Two-layer modeling of the circumstellar environment of π^1 Gru with VLTI/AMBER

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I. Abstract

The aim of this work is to determine the physical and geometrical parameters characterizing the giant S-type star π^1 Gru and its circumstellar environment . These parameters come from the literature and from the fit of the ISO/SWS spectrometric measurements with the radiative transfer numerical code DUSTY. The fit of the interferometric AMBER/VLTI measurements with an analytical thin-layer model reveals the existence of a double circumstellar layer.

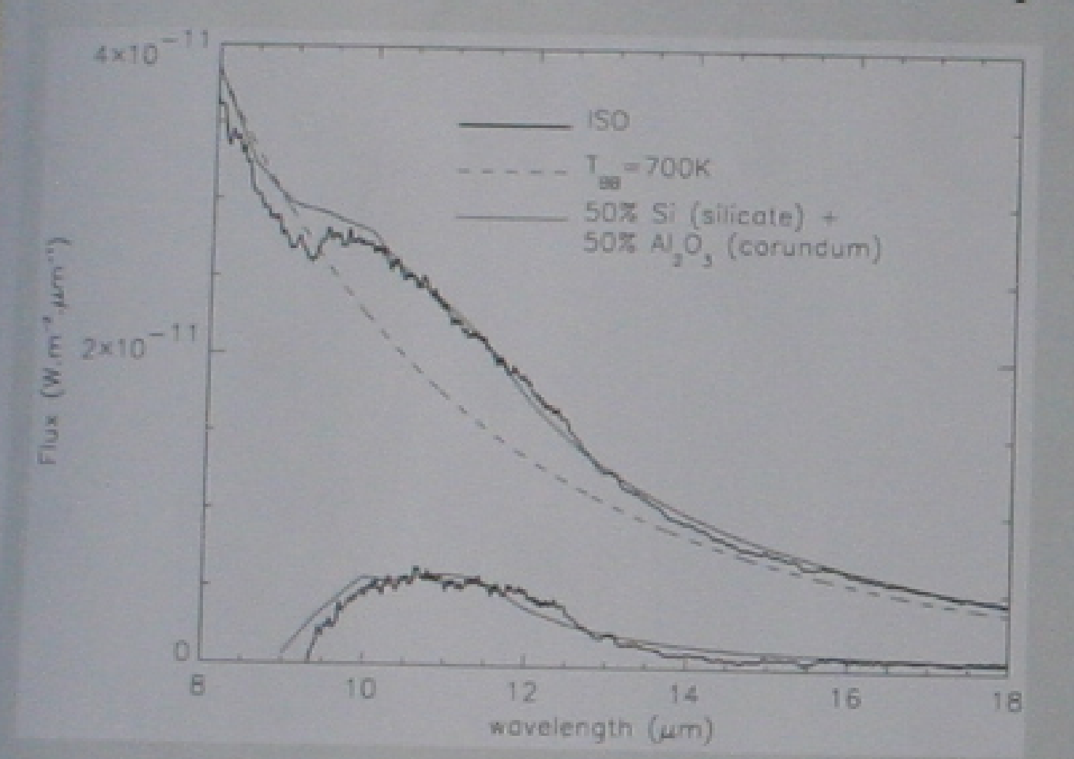
II. S-type star characteristics

	INTRINSIC	EXTRINSIC
Spectral feature	ZrO bands	
Technetium	Tc-rich	Tc-poor
K-[12]	>0.86	<0.86
F(12µm)/F(2.2µm)	≥0.1	<0.1
Circumstellar dust	detectable	undetectable
Mass-loss rate ($M_\odot$/yr)	$>10^{-7}$	$<10^{-8}$
Ratio of S stars (solar neighbourhood)	64±5%	36±5%
Mass ($M_\odot$)	~1 to ~5	1.5 to 2
Evolutive scenario	M-S-C (AGB)	Ba-S (RGB or E-AGB)

III. Central star parameters

	Pi1 Gru	
General description	Intrinsic irregular variable of type Srb	
Variation cycle	150 days	
Distance	153 pc	
Binary nature	Double (2.71" of separation, so that the companion can be neglected)	
	At maximum V brightness	At minimum V brightness
Visual magnitude	5.4	6.7
C/O ratio	0.97	0.95
Effective temperature	3100 K	3000 K
Angular diameter	19 mas	25 mas
Luminosity	7600 $L_\odot$	11600 $L_\odot$

