Elemental abundances in PNe and HII regions: lessons in parallel

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Planetary Nebulae as astronomical tools (Gdansk, 28 June 2005)

Outline

- Review of temperature and abundance dichotomy
- Dual abundance models for PNe and HII regions
- Implications for nebular abundances
- Relevance to ISM evolution studies

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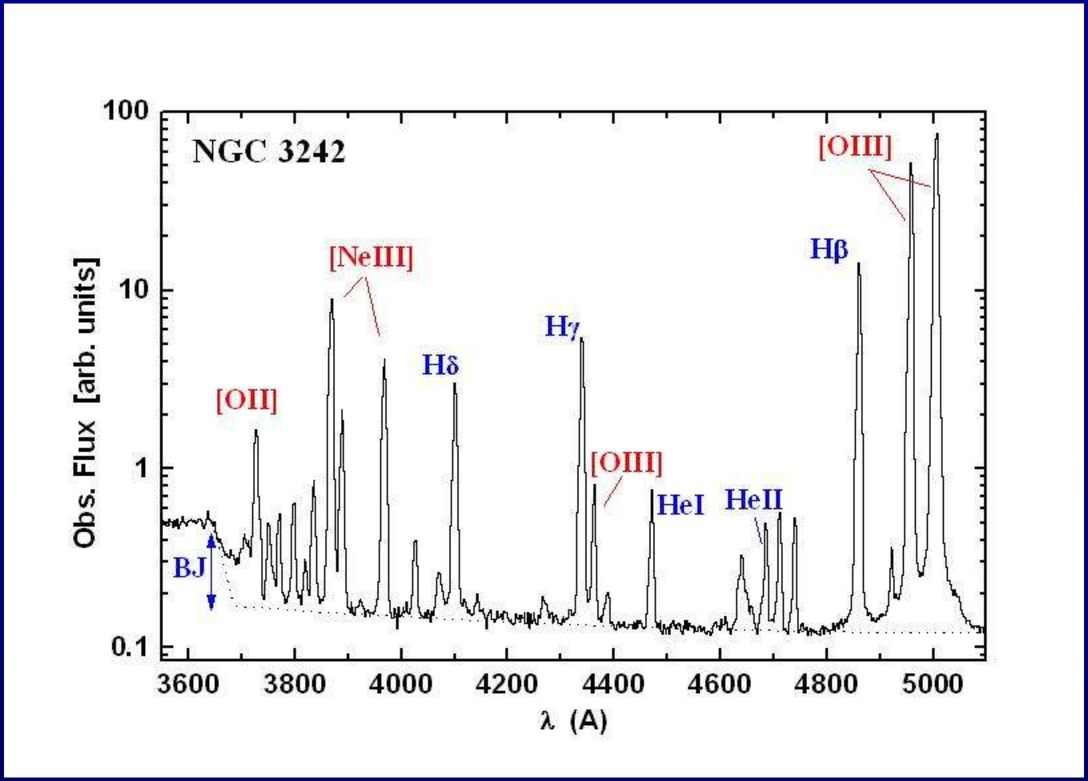
‘Strong line’ nebular spectroscopy



<u>PN NGC 3242</u>
ESO 1.52m
B&C spectrograph
220s exp.

Red: <u>Collisionally excited lines</u> (CELs; forbidden lines) of [OIII], [NeIII], etc.

