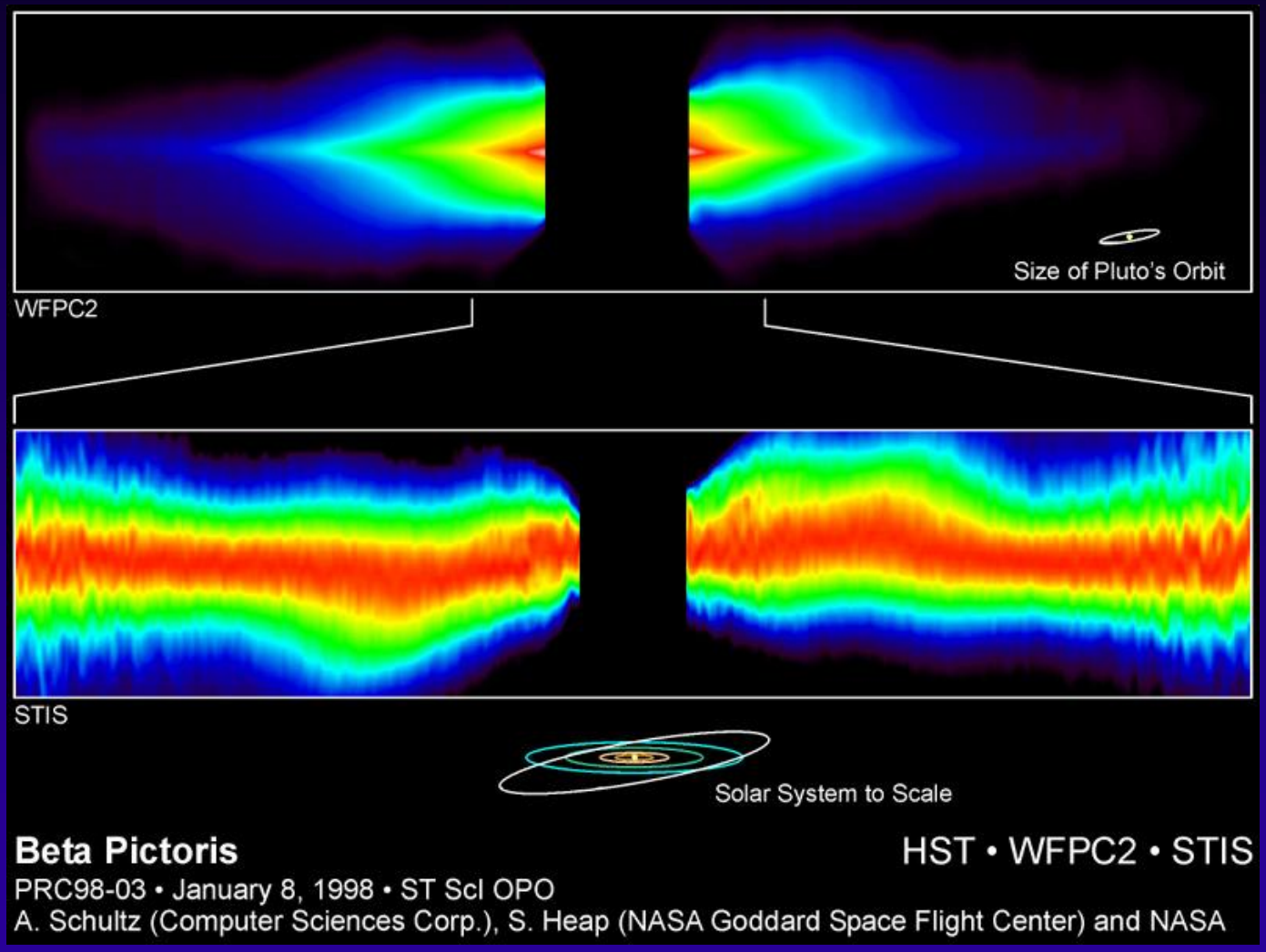
Gas in a debris disk: β Pictoris

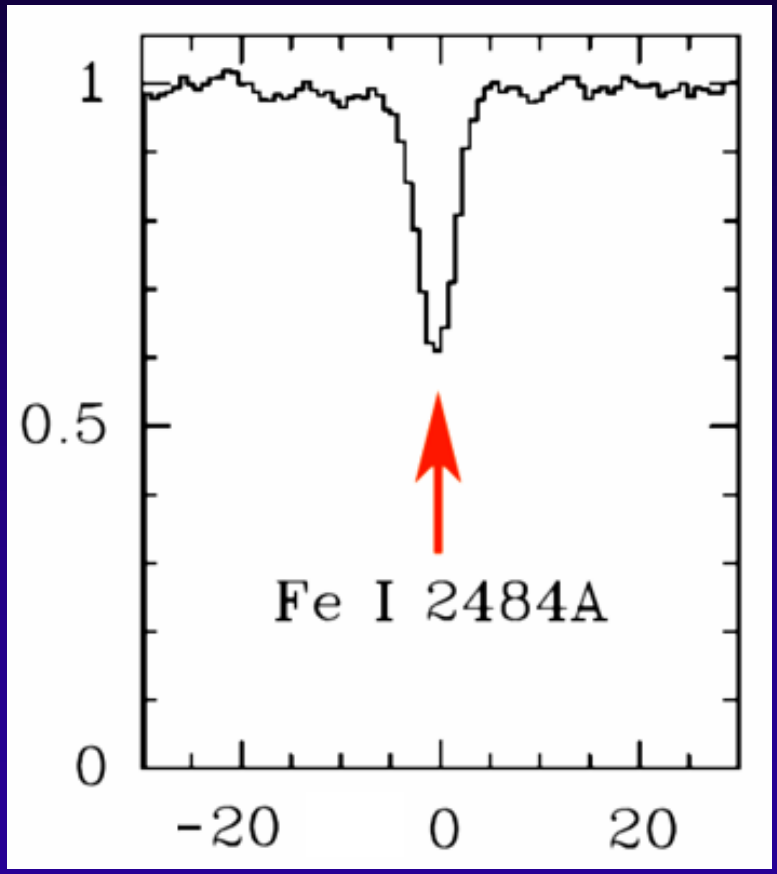
Alexis Brandeker
Stockholm Observatory

β Pictoris in scattered light



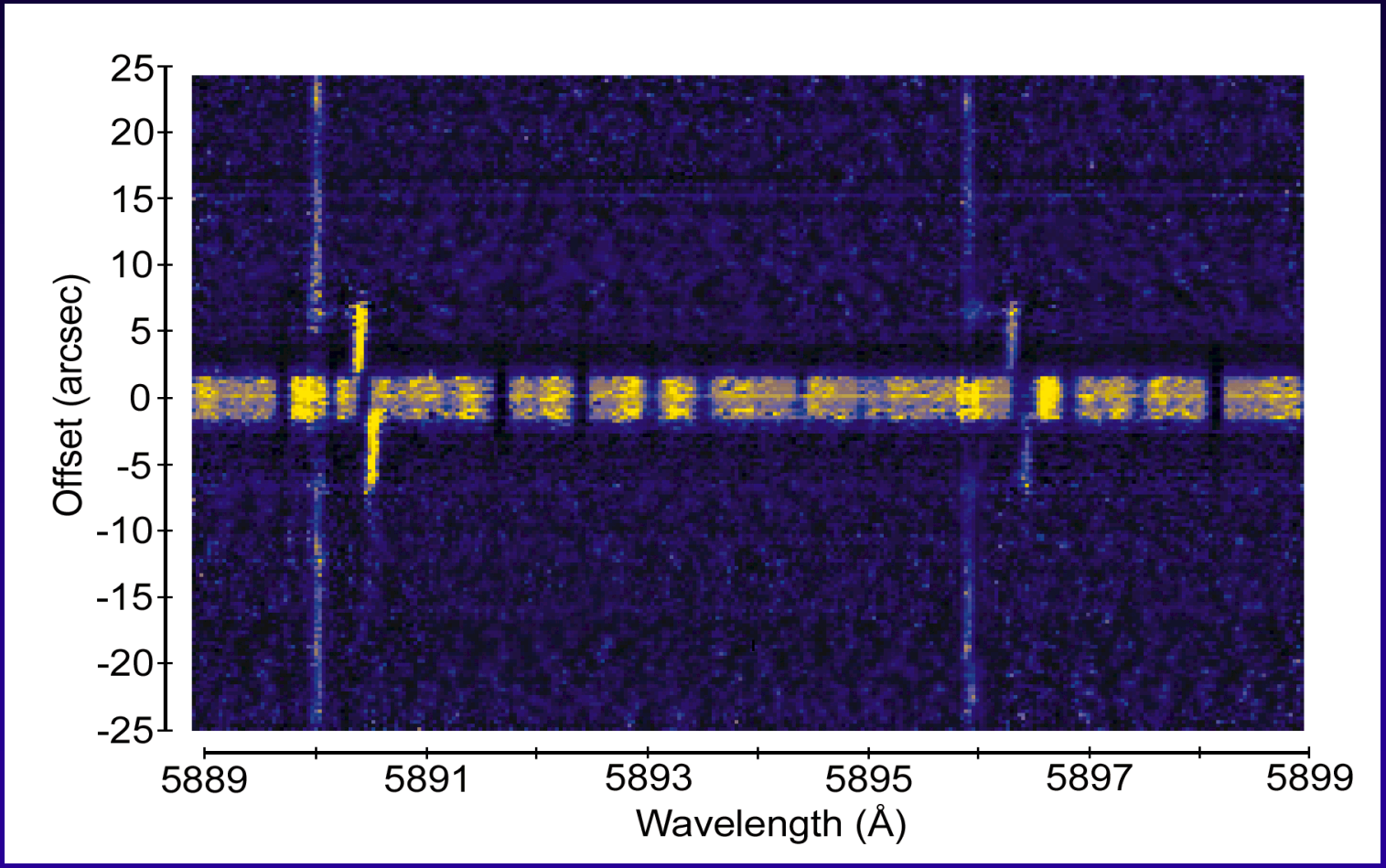
β Pictoris gas

- β Pictoris found to be "shell" star by Slettebak (1975, ApJ, 197:137)



