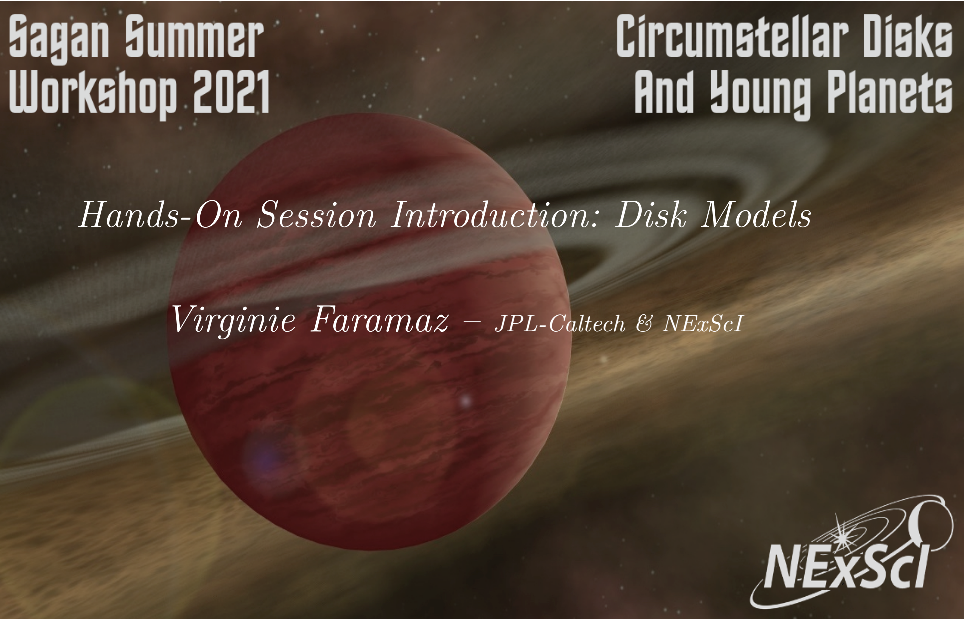


Sagan Summer Workshop 2021

Circumstellar Disks And Young Planets

Hands-On Session Introduction: Disk Models

Virginie Faramaz – JPL-Caltech & NExScI

NExScI

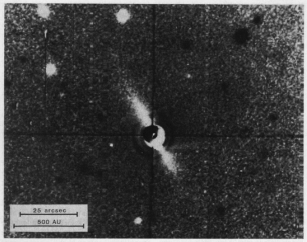
Welcome

This hands-on session will introduce you to circumstellar disks :

- how they are studied,
- how they appear at different stages of their evolution,
- the different features they can exhibit.

using :

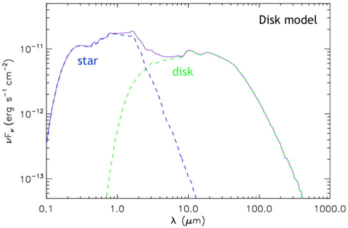
Images



β Pictoris (Smith & Terrile 1984)

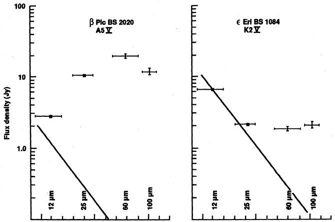
Spectral Energy Distributions (SEDs)

SEDs represents how bright a source is as a function of wavelength.

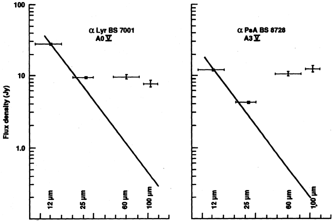


The "Fabulous Four" seen with IRAS (Backman & Paresce 1993)

β Pictoris & ϵ Eridani



Vega & Fomalhaut



Dust absorbs starlight and re-radiates that energy in the infrared

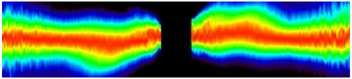
$\Rightarrow$ excess IR emission above the stellar photospheric emission.