Blue: <u>Recombination lines</u> (ORLs) of H I, He I, He II λ4686

BJ: ‘Balmer jump’ continuum break at 3643 Å, <u>recombination process</u>

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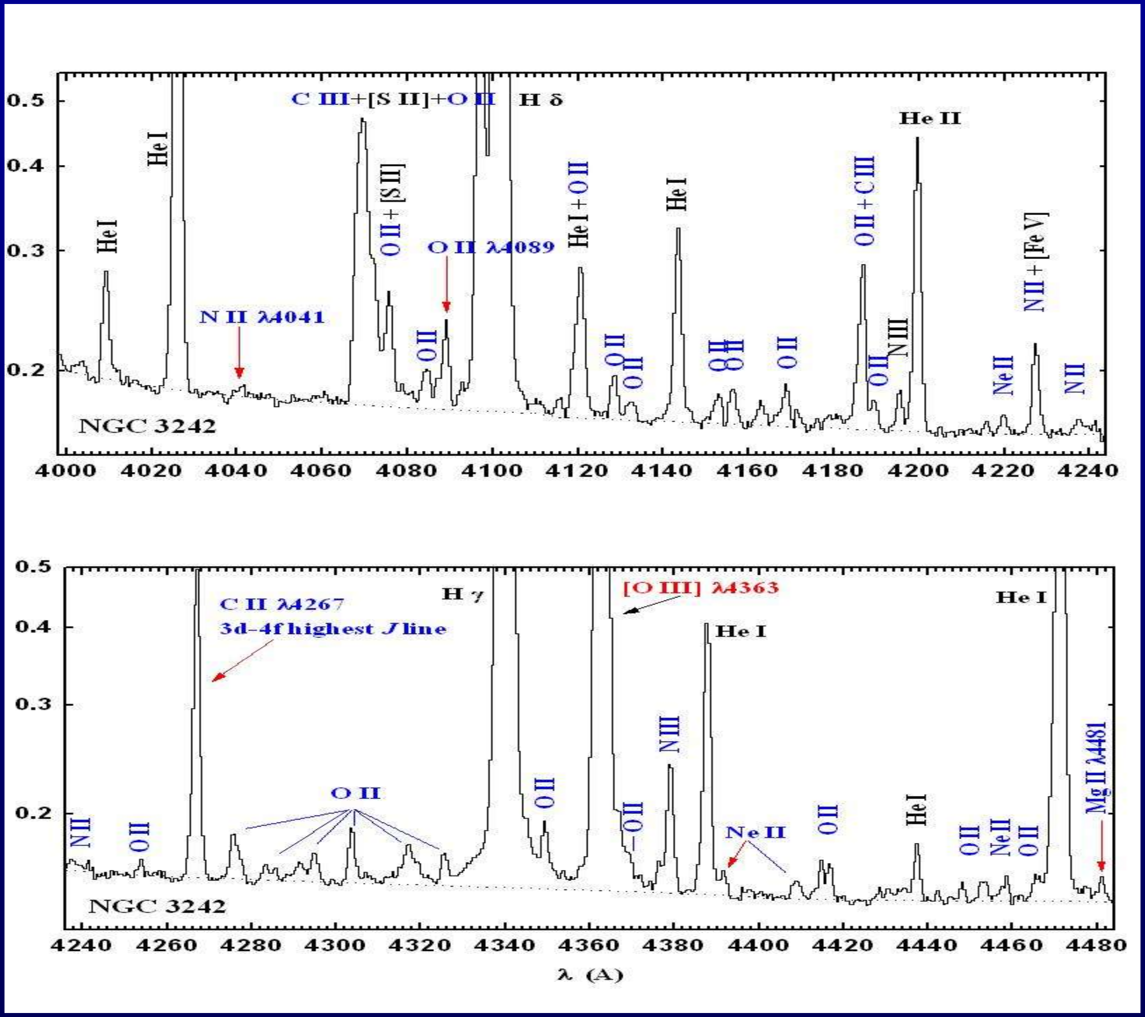
'Weak line' nebular spectroscopy



Recombination lines (ORLs) of heavy ions:

(2nd row elements)

C II λ4267 (the strongest)

O II, N II , Ne II

(3rd row element)