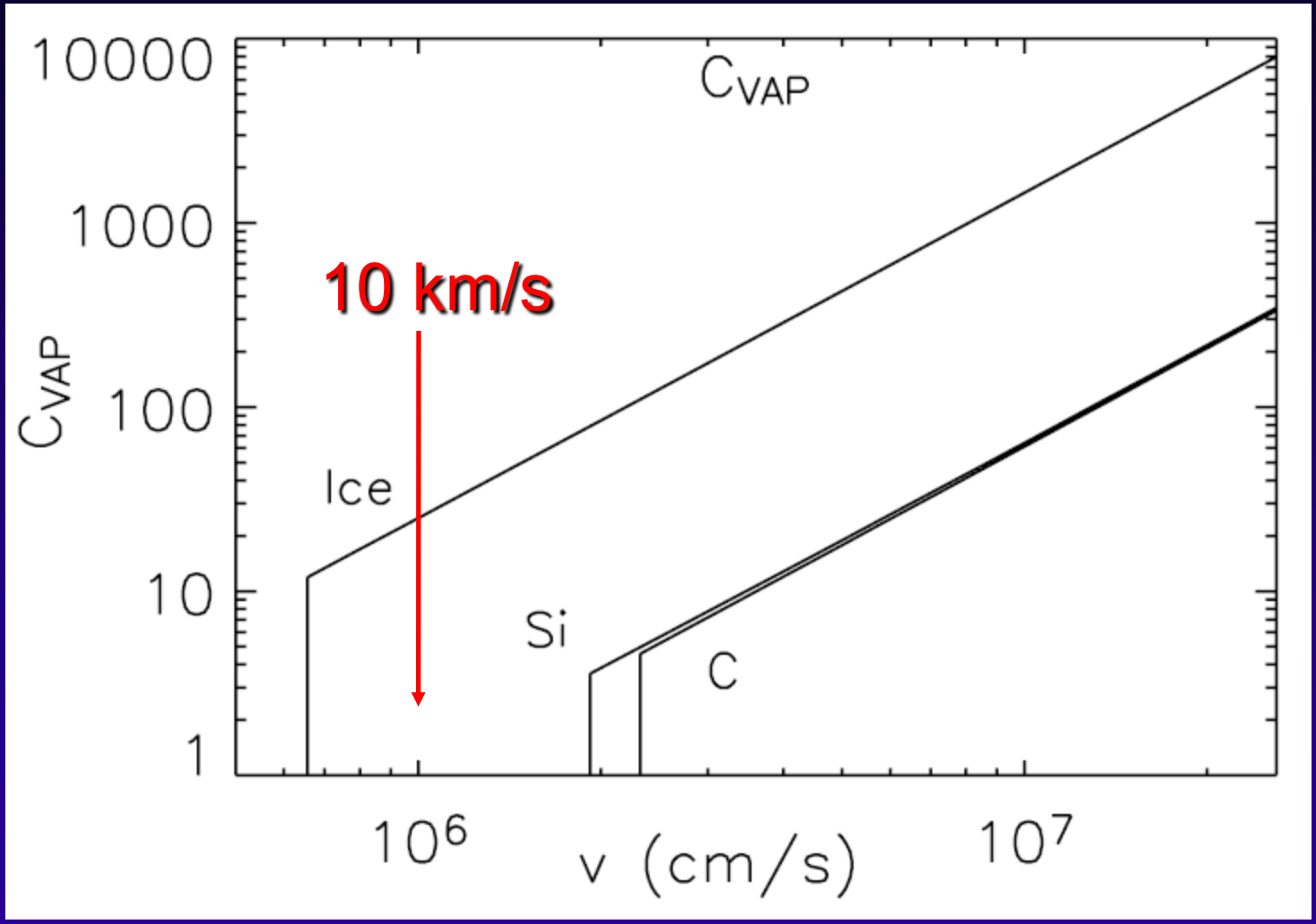
Lagrange et al. 1998, A&A 330:1091

Extended gas

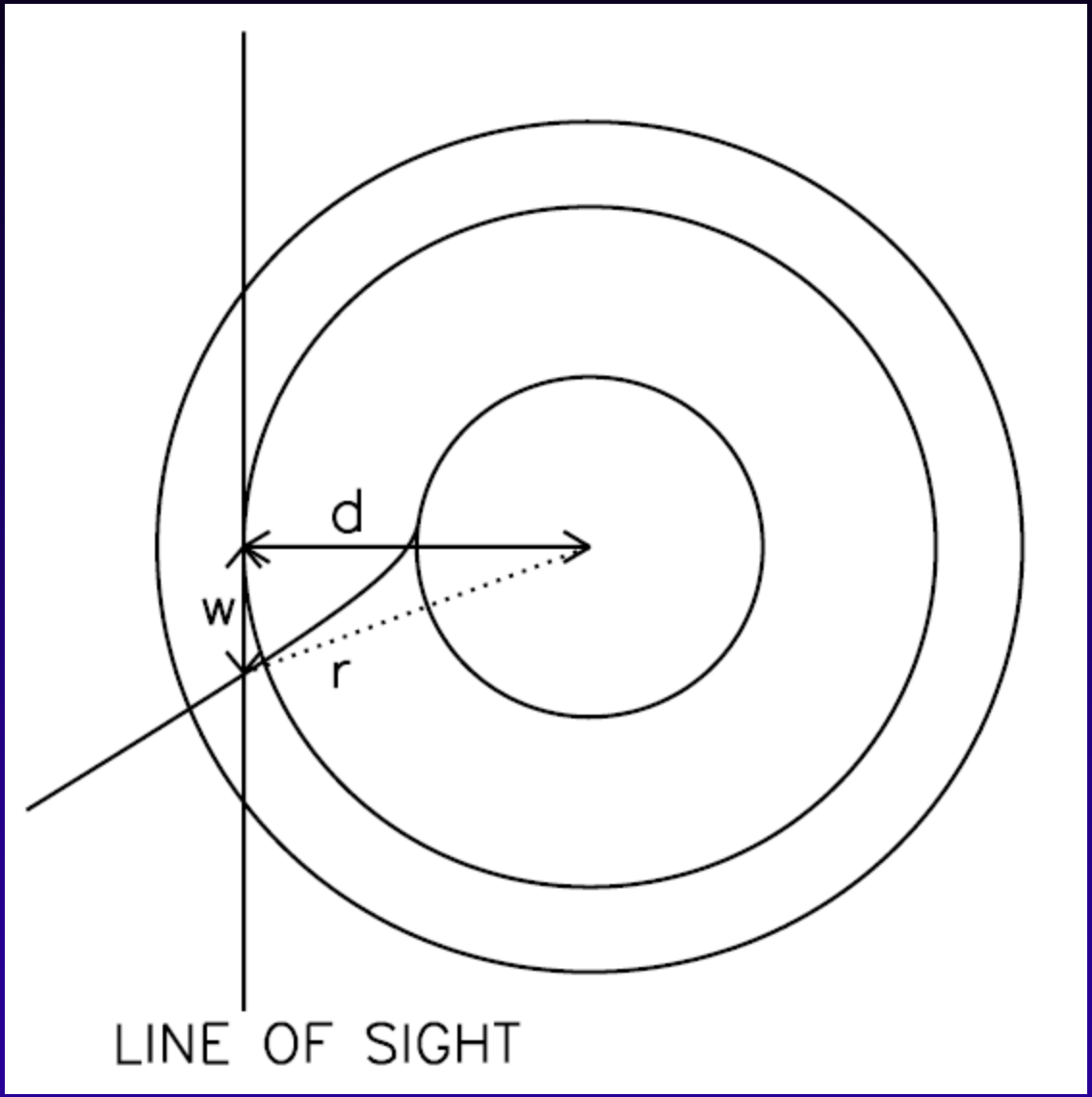


NTT/EMMI Olofsson et al. 2001, ApJ 563:L77

Grain-grain collisions

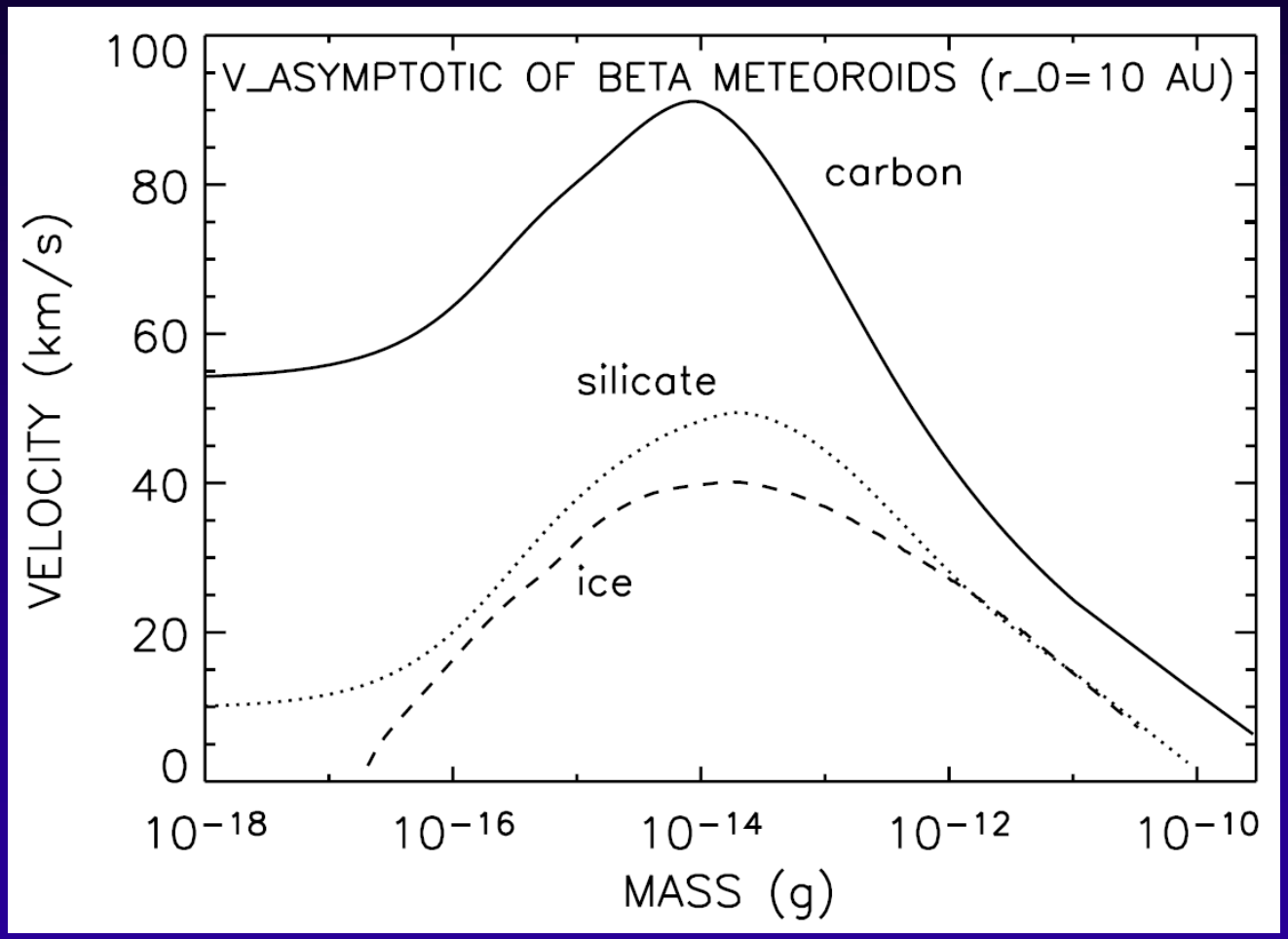


Czechowski & Mann 2007, ApJ 660:1541



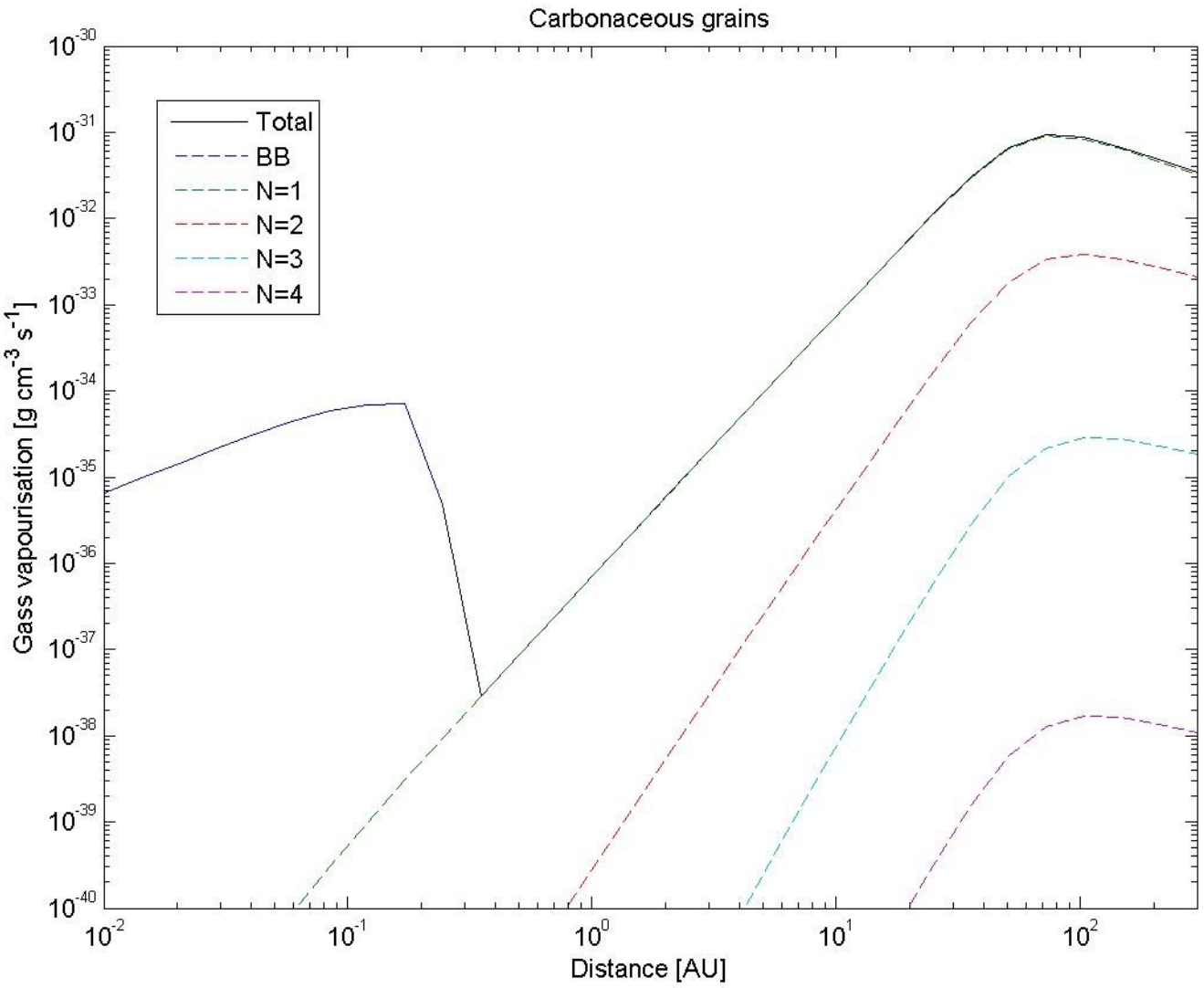
Czechowski & Mann 2007, ApJ 660:1541

β-meteroids!

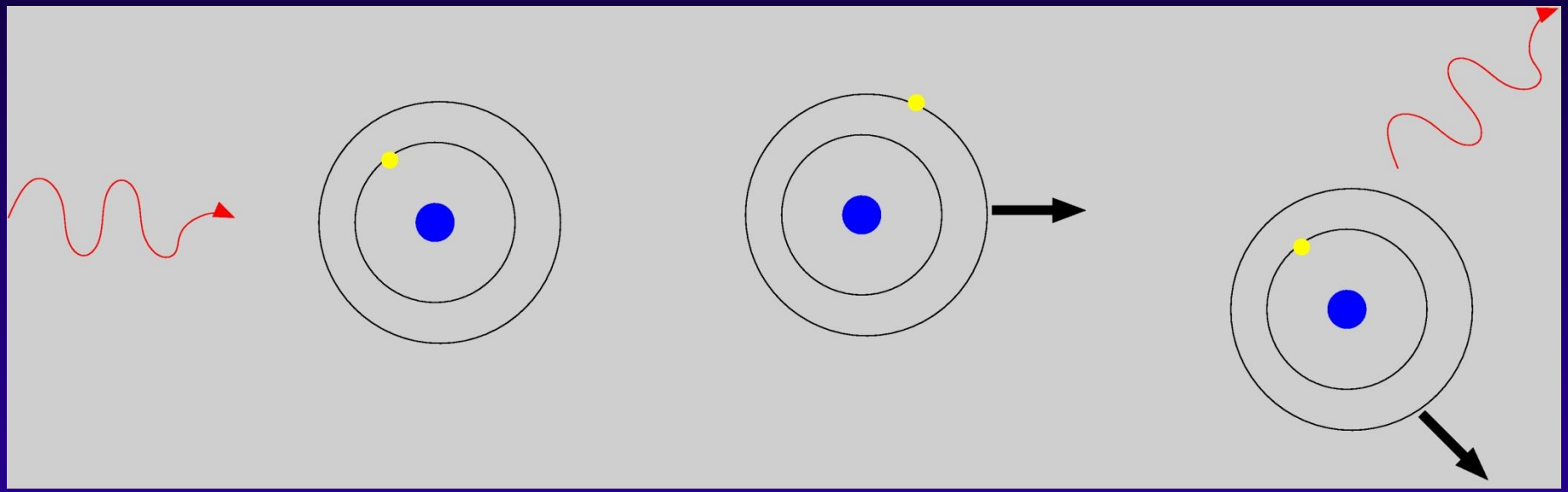


Czechowski & Mann 2007, ApJ 660:1541

β-meteroids!


Carbonaceous grains
Total
BB
N=1
N=2
N=3
N=4
Gass vapourisation [g cm^{-3} s^{-1}]
Distance [AU]
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

Radiation force



On average, atoms move in direction of incident radiation

Fernández et al. 2006, ApJ 643:509

TABLE 1

RADIATION FORCE COEFFICIENTS

Ion	$\beta^{a,b}$	Ion	β^{b}	Ion	$\beta^{a,b}$	Ion	$\beta^{a,b}$
H I	$(1.6\pm0.1)10^{-3}$	F III	$(5.0\pm1.0)10^{-9}$	S II	$(9.0\pm1.0)10^{-5}$	V I	72 ± 4
Ne III	$(9.0\pm2.0)10^{-4}$					V II	4.4 ± 0.2
Na I	360 ± 20				10^{-3}	V III	0
Na II	0				10^{-7}	Cr I	93 ± 5