A great number of disks were revealed with IRAS, and later ISO, Spitzer, Herschel..

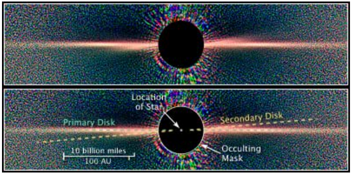
Revealing micron-sized dust grains as they reflect starlight

With the Hubble Space Telescope (HST)

β Pictoris

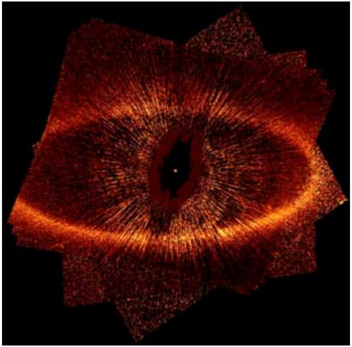


Heap et al. (2000)



Golimowski et al. (2006)

Fomalhaut

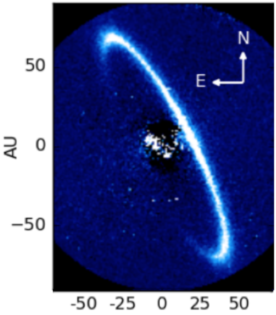


Kalas et al. (2005)

Revealing micron-sized dust grains as they reflect starlight

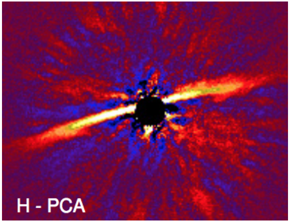
With Gemini Planet Imager (GPI) and VLT/SPHERE

HR 4796 in the J-band (1.24 μm) with GPI



Arriaga et al. (2020)

HD 106906 in the H-band (1.6 μm)



Lagrange et al. (2016)

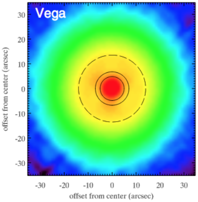
Rule of thumb : a wavelength reveals dust grains of similar size.

Images in thermal light (Far-IR up to mm wavelengths)

Revealing (sub)millimeter-sized dust grains as they re-emit starlight

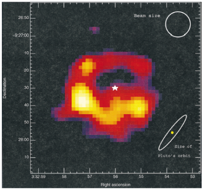
With Herschel, James Clerk Maxwell Telescope (JCMT),
Atacama Large Millimeter Array (ALMA)

Vega – Herschel/PACS 70 μm



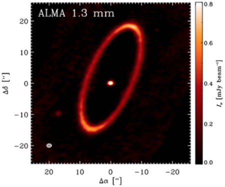
Su et al. (2013)

ϵ Eridani – JCMT 850 μm



Greaves et al. (1998)

Fomalhaut – ALMA 1.3 mm



MacGregor et al. (2017)

Images can provide a lot of information on the disks : their extent, their distance to the star, the presence of asymmetries, etc...

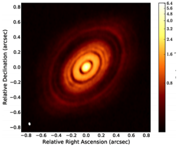
Detailed images are not always easy to obtain !

This Hands-On session will show you

- an overview of the type of characteristics you can learn about a disk from its SED,
- how sometimes different phenomena have the same effect, i.e., degeneracy,
- how images can help break the degeneracy.

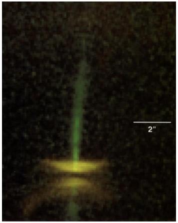
We have chosen 4 objects that represent different evolution stages of disks ; for each, we will have you explore the impact of significant parameters on images and SEDs.