Mg II λ4481

3d-4f highest-*J* lines: ✓ hydrogenic

× fluorescence, optical depth, coupling scheme

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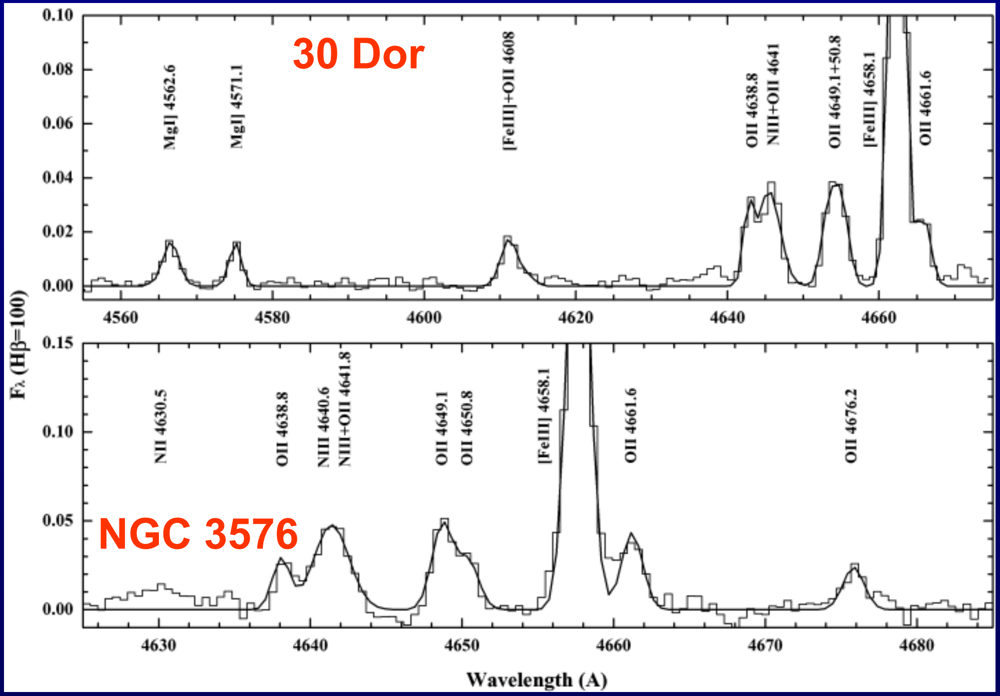
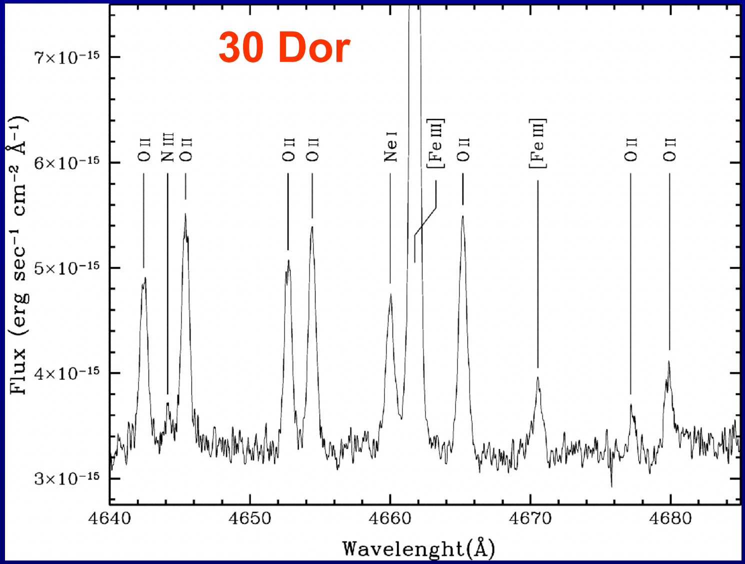
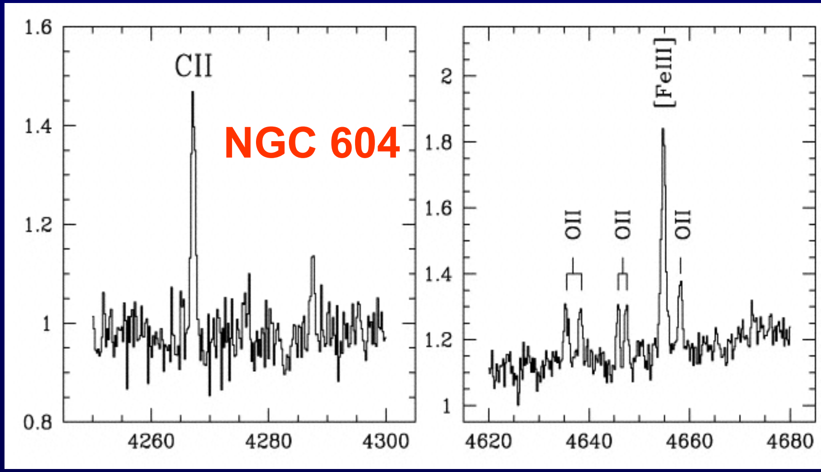
ORLs in Galactic and Local Group HII regions



Tsamis et al. 2003 (NTT 3.6m, ESO 1.52m)



Peimbert 2003 (VLT 8.2m)



Esteban et al. 2002 (WHT 4.2m)