Na III	0				10^{-6}	Cr II	$(6.0\pm3.0)10^{-7}$
Mg I	74 ± 8				10^{-6}	Cr III	...
					10^{-7}	Mn I	28 ± 3
						Mn II	7 ± 1
						Mn III	...
						Fe I	27 ± 2
					10^{-4}	Fe II	5.0 ± 0.3
C III	$(8.5\pm0.9)10^{-6}$	Al II	0.36 ± 0.05	Ca I	330 ± 40	Fe III	$(3.0\pm0.6)10^{-7}$
N I	$(2.1\pm0.1)10^{-4}$	Al III	12 ± 1	Ca II	50 ± 10	Co I	16 ± 1
N II	$(7.5\pm0.5)10^{-6}$	Si I	6.0 ± 0.6	Ca III	...	Co II	0
N III	$(7.0\pm1.0)10^{-6}$	Si II	9 ± 9	Sc I	220 ± 20	Co III	$(4.0\pm2)10^{-7}$
O I	$(3.3\pm0.2)10^{-4}$	Si III	$(5.8\pm0.6)10^{-4}$	Sc II	$(1.3\pm0.4)10^{3}$	Ni I	26 ± 2
O II	$(3.1\pm0.7)10^{-9}$	P I	3.4 ± 0.6	Sc III	$(9.0\pm3.0)10^{-2}$	Ni II	$(7.0\pm2.0)10^{-2}$
O III	$(6.5\pm0.6)10^{-7}$	P II	$(2.2\pm0.3)10^{-3}$	Ti I	97 ± 5	Ni III	$(3.0\pm2.0)10^{-7}$
F I	0	P III	$(5.0\pm2.0)10^{-4}$	Ti II	28 ± 2	p[c]	4.4×10^{-11}
F II	$(3.5\pm0.9)10^{-6}$	S I	0.56 ± 0.09	Ti III	$(5.0\pm0.1)10^{-4}$	e[c]	0.27

[a] $\beta = 0$ means that no ground state transitions are known in the range $1000\text{Å} < \lambda < 50000\text{Å}$

