differ from hydrostatic model atmosphere predictions (PHOENIX)?

4. Visibility functions predicted by CODEX models

Compute the visibility functions for the CODEX models of Section 3.

First, (re-)do the steps of Section 3 to load the proper models.

Then, compute the visibility functions:

```
viscodex4=vis_codex(diam,baseline,wavelength,radii4,la
mbda4,clv4)
viscodex5=vis_codex(diam,baseline,wavelength,radii5,la
mbda5,clv5)
viscodex6=vis_codex(diam,baseline,wavelength,radii6,la
mbda6,clv6)
viscodex7=vis_codex(diam,baseline,wavelength,radii7,la
mbda7,clv7)
```

And plot them in a new window:

```
window, 3
plot,baseline,abs(viscodex4)
oplot,baseline,abs(viscodex5),line=1
oplot,baseline,abs(viscodex6),line=2
oplot,baseline,abs(viscodex7),line=3
```

Which intensity features can be probed by visibility measurements? Which differences do you see compared to the visibility data o the hydrostatic PHOENIX models?

5. Example of a VLTI/AMBER data set of the Mira variable X Hya from Wittkowski et al. (2011)

Read the data:

```
amberdata=read_amberreport('../Data/XHya/xhya-2008-12-29-MR23.dat')
amberdata.wavelengthwidth=amberdata.wavelength/1500.

Define the baseline for these data:

baseline1=sqrt((amberdata.u1*206264.8)^2.+(amberdata.v1*206264.8)^2)*amberdata.wavelength
baseline2=sqrt((amberdata.u2*206264.8)^2.+(amberdata.v2*206264.8)^2)*amberdata.wavelength
baseline3=sqrt((amberdata.u3*206264.8)^2.+(amberdata.v3*206264.8)^2)*amberdata.wavelength
```

Plot the observed squared visibility versus wavelength for the three baselines:

```
plot,amberdata.wavelength,amberdata.vissq2
oplot,amberdata.wavelength,amberdata.vissq1
oplot,amberdata.wavelength,amberdata.vissq3
```

Initiate the following functions:

```
.r FUNCT_UD.pro
.r FUNCT_PHOENIX.pro
.r FUNCT_CODEX.pro
```

Define an initial guess for the angular diameter:

```
diamguess=3.e-3 ; 3 mas
```

Find the best-fit UD model diameter:

```
fitudamber,amberdata,diamguess,resultUD
```

resultUD(0) contains the best-fit UD diameter.
resultUD(1) is the formal error
resultUD(3) is the reduced chi^2

Compute the visibility functions for the best-fit UD model:

```
visud1=vis_ud(resultUD(0),baseline1,3000.,amberdata.wa
velength,amberdata.wavelengthwidth)
visud2=vis_ud(resultUD(0),baseline2,3000.,amberdata.wa
velength,amberdata.wavelengthwidth)
visud3=vis_ud(resultUD(0),baseline3,3000.,amberdata.wa
velength,amberdata.wavelengthwidth)
```

Overplot them on top of the data:

```
oplot,amberdata.wavelength,visud1,line=1
oplot,amberdata.wavelength,visud2,line=1
oplot,amberdata.wavelength,visud3,line=1
```

Find the best-fit PHOENIX diameter:

```
phoenixfilename='/home/linux/data/Stellar_Atmospheres/
Models/PHOENIX/lte30-0.00-0.0.reduced'
rross=1./1.17151
phoenix_vlti,phoenixfilename,rross,amberdata.wavelength,amberdata.wav
elengthwidth,clvp,radiip,lambdap,fluxp
fitphoenixamber,amberdata,phoenixfilename,rross,diamguess,resultphoen
ix
```

Compute the visibility function and overplot it:

```
visphoenix1=vis_phoenix(resultphoenix(0)*rross,baseline1,amberdata.wav
elength,radiip,amberdata.wavelength,clvp)
visphoenix2=vis_phoenix(resultphoenix(0)*rross,baseline2,amberdata.wav
elength,radiip,amberdata.wavelength,clvp)
visphoenix3=vis_phoenix(resultphoenix(0)*rross,baseline3,amberdata.wav
elength,radiip,amberdata.wavelength,clvp)

oplot,amberdata.wavelength,visphoenix1^2.
oplot,amberdata.wavelength,visphoenix2^2.
oplot,amberdata.wavelength,visphoenix3^2.
```

Find the best-fit CODEX diameter and overplot the result:
Model ‘287940’ was the best-fit model from Wittkowski et al. (2011).

```
codexseries='o54'
codexmodel='287940'
codex_vlti,codexseries,codexmodel,amberdata.wavelength
,amberdata.wavelengthwidth,clvc,radiic,lambdac,fluxc

fitcodexamber,amberdata,codexseries,codexmodel,diamgue
ss,resultcodex
viscodex1=vis_codex(resultcodex(0),baseline1,amberdata
.wavelength,radiic,amberdata.wavelength,clvc)
viscodex2=vis_codex(resultcodex(0),baseline2,amberdata
.wavelength,radiic,amberdata.wavelength,clvc)
viscodex3=vis_codex(resultcodex(0),baseline3,amberdata
.wavelength,radiic,amberdata.wavelength,clvc)

oplot,amberdata.wavelength,viscodex1^2.
oplot,amberdata.wavelength,viscodex2^2.
oplot,amberdata.wavelength,viscodex3^2.
```

Try other models at different phases, and see if you find a better-fitting one.
Note that the data file is only one of a few data sets used in Wittkowski et al. (2011).