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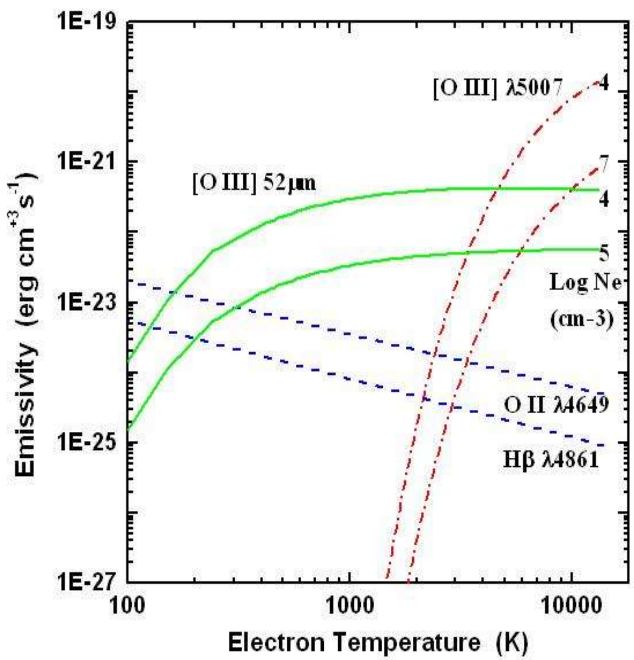
Nebular thermostats and line emissivities



Thermal balance in nebulae:

Heating: UV radiation field of (central) star ionises hydrogen & hot photoelectrons are created

Cooling: collisions of e^- with ions lead to CEL emission which escapes thus removing heat from nebula

UV/Optical lines: High exc. energy
IR lines: Low exc. energy

- CNONe ORLs are efficiently emitted at low *T*'s in a thermally stratified plasma
- UV/Optical CELs are efficiently emitted at high *T*'s in a thermally stratified plasma

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- Infrared lines are efficient coolants at low T_e

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Determination of elemental abundances in nebulae

- Empirically from collisionally excited Lines (CELs)

$$N(X^{i+})/N(H^+) \propto \begin{cases} I(\lambda)/I(H\beta)\cdot T^{-0.3}\cdot \exp(E_{exc}/kT_e), & \text{if } N_e << N_{crit} \\ I(\lambda)/I(H\beta)\cdot N_e \cdot T^{-0.3}\cdot \exp(E_{exc}/kT_e), & \text{if } N_e >> N_{crit} \end{cases}$$

✓ Very strong T_e dependence (UV/optical)

- Empirically from optical recombination Lines (ORLs)

$$N(X^{i+})/N(H^+) \propto I(\lambda)/I(H\beta)\cdot T^{-\alpha}, \quad \alpha << 1, \quad \text{independent of } N_e$$

✓ Very weak T_e dependence (due to similar emissivities)

- As a by product of self-consistent models

✓ Dependent on the goodness of fit to all observables, validity of astrophysical assumptions, predictive power of the model, etc.

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Temperature and abundance dichotomy in nebulae

Thermometers for PNe and H II regions:

- [O III] λ5007/λ4363 ratio $\Rightarrow$ T_e [O III]
- Balmer jump intensity to Hβ 4861 Å *ratio* $\Rightarrow$ T_e (BJ)

⟶ Late 60's finding: on average T_e(BJ) $<$ T_e [O III] (Peimbert 1967,1971)

✓ Concept of (classical) temperature fluctuations: *Mean* T_e would lie between T_e(BJ) and T_e[O III] for a thermally inhomogeneous nebula.

$\Rightarrow$ Intro of t^2 factor which quantifies *rms* T_e fluctuations from the mean

✓ Consequence: CNONe and heavier element abundances (from CELs) should need upward correction dictated by magnitude of t^2

⟶ Early 80's finding : Carbon abundance from C II 4267 Å ORL *higher* than that from C III] 1908 Å CEL (e.g. Barker 1982)

Problem: Are heavy element abundances in PN *and* HII regions *underestimated* and by how much?