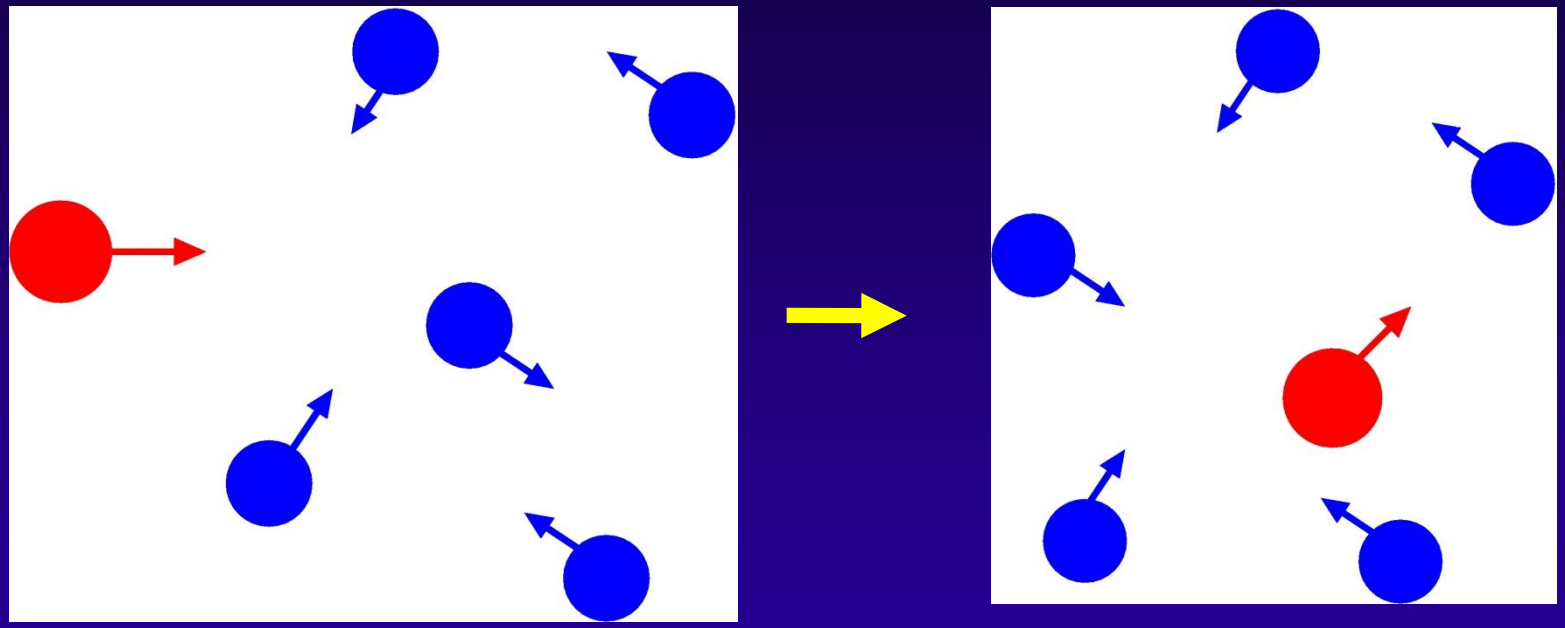
[b] Empty entries mean that no atomic data was available

[c] Proton and electron value calculated using Thomson cross section

Collisional braking: principle

before

after



Collision frequency – Braking inertia

Element	v_{ion} [b] (km s^{-1})	n_I/n_{II+} [c]
Li I	0.11	4.4×10^{-6}
Be I	58	4.4×10^{-2}
B I	0.41	6.1×10^{-4}
Na I	3.3	3.2×10^{-4}
Mg I	1.1	6.4×10^{-4}
Al I	5.0×10^{-4}	8.5×10^{-7}
Si I	0.02	1.3×10^{-4}
P I	8.7	1.5×10^{-1}
K I	0.5	1.5×10^{-4}
Ca I	0.03	3.5×10^{-6}
Sc I	3.5	7.0×10^{-4}
Ti I	0.6	3.0×10^{-4}
V I	0.2	1.2×10^{-4}
Cr I	0.9	4.8×10^{-4}
Mn I	0.4	7.6×10^{-4}
Fe I	0.5	9.0×10^{-4}
Co I	0.8	2.9×10^{-3}
Ni I	0.3	4.8×10^{-4}

Velocity at ionisation

Fernández et al. 2006, ApJ 643:509

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He I	0	Ne I	0	S III	$(2.0\pm1.0)10^{-4}$	V II	4.4 ± 0.2
He II	···	Ne II	0	Cl I	$(2.3\pm0.4)10^{-3}$	V III	0
Li I	900 ± 40	Ne III	$(9.0\pm2.0)10^{-8}$	Cl II	$(3.7\pm0.4)10^{-7}$	Cr I	93 ± 5
Li II	0	Na I	360 ± 20	Cl III	$(3.0\pm2.0)10^{-6}$	Cr II	$(6.0\pm3.0)10^{-7}$
C I	$(3.3\pm0.1)10^{-2}$	Ar I	$(1.7\pm0.3)10^{-6}$	Cr III	···		
C II	$(2.3\pm0.2)10^{-3}$	Ar II	0	Mn I	28 ± 3		
C III	$(8.5\pm0.9)10^{-6}$	Ar III	$(1.5\pm0.2)10^{-7}$	Mn II	7 ± 1		
N I	$(2.1\pm0.1)10^{-4}$	K I	200 ± 20	Mn III	···		
N II	$(7.5\pm0.5)10^{-6}$	K II	···	Fe I	27 ± 2		
N III	$(7.0\pm1.0)10^{-6}$	K III	$(4.4\pm0.2)10^{-4}$	Fe II	5.0 ± 0.3		
O I	$(3.3\pm0.2)10^{-4}$	Al II	0.36 ± 0.05	Ca I	330 ± 40	Fe III	$(3.0\pm0.6)10^{-7}$
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F II	$(3.5\pm0.9)10^{-6}$	Si III	$(5.8\pm0.6)10^{-4}$	Sc II	$(1.3\pm0.4)10^{3}$	Ni I	26 ± 2
		P I	3.4 ± 0.6	Sc III	$(9.0\pm3.0)10^{-2}$	Ni II	$(7.0\pm2.0)10^{-2}$
		P II	$(2.2\pm0.3)10^{-3}$	Ti I	97 ± 5	Ni III	$(3.0\pm2.0)10^{-7}$
		P III	$(5.0\pm2.0)10^{-4}$	Ti II	28 ± 2	p[c]	4.4×10^{-11}
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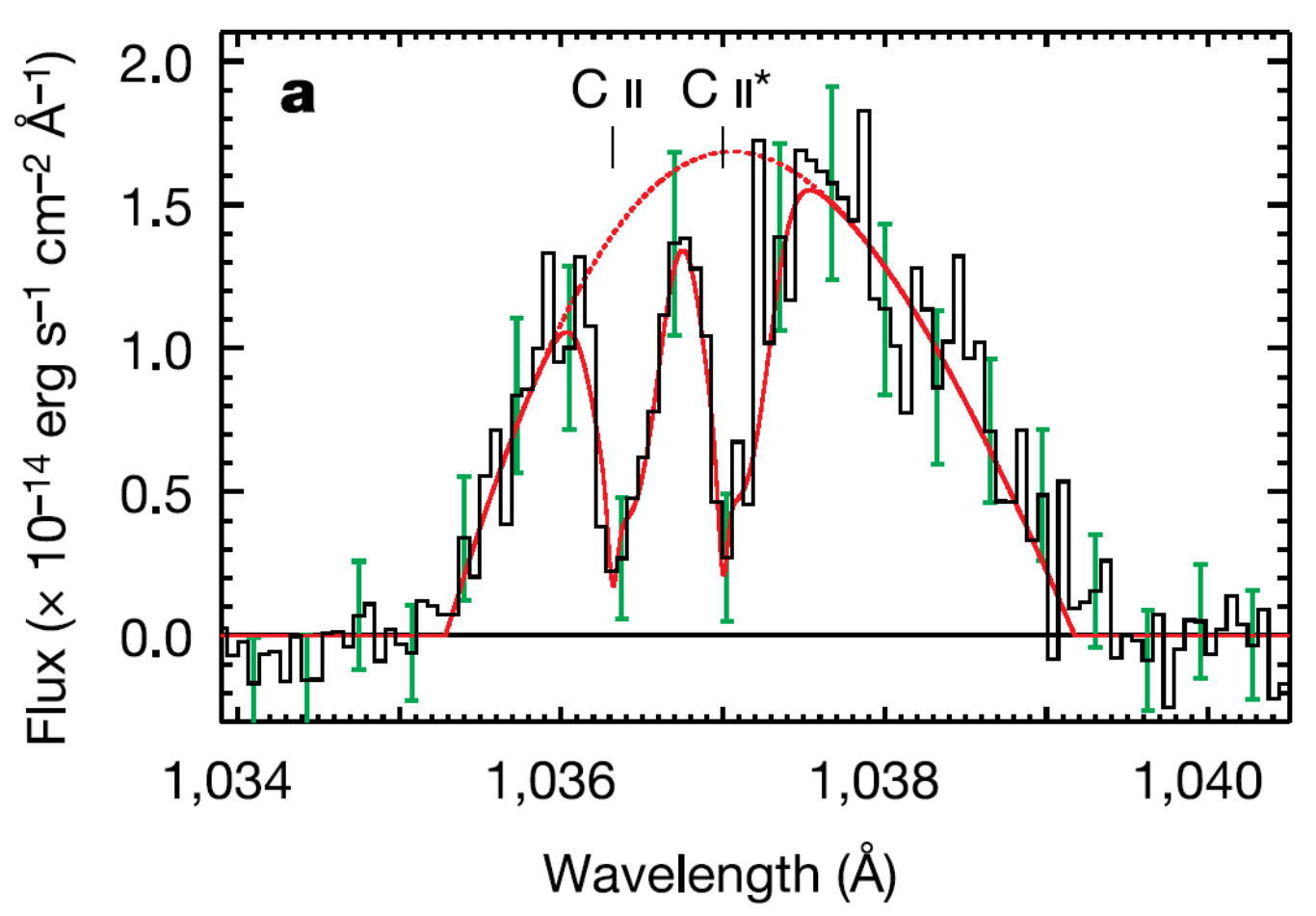
[b] Empty entries mean that no atomic data was available