IV. Fit of the ISO spectra with DUSTY

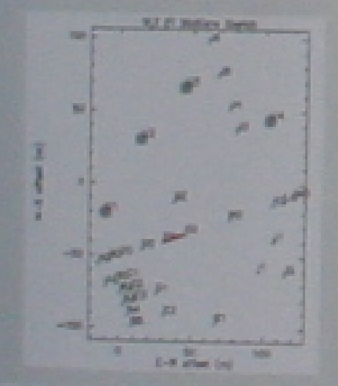


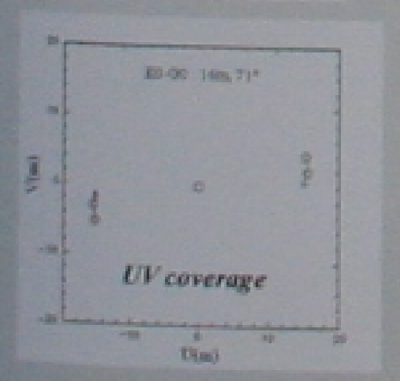
	Dust feature
Chemical composition	50±5% of Silicate and 50±5% of Corundum
Condensation temperature (K)	1500
Inner boundary radius (mas)	37±1
Optical depth @ 10µm	0.016±0.001
Dust density distribution	$\propto r^{-1.7}$
Single grain size distribution (µm)	0.1
Thickness (in r_{in})	5000

V. AMBER/VLTI observations

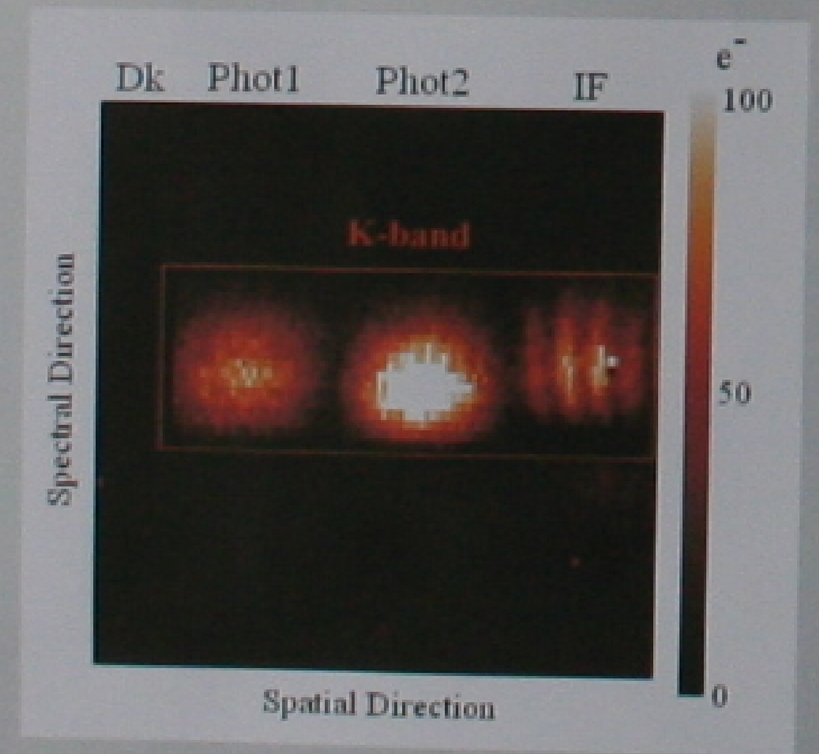
AMBER (Astronomical Multi Beam Recombiner) is the VLTI beam combiner, operating in the near-infrared, using optical fibers. The instrument can operate at a resolution up to 10^4 and delivers spectrally dispersed visibilities.

- ***π^1 Gru was observed on 2005/07/14 with the single AT-VLTI baseline E0-G0 (16m, 71°) in the low-resolution (R=35) K-band spectral mode.***
- ***Its calibration star δ Gru, of spectral type M4.5IIIa, was observed under the same instrumental conditions.***





UV coverage



Short exposure frame of the π^1 Gru signal on the AMBER detector.

First column (Dk) : masked pixels (dark current).