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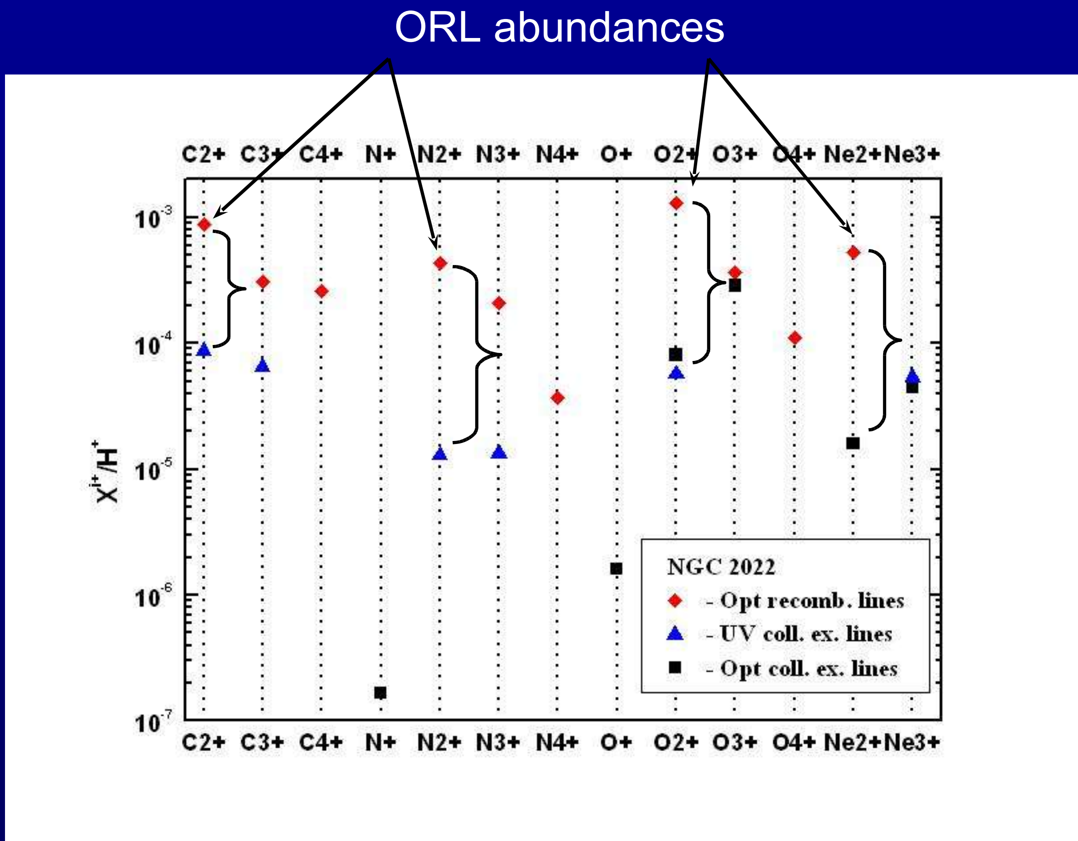
Heavy element abundances from ORLs and CELs



Tsamis et al 2004; cf. also NGC 7009, 6153, Liu et al 1995, 2000

PN NGC 2022

- Ionic abundances from RLs are a factor of **~15** larger than those from CELs
- Classical analysis yields *subsolar* CNONe
- ORL - emitting regions show *supersolar* composition
- $t^2 > 0.1$ NOT supported by Chemically homogeneous model

	He/H	$10^4\times$C/H	$10^4\times$N/H	$10^4\times$O/H	$10^4\times$Ne/H
ORLs	0.110	14.8	6.88	18.0	—
CELs	—	2.12	0.29	4.55	0.69
Solar	0.098	2.45	0.93	4.90	1.23