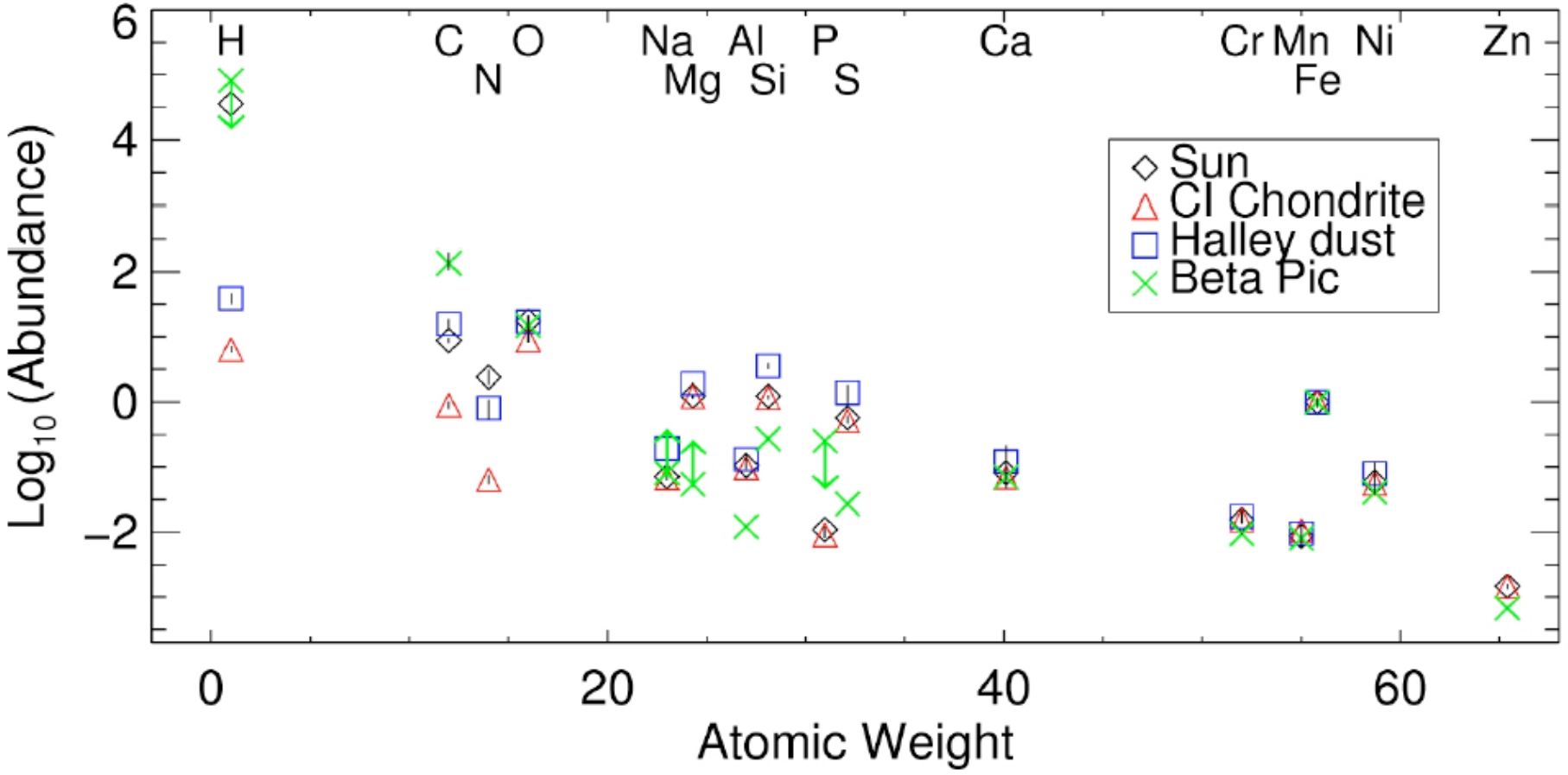
[c] Proton and electron value calculated using Thomson cross section

FUSE: Carbon absorption



Roberge et al. 2006, Nature 441:724

β Pictoris gas disk composition



Roberge et al. 2006, Nature 441:724

Element	v_{ion} [b] (km s^{-1})	n_I/n_{II+} [c]
Li I	0.11	4.4×10^{-6}
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B I	0.41	6.1×10^{-4}
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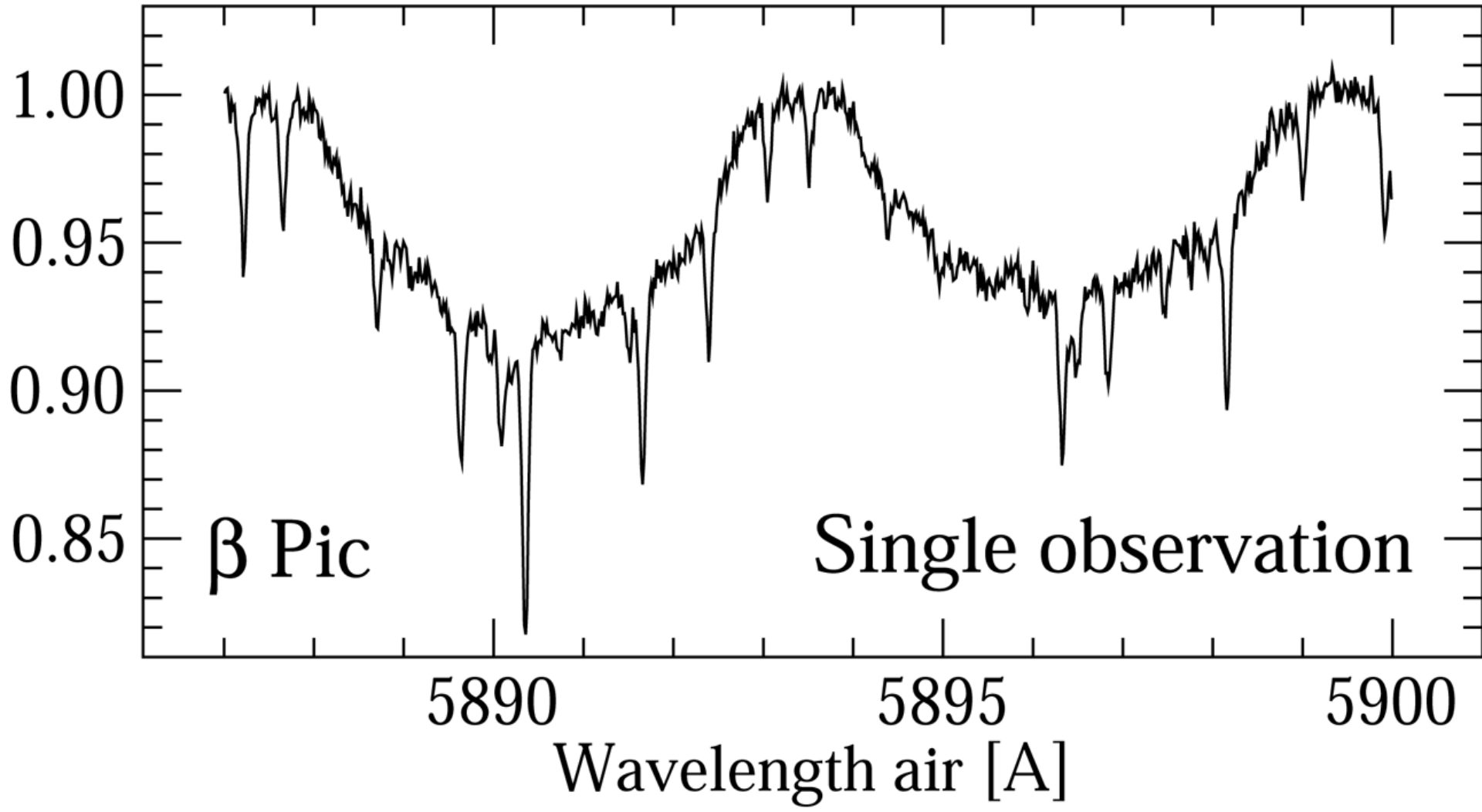
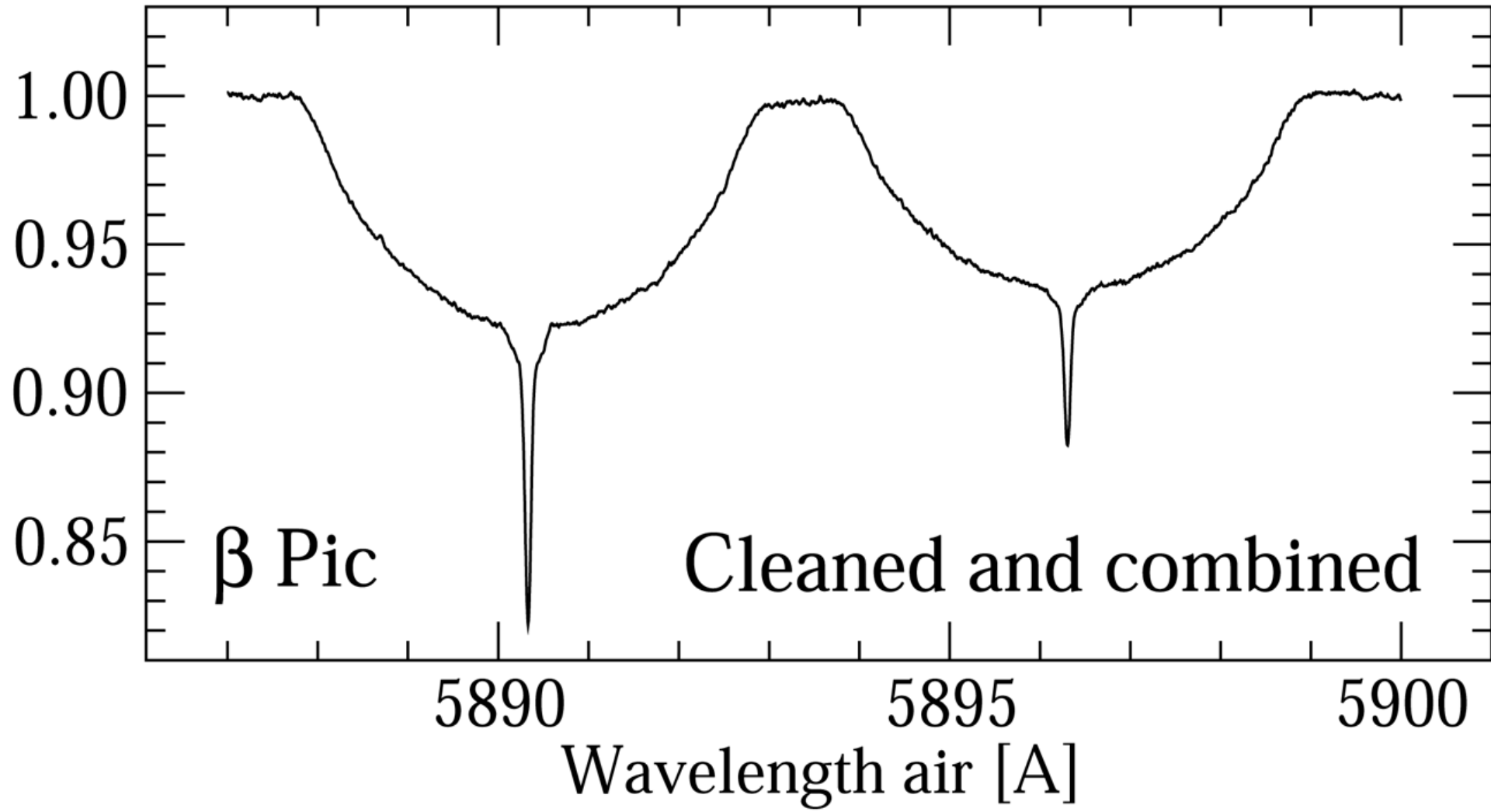
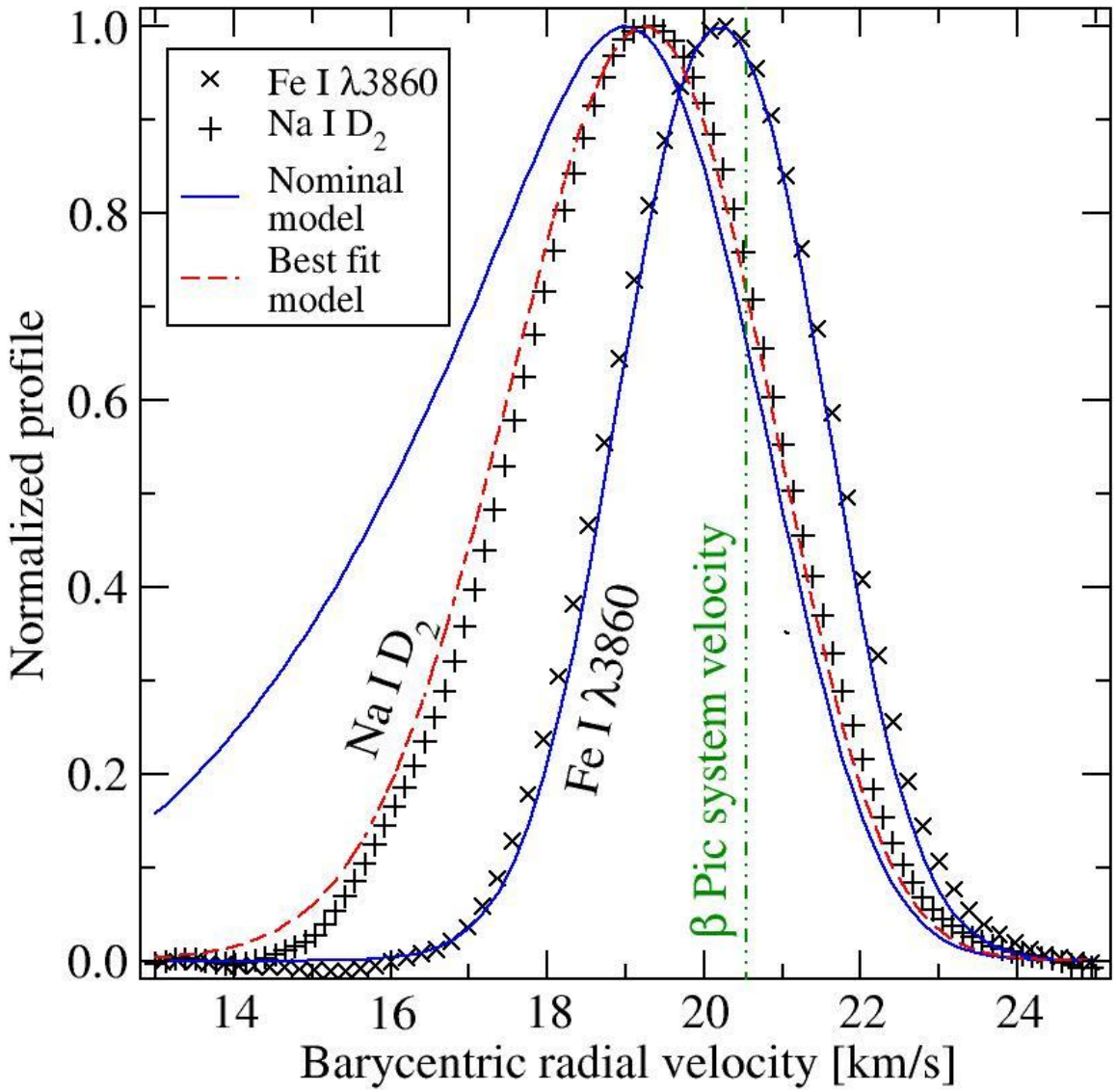
Ca I	0.03	3.5×10^{-6}
Sc I	3.5	7.0×10^{-4}
Ti I	0.6	3.0×10^{-4}
V I	0.2	1.2×10^{-4}
Cr I	0.9	4.8×10^{-4}
Mn I	0.4	7.6×10^{-4}
Fe I	0.5	9.0×10^{-4}
Co I	0.8	2.9×10^{-3}
Ni I	0.3	4.8×10^{-4}

