HOW WELL DO WE KNOW THE PHYSICAL-CHEMICAL PROPERTIES OF PNe?

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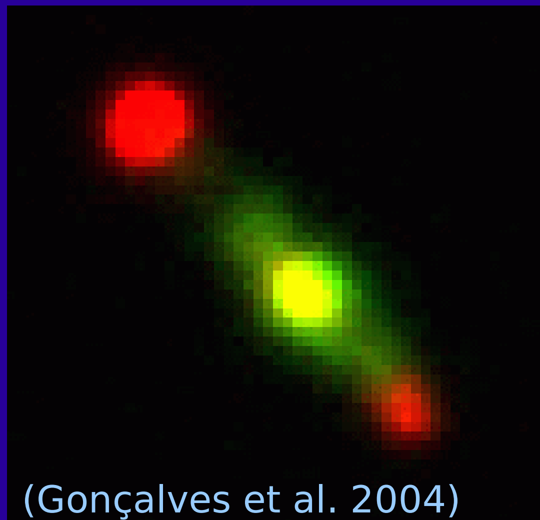
An introduction

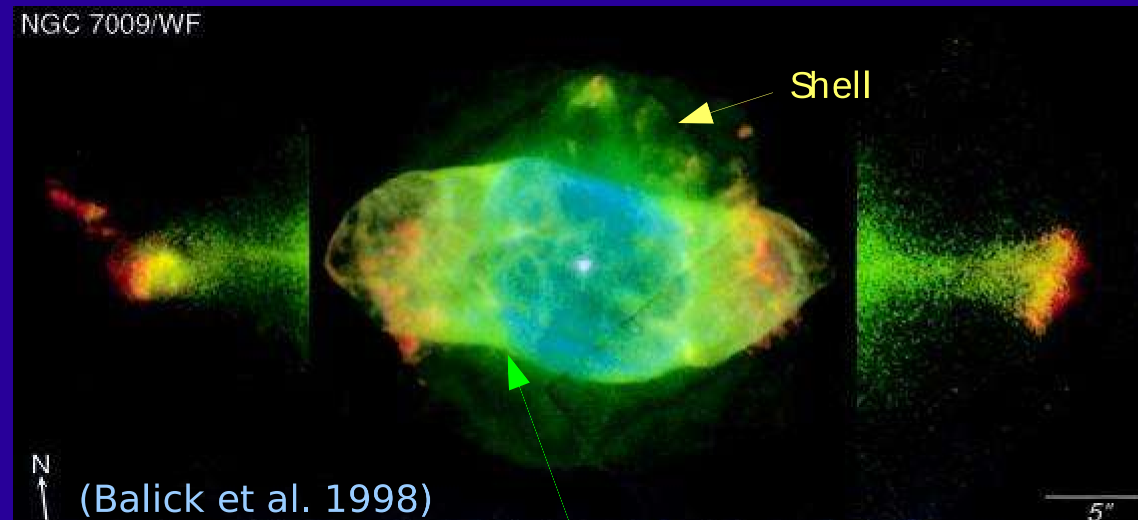
K 4- 47

NGC 7009

[OIII] [NII] HeII



K1 Core K2

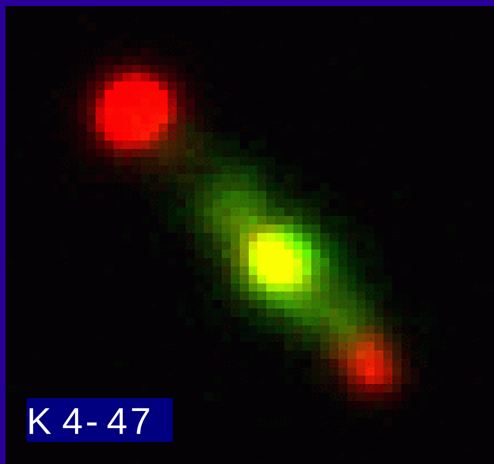


K1 J1 K2 Rim K3 J2 K4

Components:	a higher excitation Core, 1 pair of lower excitation knots (FLIERs)	an [OIII] attached shell, an [OIII] and HeII E rim, 1 pair of jets, 2 pairs of lower excitation knots (FLIERs)
Adopted D:	5.9 kpc	0.86 kpc
	K 4- 47	NGC 7009