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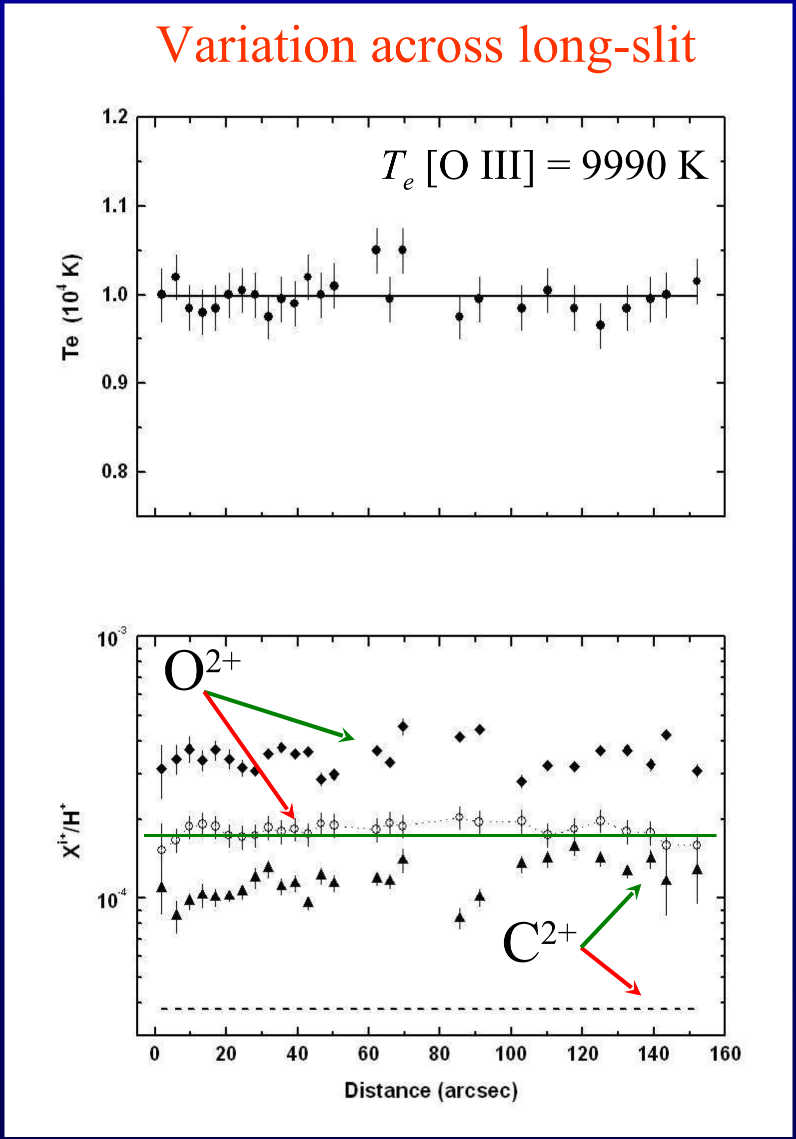

Tsamis et al 2003

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30 Doradus

- Abundance discrepancy factor **~ 2**
- T_e across slit is constant with a 2% variation only.
- T_e fluctuations of ~20% (t^2 = 0.03) required to reconcile ORL & CEL abundances: Not evident.
- O^{2+} from IR CELs agrees with that from optical CELs: Classical T_e fluctuations not responsible for the discrepancy.
- N_e < 3500 cm^{-3} in ORL emitting plasma: T_e [O III] not biased by high densities.

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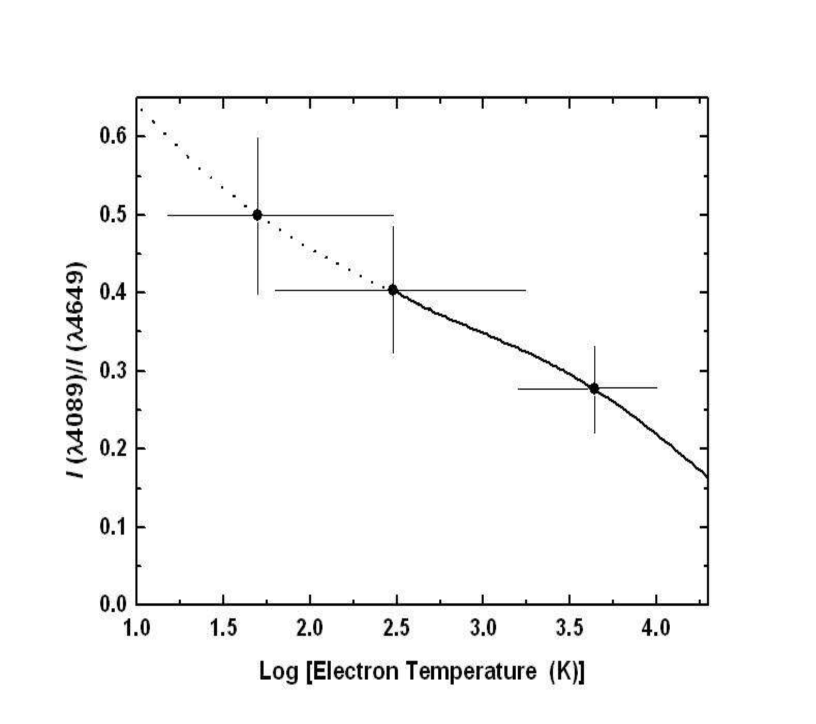
Temperature from ratio of O II ORLs