HL Tau, the toddler



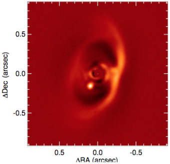
ALMA Partnership et al. (2015)

HH30, the teenager



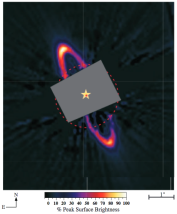
Burrows et al. (1996)

PDS 70, the grown-up



Müller et al. (2018)

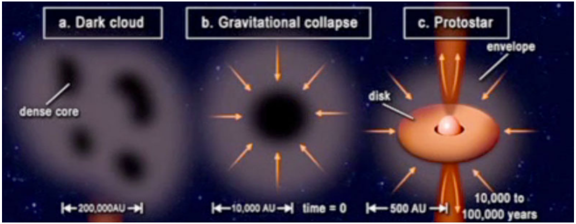
HR 4796, the elderly

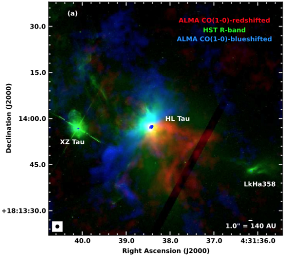


Schneider et al. (2009)

HL Tau

Stars are born in molecular cloud cores, surrounded by large envelopes of dust and gas. The envelope falls onto a disk and is accreted from there onto the star.





ALMA Partnership et al. (2015)

HL Tau harbours a protoplanetary disk, and is also still surrounded by a large envelope.

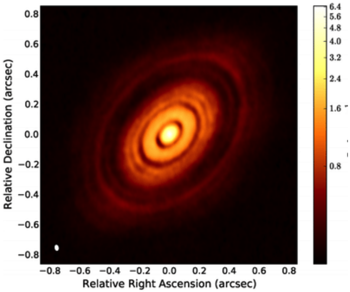
Explore the effect of the envelope mass

HL Tau

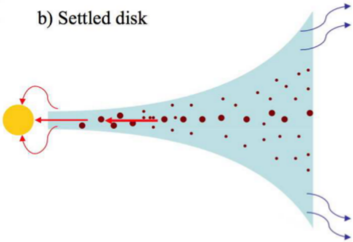
HL Tau became famous when ALMA pierced through the envelope.

It revealed that the largest grains in the disk :

- harbored a series of gaps.
- have settled in the midplane.



ALMA Partnership et al. (2015)



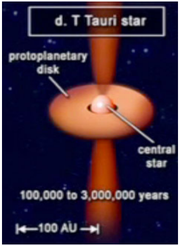
Explore the effect of the disk scale height and the presence of gaps

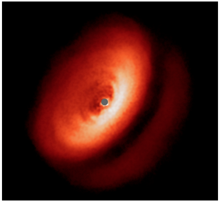
HH 30

Over the course of a few hundred thousand years, the envelope is depleted.

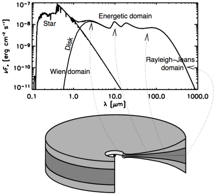
The young star is left with its circumstellar accretion disk.

These stars are known as T Tauri stars.





IM Lup Avenhaus et al. (2018)

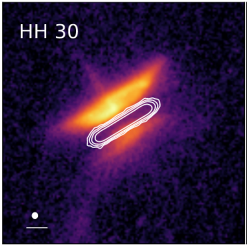


Dullemond et al. (2007)

The small grain distribution in the disks they harbour appear flared.

HH 30

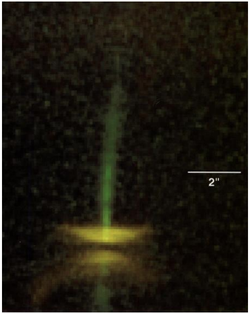
HH30 hosts an edge-on protoplanetary disk.



Villenave et al. (2020)

The large dust grains have settled onto the disk midplane into a flat structure.

The small grains in their disks have a flared distribution.