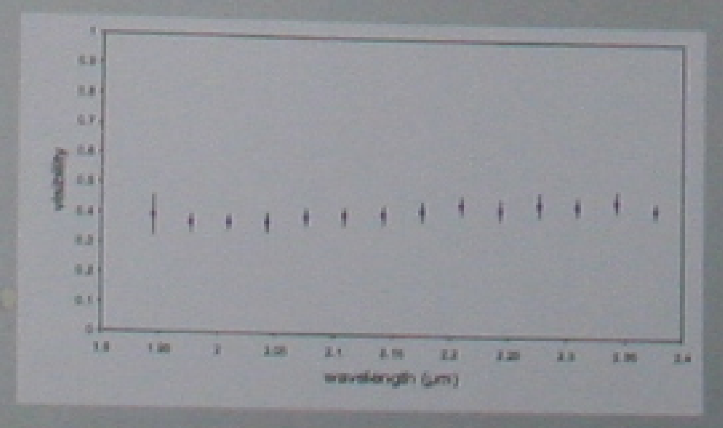
Second (Phot1) and Third (Phot2) columns : beams coming from the first and the second telescope respectively.

Fourth column (IF) : fringe pattern obtained by superposition of the two beams.

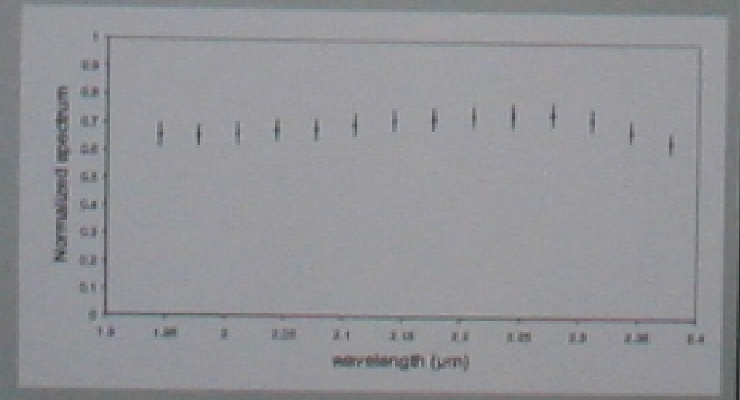
<u>Calibration process :</u>

- ✓ ***Cosmetics and flat field***
- ✓ ***Image selection criteria***
- ✓ ***Spectral calibration***
- ✓ ***Instrumental calibration***

Calibrated visibilities



Calibrated spectrum normalized by the flux of the central star



VI. The analytical thin-layer model

Expression of the emergent intensity, solution of the radiative transfer equation through an optically and geometrically thin layer :

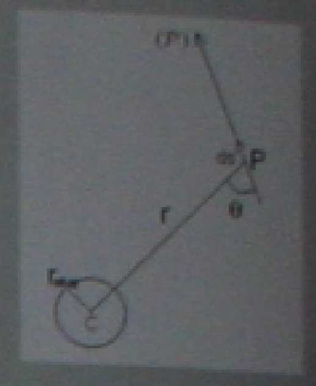
$$dI_\lambda=(S_\lambda-I_\lambda)d\tau_\lambda$$

with :

$$d\tau_\lambda=\kappa_\lambda ds$$

and :

$$\kappa_\lambda=\kappa_{a\lambda}+\kappa_{s\lambda}$$



P point intensity :

$$I_\lambda(r;\theta)=B_\lambda(T_{star})e^{-\tau_\lambda}\Theta(r_{star}-r\sin\theta)+I_{layer\,\lambda}$$

<u>If we consider :</u>

$$I_{layer\lambda}=\int_0^{\tau_\lambda}S_\lambda\exp(\tau'_\lambda-\tau_\lambda)d\tau'_\lambda$$

No scattering :

$$\kappa_{s\lambda}=0$$

Thermodynamic equilibrium :

$$S_\lambda\approx B_\lambda(T_{layer})$$

<u>If we consider</u> : *an optically thin layer*

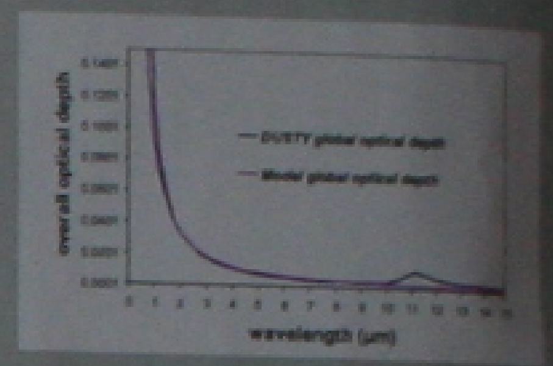
$$I_\lambda(r_{out};\theta)=B_\lambda(T_{star})\Theta(r_{star}-r_{out}\sin\theta)+B_\lambda(T_{layer})\tau_\lambda(r_{out},\theta)$$