Velocity at ionisation

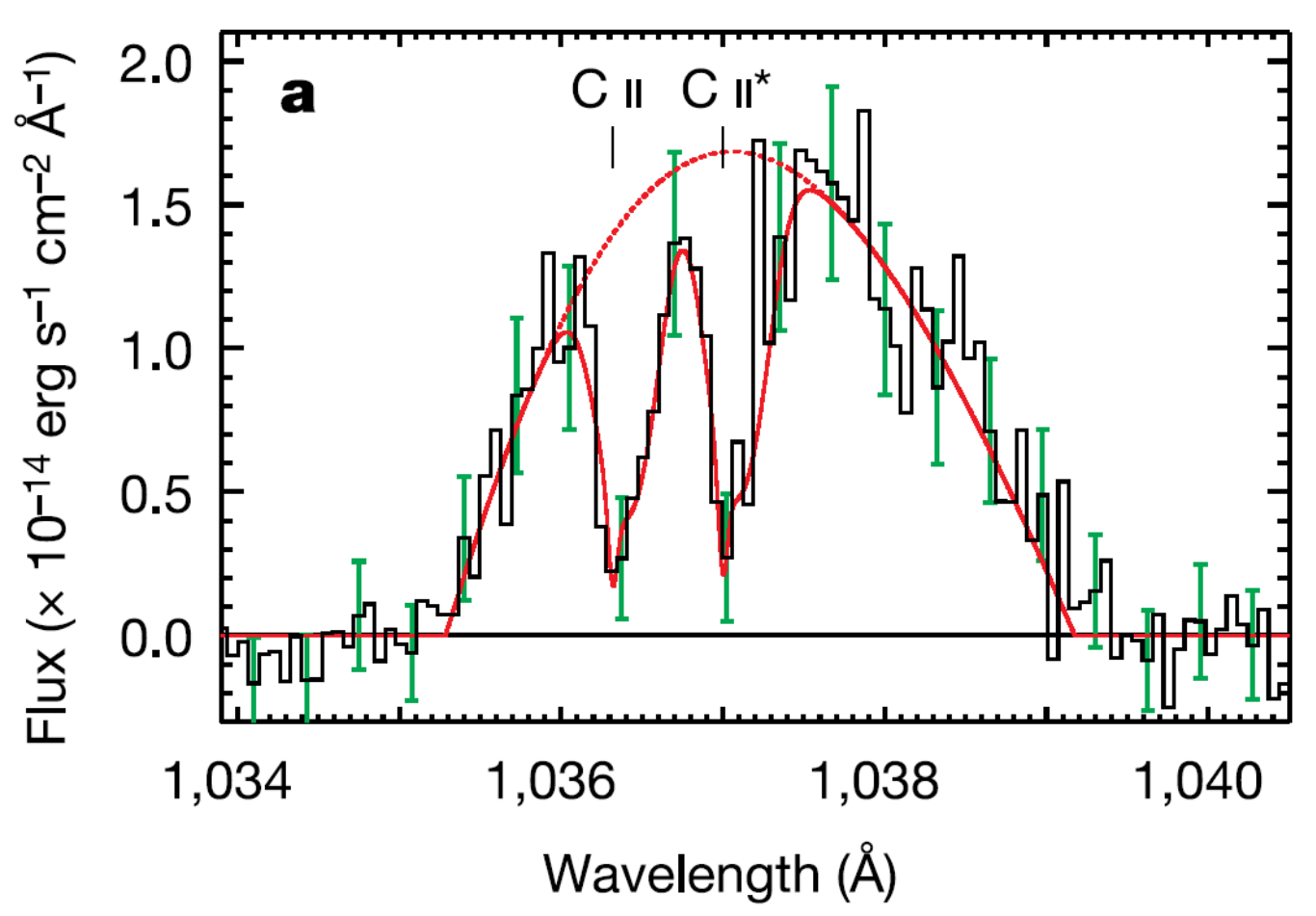
Ion	Δv km s^{-1}	$\sigma_{\Delta v}$ km s^{-1}
Fe I	−0.0	0.3
Na I	−1.2	0.3
Ca II	−0.3	2.1
Ti II	0.2	0.8
Ni I	0.4	0.4
Ni II	2.8	3
Cr II	2.2	3


1.00
0.95
0.90
0.85
β Pic
Single observation
5890
5895
5900
Wavelength air [A]

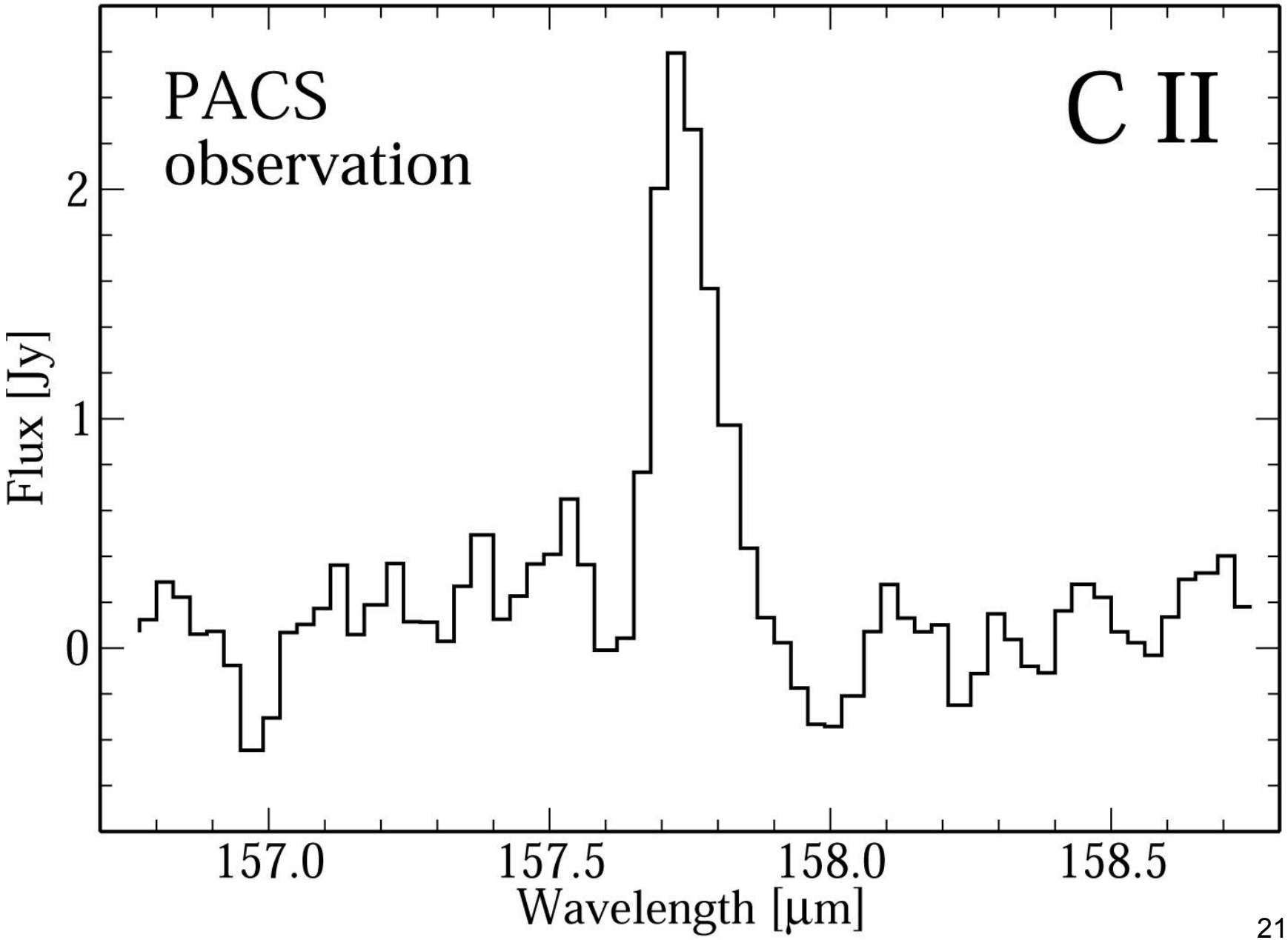

1.00
0.95
0.90
0.85
β Pic
Cleaned and combined
5890
5895
5900
Wavelength air [A]