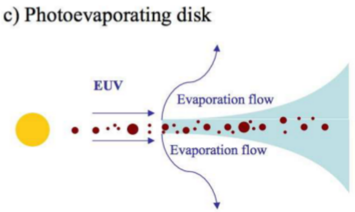


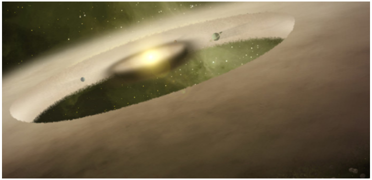
Burrows et al. (1996)

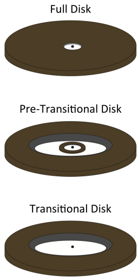
Explore the effect of the disk flaring index, inclination, and dust mass.

PDS 70

A transition disk is characterized by the presence of a large central cavity.





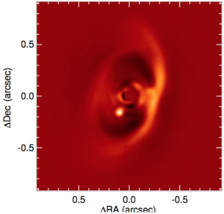


It may be carved out by some combination of :

- stellar wind
- radiation pressure
- grain growth
- accretion of primordial material onto the star
- perhaps even forming planets

PDS 70

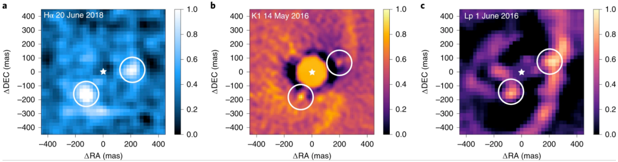
PDS 70 is surrounded by a pre-transition disk.



Müller et al. (2018)

There is a large gap extending from 1 AU to 60 AU.

Two planetary-mass companions were detected within the cavity.



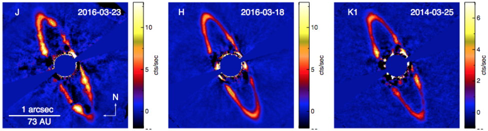
Haffert et al. (2019)

Explore the effect of the gap width, the gap depth, and the presence and temperature of a planet.

HR 4796

After a few million years, the gas in the disk is dispersed and the star becomes a main-sequence star. What is left is a debris disk :

- analogous to the objects first discovered by IRAS ;
- much less massive than a protoplanetary disk (little or no gas)
- dominated by a second generation of dust formed from collisions of large remnant bodies.



Chen et al. (2020)

This debris disk is a narrow ring, perhaps shepherded by the presence of one or more planets.

Explore the effect of the radial location of the ring and the dust grain size.

Studying Disk Properties

You will investigate science questions of the following type :

- What can an SED tell me about X for this specific system ?
- And what do images tell me about X ?
- Do I need an image to complement the SED or is the SED sufficient to retrieve the information I need ?
- Is there an underlying physical phenomenon at play ?

Property explored	Object			
	HL Tau	HH 30	PDS 70	HR 4796
Envelope Mass	■			
Presence of Gaps	■			
Scale Height	■			
Inclination		■		
Flaring		■		
Disk Mass		■		
Cavity Size			■	
Cavity Depth			■	
Presence of a Planet			■	
Distance of Dust from Star				■
Dust Grain Size				■

QUESTIONS

1. How does the gap width affect the SED?
2. How does the gap depth affect the SED?
3. And how do both of these parameters affect the images?
4. Can you derive the depth and width of the gap from the SED only?
5. Can a planet be detected via the SED?

You will find all the questions gathered in a Multiple Choice Questions Google Form.

Find these questions, as well as all the background on each disk in the Disk Models documentation (linked from the hands-on session page)

You will be provided with the **outputs** , i.e., SEDs and images, of a radiative transfer code called RADMC-3D, developed by Cornelis P. Dullemond.

This code computes how a disk dust grains interact with the light from the star, either reflecting it (scattered emission) or absorbing and re-emitting it (thermal emission).

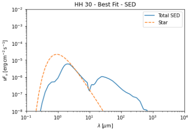
You will use RADMC3DPy, a Python library developed to process the outputs of RADMC-3D runs.