Tsamis et al 2004; Liu et al 2004

	T_e [O III]	T_e (BJ) (K)	T_e (O II ORL)
IC 4191	10000	9200	300
NGC 3242	11700	10200	< 300
NGC 5315	9000	8600	< 4350
NGC 6153	9100	6100	< 400

Evidence for ultracold plasma in normal PN

- ✓ The weak T_e sensitivity of O II recombination lines can be used to probe the temperature of the nebular regions which emit them
- ✓ cf. also Bastin & Storey (this Conf.) for their use as N_e diagnostics

Dual abundance nebular models

The low T_e(BJ) and *even lower* T_e(O II) observed for several PN suggest that even typical nebulae contain two distinct phases:

- A 'normal' component with a 'normal' temperature (T_e ~ 10^4 K) and 'normal' composition emitting the strong CEL flux
- An H-deficient component of very low temperature (T_e ~ 10^3 K) and very high heavy element (CNONe) abundances, emitting most of the metallic ORL flux, but essentially no CELs.

→ The Abundance and Temperature dichotomy is due to compositional inhomogeneities within the nebulae

(precedent of H-poor knots in Abell 30, Harrington & Feibelman 1984; Ercolano et al 2003; cf. also NGC 6153: Liu et al 2000; Pequignot et al 2002)

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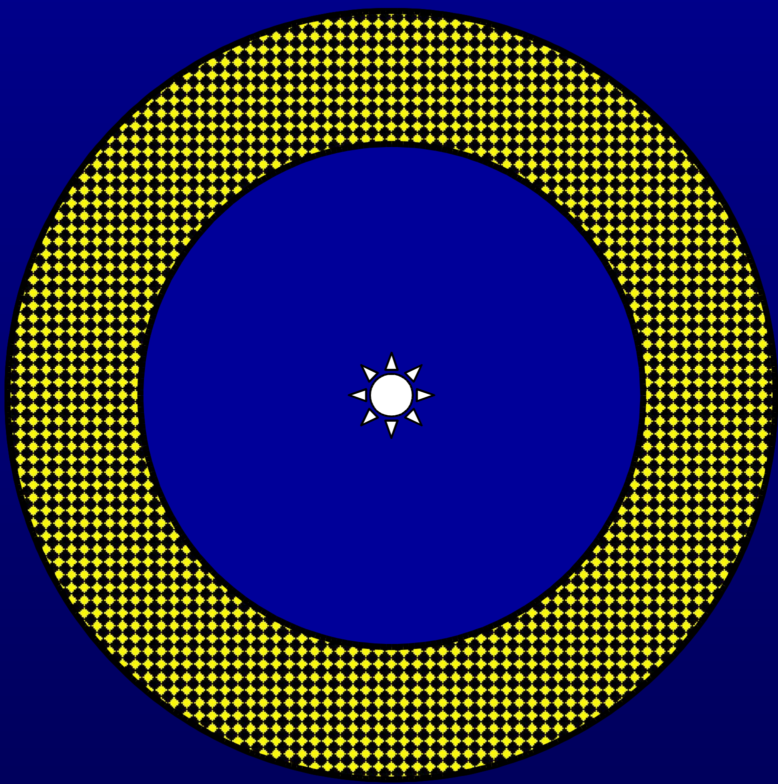
30 Doradus: Self-consistent dual abundance model



Two phases in *P* equilibrium

- H-poor gas: 2% of total mass
- Cool: 4120 K (~ half of mean T_e)
- relatively Dense: N_e = 700 cm^{-3} (~ 3 × mean N_e)

Phase *relative* composition

O/H (H-poor)	≈ 8 × (H-rich)
C/H	≈ 15 ×
N/H	≈ 13 ×
Ne/H	≈ 14 ×
S/H, Ar/H	≈ 7 ×

Tsamis & Péquignot (2005, MNRAS, submitted)