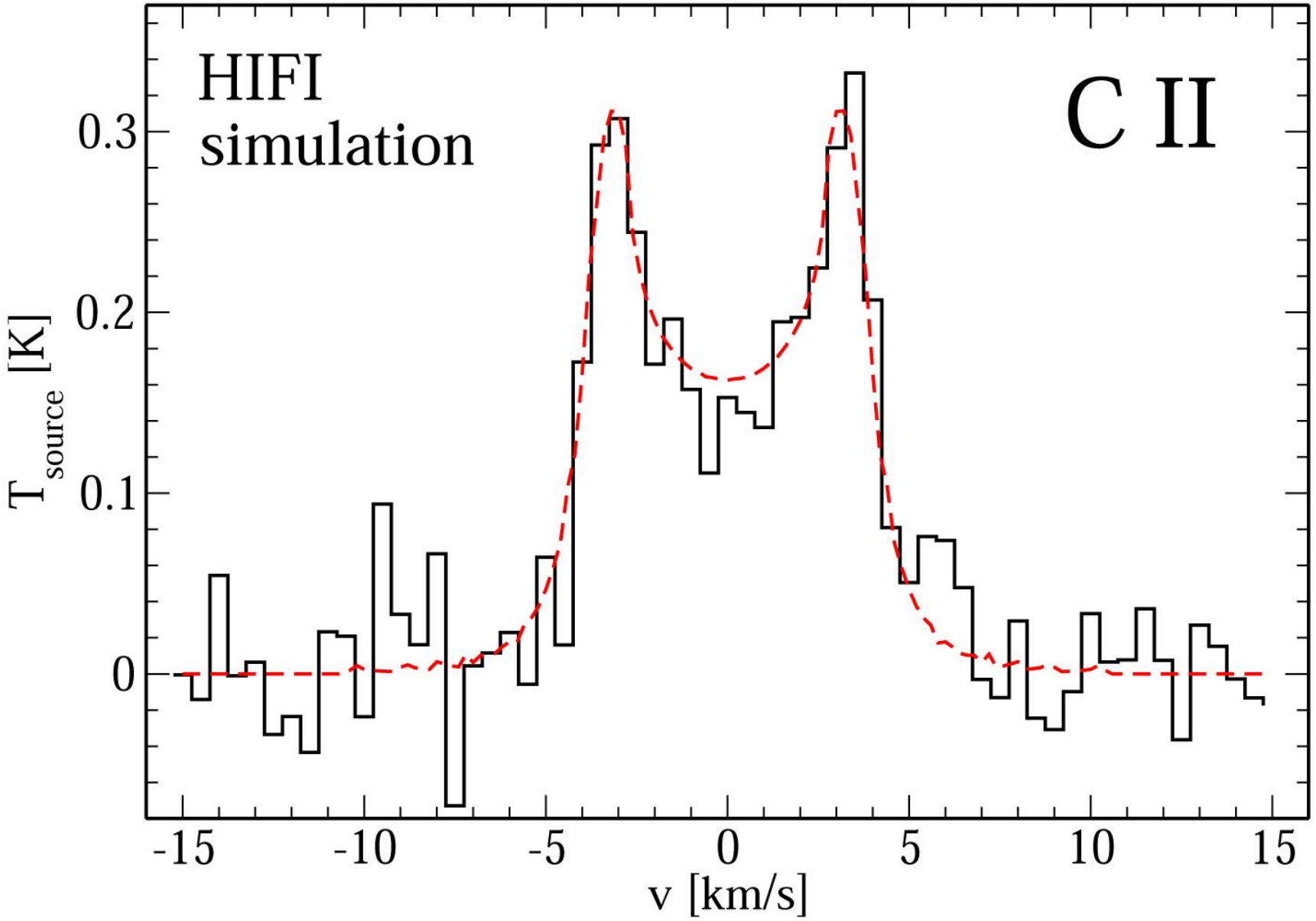

Fe I λ3860
Na I D2
Nominal model
Best fit model
Normalized profile
Barycentric radial velocity [km/s]
Na I D2
Fe I λ3860
β Pic system velocity
1.0
0.8
0.6
0.4
0.2
0.0
14
16
18
20
22
24

FUSE: Carbon absorption



Roberge et al. 2006, Nature 441:724


PACS
observation
C II
Flux [Jy]
2
1
0
157.0
157.5
158.0
158.5
Wavelength [μm]


HIFI
simulation
C II
0.3
0.2
0.1
0
T source [K]
-15
-10
-5
0
5
10
15
v [km/s]

Extra

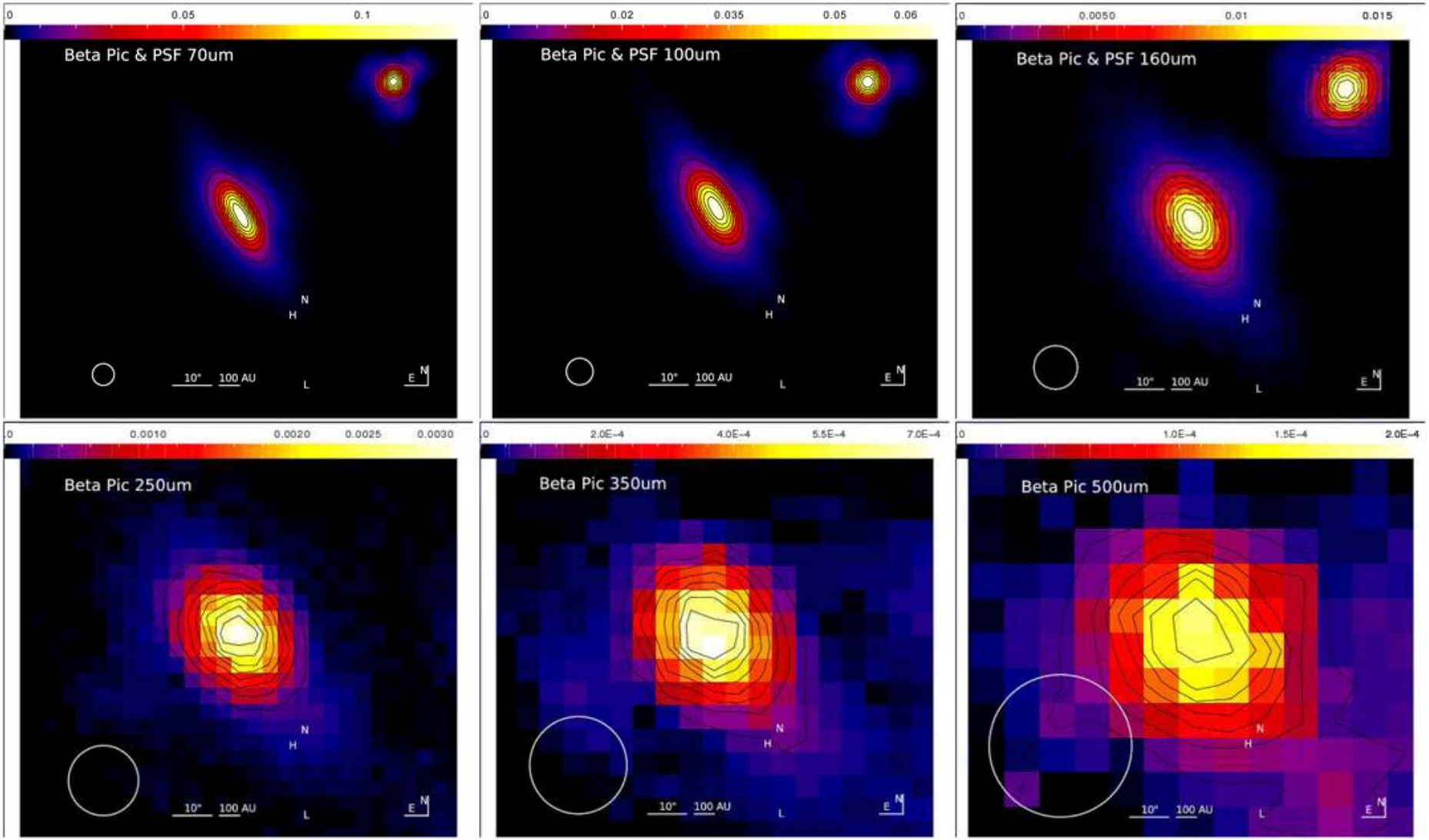
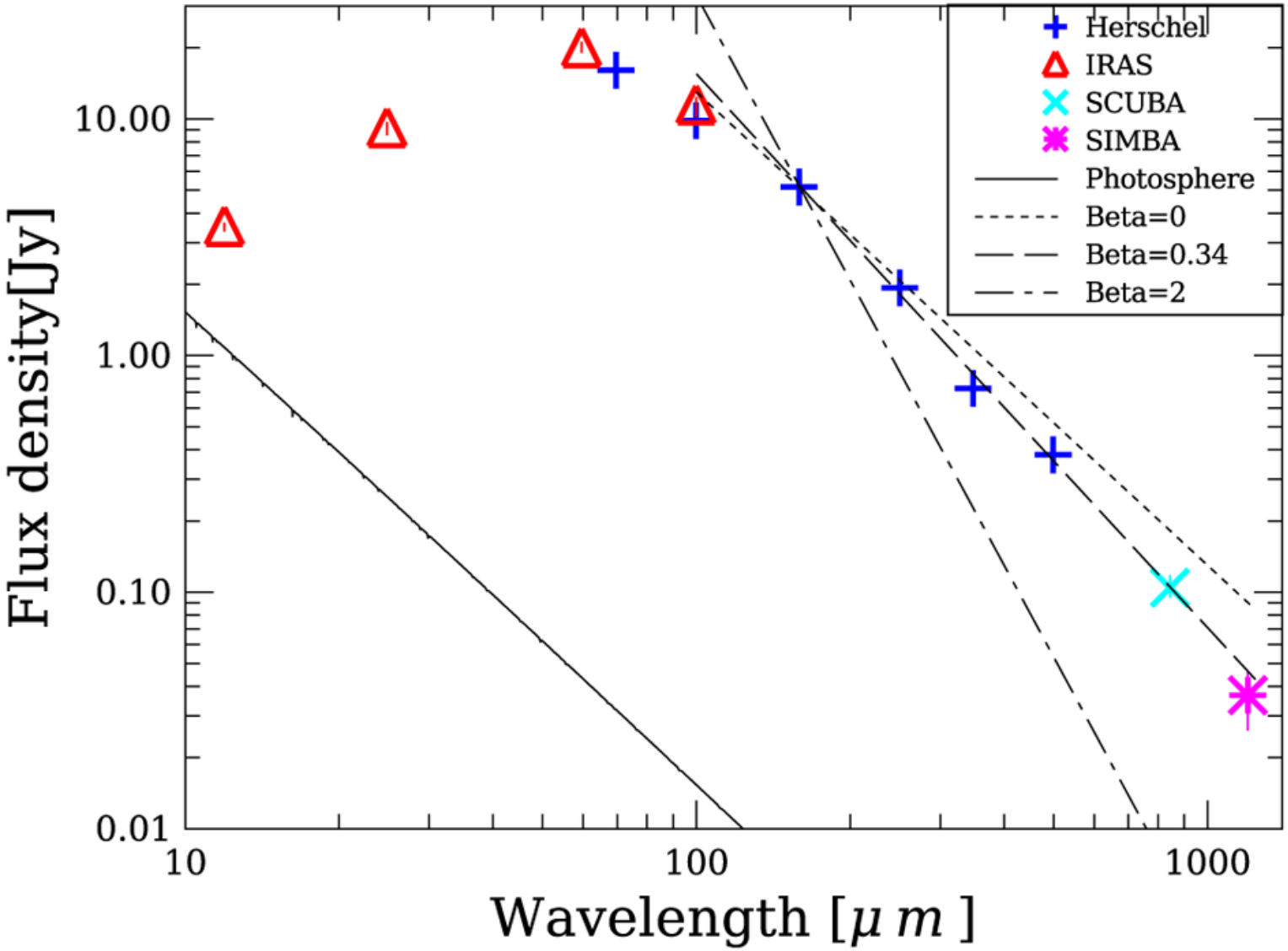
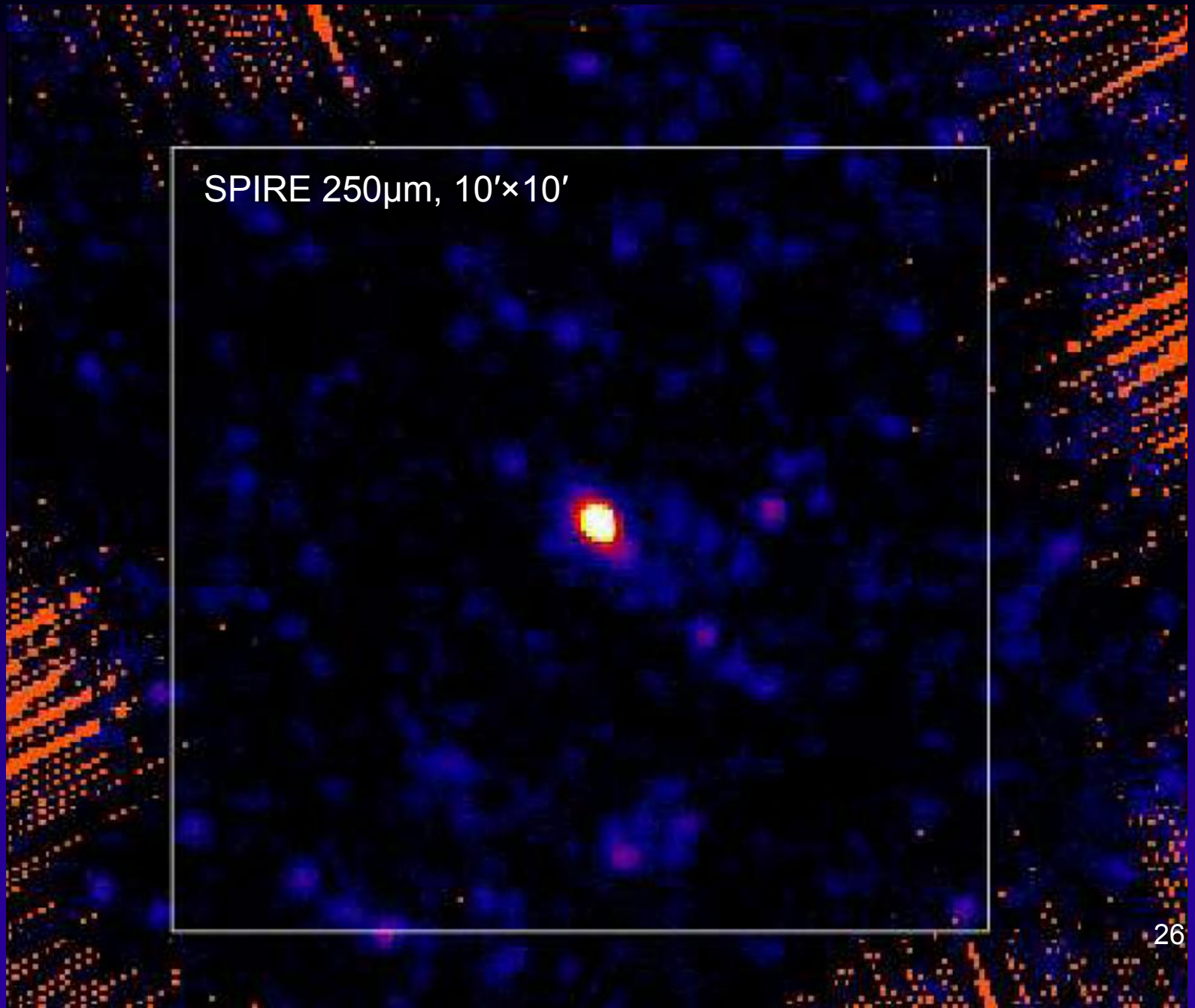