Spectral Energy Distribution

In [3]:
```
os.chdir(cwd+'/HH30_Best_Fit')
fig  = plt.figure()
s     = readSpectrum('HH30_SED_Best_fit.out')
star  = readStars()
lam   = s[:,0]
nu    = 1e4*cc/lam
fnu   = s[:,1]
nufnu = nu*fnu
plt.loglog(lam,nufnu,label='Total SED')
plt.loglog(lam,nu*star.fnustar[:,0],label='Star',linestyle='dashed')
plt.axis([1e-1, 1e4, 1e-8, 1e-2])
plt.xlabel('$\lambda\; [\mu \mathrm{m}$]')
plt.ylabel('$\\nu F_\\nu \; [\mathrm{erg}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$')
plt.title('HH 30 - Best Fit - SED')
plt.legend()
```

```
Reading wavelength_micron.inp
```

Out[3]: <matplotlib.legend.Legend at 0x114cbbc40>

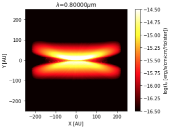


Images at 0.8 μm (scattered light)

In [8]:
```
#0.8 microns: scattered light

os.chdir(cwd+'/HH30_Best_Fit')
image = readImage('HH30_08um_Best_fit.out')
fig = plt.figure()
plotImage(image,au=True,log=True,vmax=-14.5,vmin=-16.5,bunit='inu',cmap='hot')
plt.title('HH 30 - Best Fit - 0.8 microns')
plt.close()
```

```
Reading HH30_08um_Best_fit.out
```



Note that what we call best fit is actually more like the nominal model that fits certain aspects of the SEDs and images, and we use that "best fit" to show the effect of varying model parameters.

Jupyter and Google Colab Notebooks

You will either use Jupyter or Google Colab Notebooks

Please refer to the Hands-on Session website

Before the Workshop

For each set of hands-on session, you can choose to either install Python and associated software packages on your computer, or download and use Google Colaboratory (Colab) notebooks, which run in your Google Drive using a virtual machine and do not require a Python installation. Either choice will allow you to go through the same hands-on activities; if you install Python, you will work with Jupyter notebooks, and if you use Google, you will work with Google Colab notebooks. No prior Python experience is required to participate in the hands-on sessions.

CLICK HERE FOR THE PYTHON INSTRUCTIONS

CLICK HERE FOR THE GOOGLE COLAB INSTRUCTIONS

- Jupyter notebooks require Python installation
- Google Colab does not require Python installation, but you need to set-up the notebook.

Please do this BEFORE the session (takes about 1/2 hour)

Do not hesitate to take a look at/use the #python-help Slack channel.

Jupyter and Google Colab Notebooks

There will be one Jupyter/Google Colab notebook per disk. You will work through it, cell by cell :

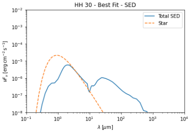
- use the pre-filled code and modify it, changing the file name for the model SED or image
- or copy/paste the code into new cells.

Spectral Energy Distribution

```
In [3]: os.chdir(cwd+'/HH30_Best_Fit')
        fig   = plt.figure()
        s     = readSpectrum('HH30_SED_Best_fit.out')
        star  = readStars()
        lam   = s[:,0]
        nu    = 1e4*cc/lam
        fnu   = s[:,1]
        nufnu = nu*fnu
        plt.loglog(lam,nufnu,label='Total SED')
        plt.loglog(lam,nu*star.fnustar[:,0],label='Star',linestyle='dashed')
        plt.axis([1e-1, 1e4, 1e-8, 1e-2])
        plt.xlabel('$\lambda\; [\mu \mathrm{m}$]')
        plt.ylabel('$\\nu F_\\nu \; [\mathrm{erg}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$')
        plt.title('HH 30 - Best Fit - SED')
        plt.legend()

        Reading wavelength_micron.inp

Out[3]: <matplotlib.legend.Legend at 0x114cbbc40>
```