Empirical physical/chemical properties

(Gonçalves et al. 2004)



K1 Core K2

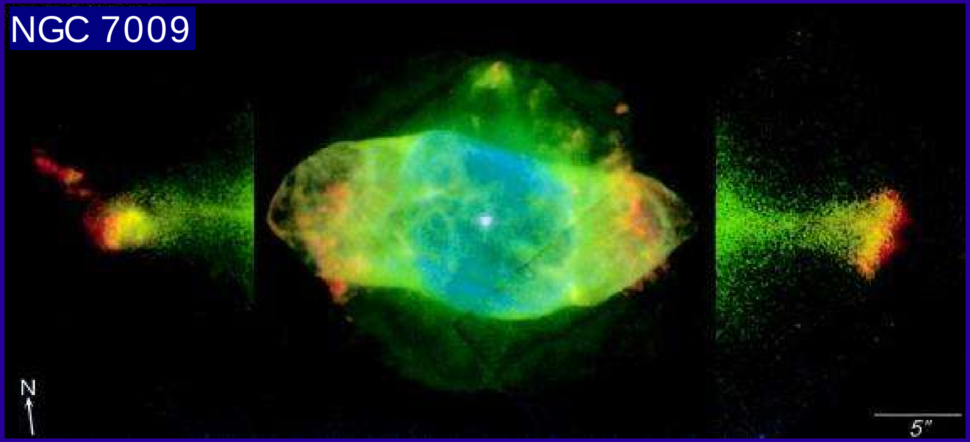
Ne and Te	Knot1	Core	Knot2
Ne[SII] (cm^{-3})	4600 ±800	1900 ±400	2400 ±400
Te[NII] (K)	18900±2900	>21000	16900±2800
Te[OIII] (K)	>21000	19300 ±2300	16100±4400

	He/H	O/H	N/H	Ne/H	S/H
Core	1.39E-1(14%)	7.37E-5(32%)	3.74E-4(40%)	1.74E-5(66%)	1.96E-6(48%)
Type-I	1.3±0.018	(4.93±2.22)E-4	(5.32±3.34)E-4	(1.25±0.63)E-4	(8.08±6.19)E-6

From the empirical O, Ne and S (and the large height on the Galactic plane)
⇒ halo PN, Peimbert´s Type-IV
From the empirical He and N => extreme bipolar PN, Peimbert´s Type-I

- Te, not only of knots, but also of the Core are very high!
- Can these high Te represent a photoionized region, or shocks are playing a role?
- With these Te (lower limits in certain zones), we cannot trust on the chemistry!

Empirical physical/chemical properties



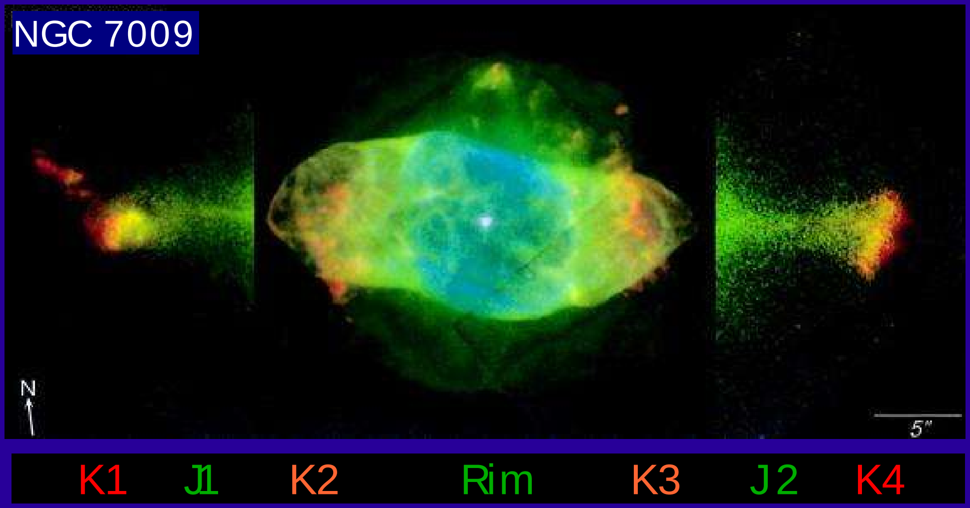
- Te are those typical of PNe.
- But, we did not obtain any Te for the “low-ionization” species at the jets position.

and the chemistry...