Fig. 1. Surface brightness maps of the β Pic debris disk at 70, 100, 160, 250, 350, and 500 μm. The PACS PSFs, rotated to match the position angle of the telescope at the time of the β Pic observations are depicted in the upper right corner of the images. The SPIRE PSFs are depicted in Fig. A.6. All images are scaled linearly, contour lines are in steps of 10% of the peak flux. The surface brightness unit is Jy arcsec^{-2}. The white circle shows the beam FWHM. The position of the flux peaks observed at 850, 870, and 1200 μm by Holland et al. (1998), Nilsson et al. (2009), and Liseau et al. (2003) are indicated with H, N, and L.


Herschel
IRAS
SCUBA
SIMBA
Photosphere
Beta=0
Beta=0.34
Beta=2
10.00
1.00
0.10
0.01
10
100
1000
Flux density[Jy]
Wavelength [μm]


SPIRE 250μm, 10′×10′

Vega

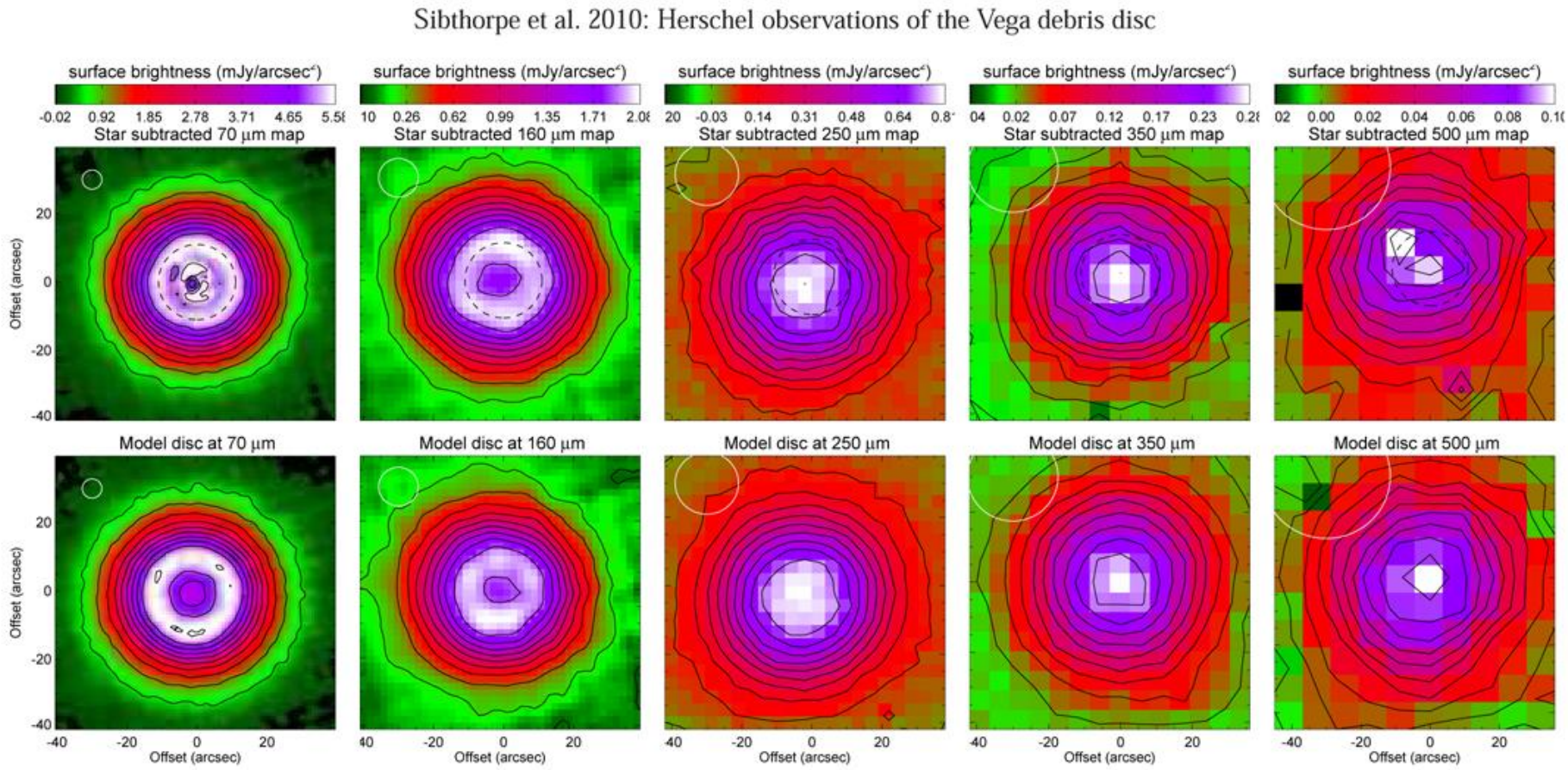


Fig. 1. Data for the Vega debris disc from 70 μm to 500 μm from left to right respectively (top row - star-subtracted images; bottom row - modelled images). All images are scaled linearly, and both images within a given band are equally scaled. The white circle represents beam FWHM in each band, and the contour lines are in steps of 5% of the peak flux. The black dashed circle represents the location of the disc at a radius of 11″.

Vega