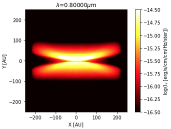


Images at 0.8 μm (scattered light)

```
In [8]: #0.8 microns: scattered light

        os.chdir(cwd+'/HH30_Best_Fit')
        image = readImage('HH30_08um_Best_fit.out')
        fig = plt.figure()
        plotImage(image,au=True,log=True,vmax=-14.5,vmin=-16.5,bunit='inu',cmap='hot')
        plt.title('HH 30 - Best Fit - 0.8 microns')
        plt.close()

        Reading HH30_08um_Best_fit.out
```



Link to the Google form at the very bottom of each Notebook. Fill it out several times (e.g., each time you are done with a disk) & skip questions you cannot answer.

After submitting you will see the answer key for the questions you submitted.

Live Hands-On Session - Tuesday 12 :45pm (PT)

Leads : Virginie Faramaz & Elise Furlan

Our wonderful team of volunteers !

- Isabel Rebollido – HLTau
- Marion Villenave – HLTau
- Lina Kimmig – HH30
- Karl Stapelfeldt – HH30
- DJ Dong – PDS70
- Kellen Lawson – PDS70
- Shih-Yun Tang – PDS70
- Geoff Bryden – HR4796
- Daniel Carrera – HR4796

You will be assigned randomly to one of our nine zoom breakout rooms.

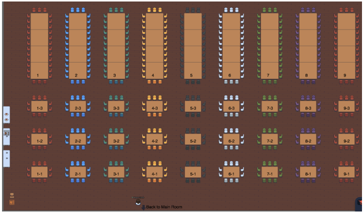
Each room will have a primary object assigned, as well as helper.

Please use the Zoom chat function to ask questions to your helper.

If you've finished working on the object assigned to the room, don't change room, change object !

After the Live Session

We'll be here throughout the week to help you !



You can use

- The documentation and references therein.
- Slack to ask your questions.
- The Hands-On Lab in Gather to work in groups.
- The Multiple-choice questions Google Form.

After the workshop, we will hand you a complete documentation that will include detailed answers to the questions, as well as input commands from RADMC3D (in case you ever want to run the code yourself).

We hope you will enjoy what we have prepared for you and will have pleasant learning experience !

ALMA Partnership, Brogan, C. L., Pérez, L. M., et al. 2015, ApJ, 808, L3

Arriaga, P., Fitzgerald, M. P., Duchêne, G., et al. 2020, AJ, 160, 79

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Backman, D. E. & Paresce, F. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine, 1253

Burrows, C. J., Stapelfeldt, K. R., Watson, A. M., et al. 1996, ApJ, 473, 437

Chen, C., Mazoyer, J., Poteet, C. A., et al. 2020, ApJ, 898, 55

Dullemond, C. P., Hollenbach, D., Kamp, I., & D'Alessio, P. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil, 555

Golimowski, D. A., Ardila, D. R., Krist, J. E., et al. 2006, AJ, 131, 3109

Greaves, J. S., Holland, W. S., Moriarty-Schieven, G., et al. 1998, ApJ, 506, L133

Haffert, S. Y., Bohn, A. J., de Boer, J., et al. 2019, Nature Astronomy, 3, 749

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Kalas, P., Graham, J. R., & Clampin, M. 2005, Nature, 435, 1067

Lagrange, A. M., Langlois, M., Gratton, R., et al. 2016, A&A, 586, L8

MacGregor, M. A., Matrà, L., Kalas, P., et al. 2017, ApJ, 842, 8

Müller, A., Keppler, M., Henning, T., et al. 2018, A&A, 617, L2

Schneider, G., Weinberger, A. J., Becklin, E. E., Debes, J. H., & Smith, B. A. 2009, AJ, 137, 53

Smith, B. A. & Terrile, R. J. 1984, Science, 226, 1421

Su, K. Y. L., Rieke, G. H., Malhotra, R., et al. 2013, ApJ, 763, 118

Villenave, M., Ménard, F., Dent, W. R. F., et al. 2020, A&A, 642, A164