Ne and Te	R1 / R2	J1 / J2	K2 / K3	K1 / R4
Ne[SII] (cm^{-3})	5500 / 5900	1300 / 1100	4500 / 5000	2000 / 1300
Ne[Cl III] (cm^{-3})	5200 / 5900	... / 1300	4700 / 6000	... / 1900
Te[OIII] (K)	10000 /10200	10400 / 11600	9300 / 10100	9600 / 10400
Te[NII] (K)	10400 /12800	.... /	9400 /10400	11000 / 11700
Te[SII] (K)	.... /...	.... /	8300 / ...	7100 / 9400

(Gonçalves et al. 2003)

Empirical physical/chemical properties



- As we did not obtain Te[NII] nor Te[SII] for the jets, their chemistry are very uncertain.
- The N/H of the outer knots(K1/K4) is 2.5 times that of the rim!

(Gonçalves et al. 2003)

Element	R1 / R2	J1 / J2	K2 / K3	K1 / K4
He/H	0.108 / 0.116	0.124 / 0.108	0.109 / 0.105	0.102 / 0.095
O/H x E+4	4.5 / 4.8	6.4 / 3.0	6.2 / 4.7	5.8 / 4.5
N/H x E+4	0.7 / 1.8	0.62 / 0.86	2.4 / 1.8	3.8 / 2.5
Ne/H x E+4	1.1 / 1.1	1.1 / 0.96	1.2 / 1.1	1.1 / 1.3
S/H x E+6	6.1 / 4.9	6.3 / 4.4	16.0 / 8.1	13.9 / 9.3
N/O	0.15 / 0.40	0.40 / 0.28	0.40 / 0.40	0.66 / 0.56

Why do we need CLOUDY, MAPPINGs and MOCASSIM?

- K 4-4's spectra of the knots as well as of the core look like those of shock excited emission regions

  => we use CLOUDY to check whether or not the core high
  Te represents a photoionized region or if shocks are present
  => and MAPPINGS for the bow-shock modeling of the knots

- On the other hand, NGC 7009 has well behaved Te,
  but suspicious N overabundant outer knots (FLIERs)

  => we use MOCASSIN (3D photoionization code) to check if
  this overabundance is due to ionization effects

CLOUDY modeling of K 4-47's Core

CLOUDY Inputs:

- shape and intensity of the radiation source;
- chemical composition;
- geometry, size and density.

	Core Inputs
D (kpc)	5.9
Size (")	1.9 (optical)
Ne (cm^{-3})	1900 (optical)
T_{eff} (K)	120 000 K
L (L_{solar})	550
Dust grains	ISM graphite + silicate
Chemistry	Type-I PN

- Important lines for diagnosis are well reproduced: [NII], [SII], [OII], [OIII], HeI, HeII

- [OIII] 4363Å and [NII] 5755Å are largely underestimated (by a factor around 3)

- This model implies a Core size of 4" (twice the optical size we measured)

Therefore we try models with much higher densities: Ne=3E+5(inferred from the very compact radio core)

CLOUDY modeling of K 4-47's Core

In some PNe and related objects high [OIII] 4363Å and [NII] 5755Å indicate the presence of very high core densities, since at densities higher than Ne=3E+5 cm^{-3} the ([OIII] 4363Å and [NII] 5755Å) auroral lines to ([OIII] 4959Å and [NII] 6583Å) nebular lines give densities rather than temperatures.

	Core Inputs
D (kpc)	5.9
Size (")	0.25 (radio)
Ne (cm^{-3})	3E+5 (radio)
T_{eff} (K)	120 000 K
L (L_{solar})	550
Dust grains	ISM graphite + silicate
Chemistry	Type-I PN

- Now the auroral [OIII] 4363Å and [NII] 5755Å are well reproduced!
- But other important doublets lines for diagnosis: [OII]; [NII]; [SII] are largely underestimated due to collisional quenching

Possible solution: a strong density stratification in the core!