Expression of the global optical depth for a geometrically thin layer :

$$\tau_\lambda(r_{out};\theta)=\kappa_\lambda^{in}\left(\frac{r_{in}}{r_{out}}\right)^p l(r_{out},\theta)$$

with :

$$\kappa_\lambda^{in}=\kappa_{\lambda_0}^{in}\left(\frac{\lambda}{\lambda_0}\right)^{-\beta}$$

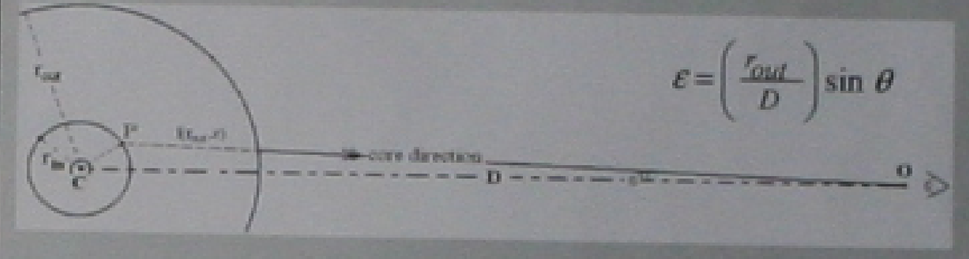


and :

$$l(r_{out};\theta)=r_{out}\cos\theta-\Theta(r_{in}-r_{out}\sin\theta)\sqrt{r_{in}^2-r_{out}^2\sin^2\theta}$$

layer geometrical thickness

« core » direction ($0\leq\varepsilon\leq\varepsilon_{in}$)



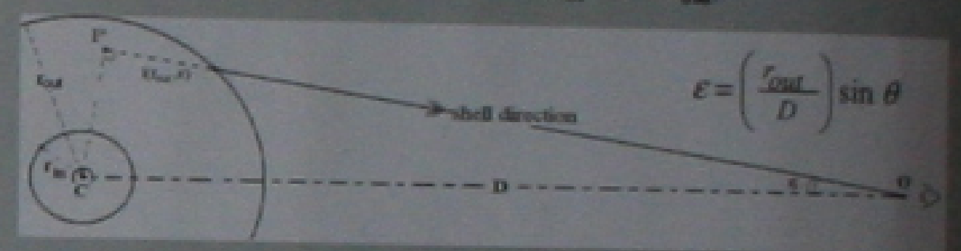
Output radiation dominated by material located at the inner boundary (P').

Temperature in P' equal to the inner boundary temperature :

$$T_{layer}=T_{in}$$

$$I_\lambda^{core}(\varepsilon)=B_\lambda(T_{in})\kappa_\lambda^{in}\left(\frac{\varepsilon_{in}}{\varepsilon_{out}}\right)^p D\left[\sqrt{\varepsilon_{out}^2-\varepsilon^2}-\sqrt{\varepsilon_{in}^2-\varepsilon^2}\right]$$

« shell » direction ($\varepsilon_{in}\leq\varepsilon\leq\varepsilon_{out}$)



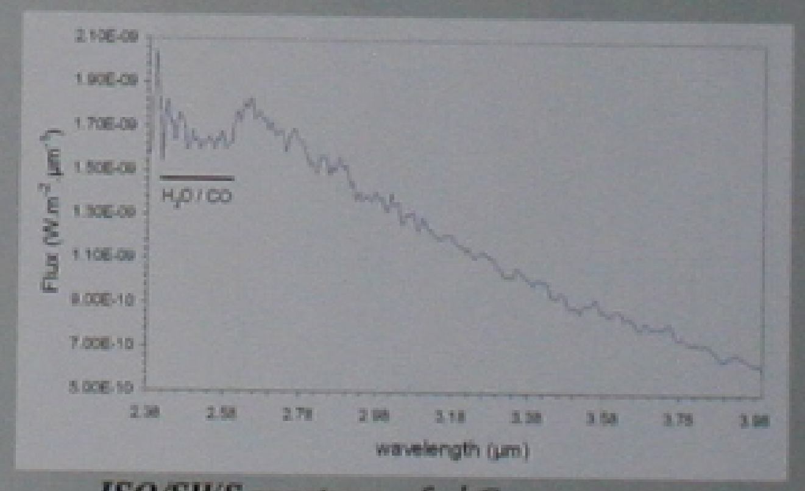
Hottest and most numerous material located at the P' point, closest from the center C.