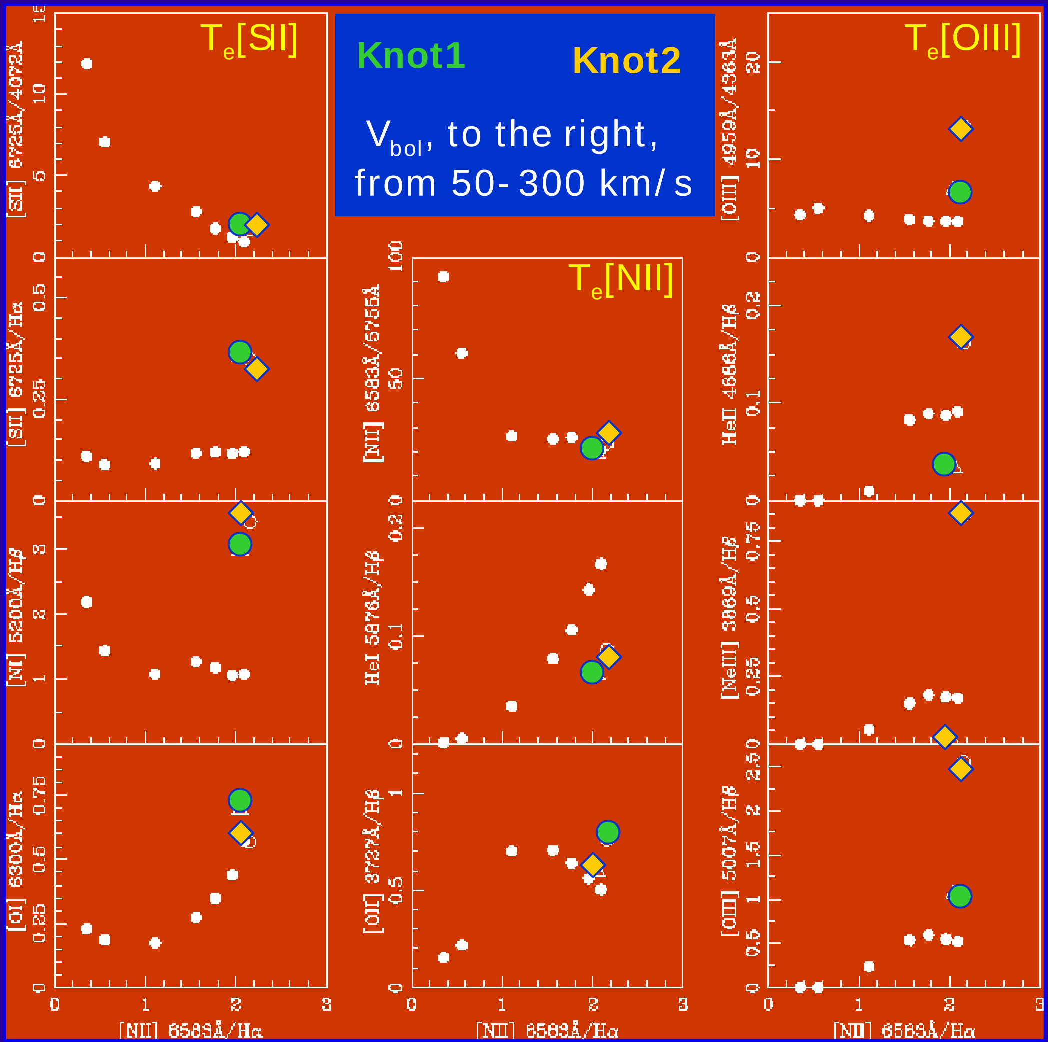
An inner zone with extremely high density (3 10^{+5} cm^{-3}) and an outer zone matching the empirical Ne determined from the [SII] lines (2000 cm^{-3}).

(Gonçalves et al. 2004)

MAPPINGS modeling of K 4-47's knots

MAPPINGS Ic

(Dopita et al. `84; Binette et al. `85)



MAPPINGS INPUTS:

- pre-ionization;
- chemical composition;
- geometry, size and density.

Knots move with 250 – 300 km/s

They have Type-I PN abundances

Knot´s T_e[NII] = 17800 K

The [OIII] (4959Å/4363Å) ratio is underestimated by 30% (Knot1) and 70% (knot2).

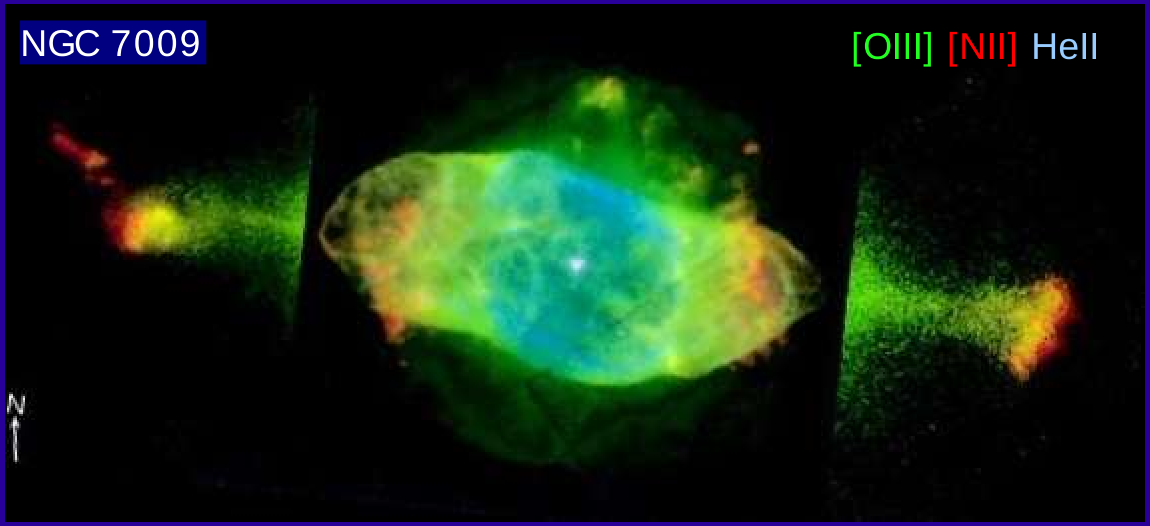
(Gonçalves et al. 2004)

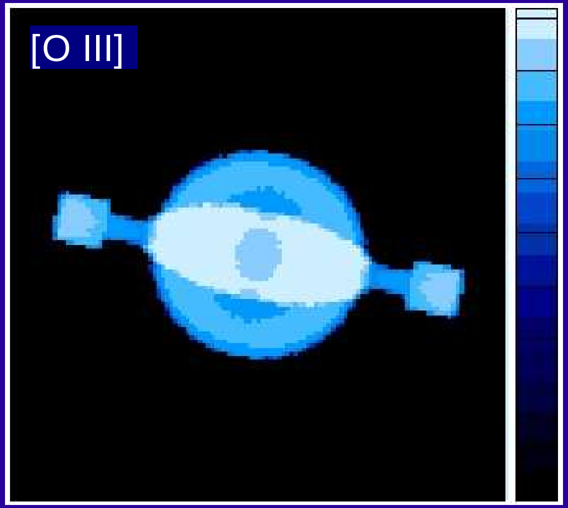
Caution: the pre-photoionization of the knots was not considered!

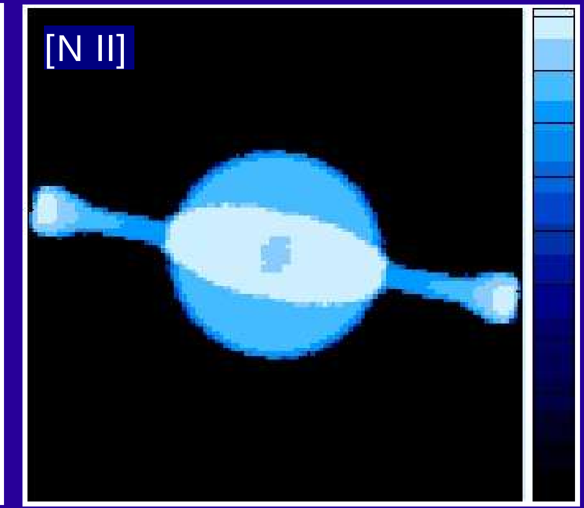
MOCASSIN modeling of NGC 7009

- We model an elliptical rim + a spherical shell + a cylindrical jet + a disk-shaped outer knot
- We do not model the inner knots
- The abundance is homogeneous across the nebula!