Temperature in P' defined at the thermodymanical equilibrium :

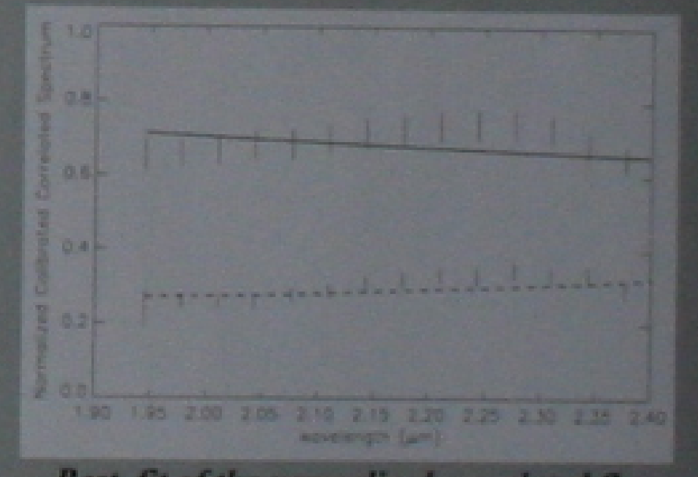
$$T_{layer}=T_{in}\left(\frac{\varepsilon}{\varepsilon_{in}}\right)^{-\frac{2}{\beta+4}}$$

$$I_\lambda^{shell}(\varepsilon)=B_\lambda\left(T_{in}\left(\frac{\varepsilon}{\varepsilon_{in}}\right)^{-\frac{2}{\beta+4}}\right)\kappa_\lambda^{in}\left(\frac{\varepsilon_{in}}{\varepsilon_{out}}\right)^p D\sqrt{\varepsilon_{out}^2-\varepsilon^2}$$

VII. Two-layer modeling

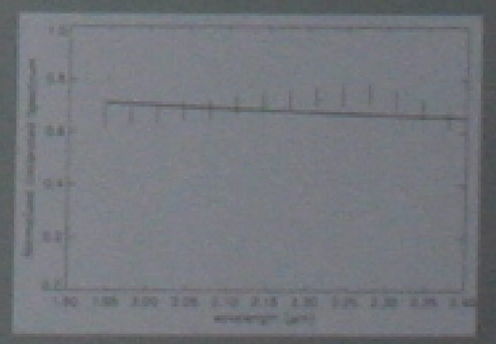


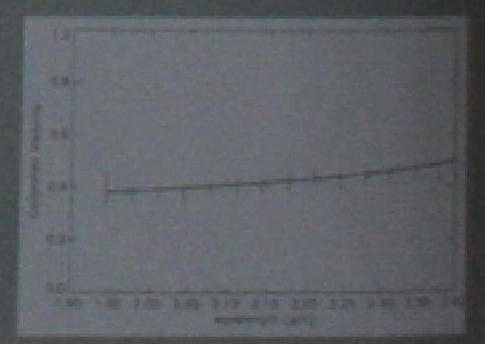
ISO/SWS spectrum of π^1 Gru.
Absorption feature between 2.4 and 2.6 µm corresponds to H_2O or CO molecules.



Best fit of the normalized correlated flux given by the two-layer analytical model

Minimization of the correlated spectrum (F×V) simultaneously fits the visibility and the spectrum :





Parameters	*Internal layer*	*External layer*
Optical depth	**1.58±0.08 (@2.4µm)**	**0.24±0.01 (@2.2µm)**
Inner boundary temperature (K)	**1391±18**	**1551±15**
Inner boundary radius (mas)	**20.5±0.2**	**40.2±0.8**
Outer boundary radius (mas)	**23.0±0.2**	**89±5**

VIII. Conclusion

Interferometry gives complementary knowledge to the spectrophotometric study of the circumstellar environment. In the case of π^1 Gru, VLTI/AMBER observations give the physical and geometrical parameters associated to the internal and external layers. Both layers were suspected by ISO/SWS spectrometric measurements.