Input parameters	
L (solar units)	3136
Teff (K)	80,000
Rin (cm)	0.0
Rout (cm)	3.88E+17
He/H (0.11)	0.112
C/H	3.2E-4
N/H (1.7E-4)	2.0E-4
O/H (4.7E-4)	4.5E-4
Ne/H (1.14)	1.06E-4
S/H (8.3E-6)	9.0E-6
Ar/H	1.2E-6







Mean Te (K) weighted by ionic species

Element	I	II	III
N	9,798	9,875(11,600)	10,098
	10,684	10,625(11,350)	10,555
	10,402	10,015(10,300)	10,110
O	9,795	9,863	10,073(10,100)
	10,697	10,621	10,549(10,000)
	10,529	9,987	10,082(10,100)
S	9,793	9,845	10,021
	10,635	10,605(8,259)	10,560
	10,221	9,973	10,040

Rim = R
Knots = K
NEB

Te is constant along the main axis, as empirically derived!

Averaged fractional ionic abundances

Element	I	II	III	IV	V...
He	7.00(-4)	0.814	0.185		
	7.39(-3)	0.992			
	7.74(-4)	0.817	0.181		
N	1.37(-6)	5.84(-3)	0.546	0.443	4.12(-3)
	3.73(-4)	0.136	0.823	4.01(-2)	
	4.47(-6)	7.14(-3)	0.551	0.437	4.03(-3)
O	4.83(-6)	9.72(-3)	0.862	0.125	3.13(-3)
	2.86(-3)	0.188	0.808		
	2.81(-5)	1.15(-2)	0.863	0.122	3.07(-3)
Ne	3.56(-6)	1.07(-2)	0.917	7.11(-2)	7.20(-4)
	1.56(-4)	6.67(-2)	0.933		
	4.98(-6)	1.14(-2)	0.918	6.95(-2)	7.04(-4)
S	6.84(-7)	8.13(-3)	0.343	0.546	9.89(-2)
	8.16(-5)	0.155	0.755	8.81(-2)	6.71(-4)
	1.42(-6)	9.71(-3)	0.350	0.540	9.70(-2)

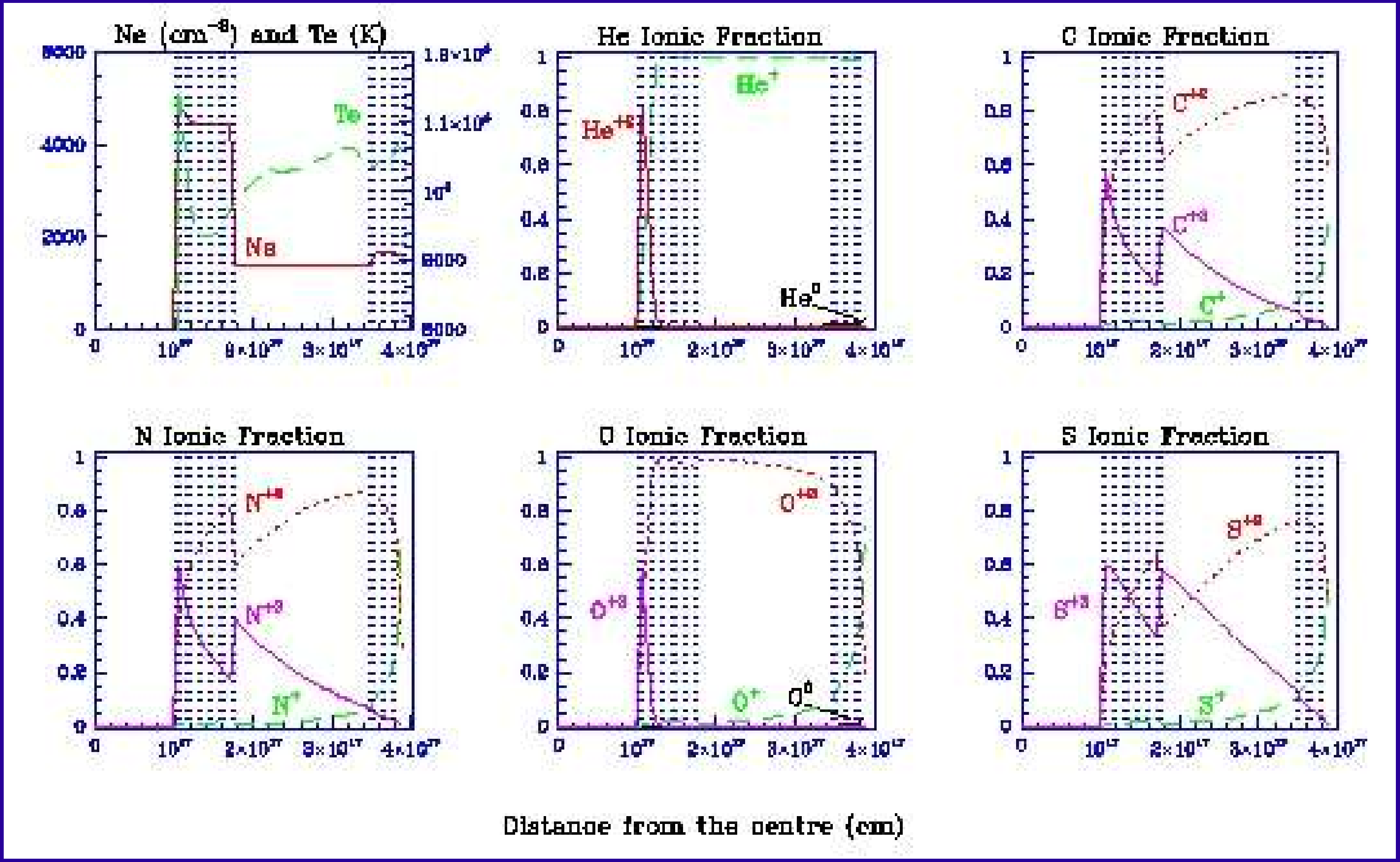
N^+/N= 1.39 O^+/O
1.66 O^+/O
1.61 O^+/O
contrary to the equality of the ICF method!

Only 0.7%, 14% and 0.6% of N is in form of N^0 and N^+, the observed ions.

(Gonçalves et al. 2005, submitted)

MOCASSIN profiles of NGC 7009

(Gonçalves et al. 2005)



Note the strong dependence of the ionization level on the geometry and density distribution of the gas

=> An apparent overabundance of N^{+} in the knots can be created if a high gas opacity avoids the direct incidence of the stellar photons!

In summary

On one hand...

CLOUDY and MAPPINGS modeling of K 4-47 gives strong evidence for a high density stratification in its core and shock excitation in its FLIERs knots

=> If so, the empirically derived Te and the chemistry would be wrong, because the auroral and nebular lines involved are not co-spatial

=> This is not usual, but was also found in other PNe (Corradi 1995)

On the other hand...

MOCASSIN modeling of NGC 7009 strongly suggests that N overabundance of FLIERs is not real, but due to ionization effects (Alexander & Balick 1997; Gruenwald & Viegas 1998; Mampaso 2004)

=> The $N^+/N=O^+/O$ hypothesis assumed for obtaining the empirical ICF abundances is not confirmed

=> $(N^+/N)/(O^+/O)$ --higher in the FLIERs than in the rim-- is extremely sensitive to the shape of the local radiation field

But why? Charge exchange? Difference in the IP of the relevant ions?

=> So, realistic density distribution is essential to model a non-spherical PN, with spatially resolved spectroscopic data!

In conclusion

We should keep these problems in mind when obtaining Te and chemical abundances (N/O) of PNe and also other ionized nebulae at the Galaxy and beyond!