Code: NEBU - Péquignot et al 2001

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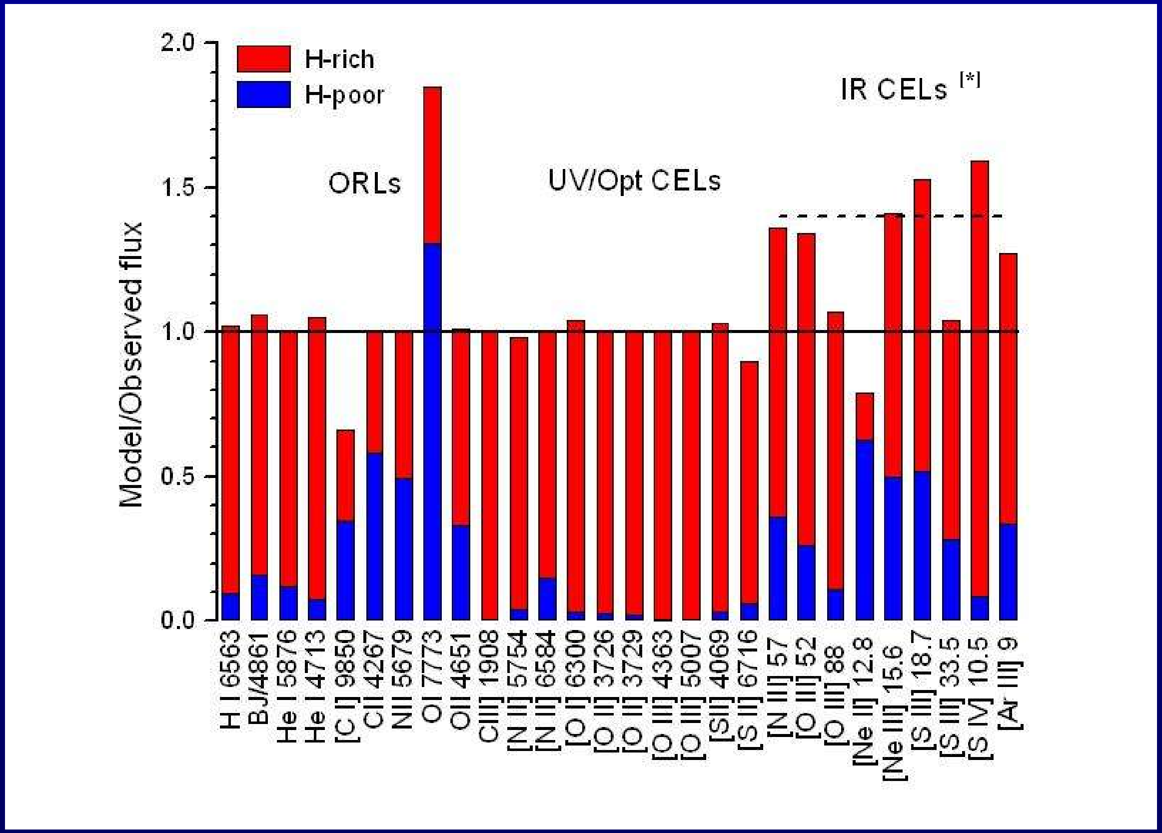
30 Doradus: Self-consistent dual abundance model



Tsamis & Péquignot (2005, MNRAS, submitted)

Average metal abundances:
0.1 dex (max.) *higher* than in Chemically homogeneous model
and
up to factor ~2 *lower* (e.g. for C and Fe) than t^2 methods

H-poor phase: Mixture of SNR ejecta with LMC gas?

- ✓ Ionization balance: [O I], [O II], [O III], ok
- ✓ Temperature: [O III] 4363/5007, ok
- ✓ Density: [O II] 3726/3729, ok

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- ✓ BJ and T_e [O III] fitted in tandem
- ✓ CNO ORLs fitted
- ✓ ORL *vs.* CEL anomaly solved

[*] the IR *vs*. Opt abs. calibration is uncertain

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Conclusions: Abundances

Nebular Abundances under the ‘Dual-Abundance’ paradigm:

- Metallic ORLs (e.g. C II λ4267) are NOT accurate probes of *overall* PN or H II region (CNONe) abundances

- Independent supporting fact: Mean PN and recently revised (-0.21 dex; cf. Allende-Prieto et al 2001) solar O/H forbidden-line abundance *in agreement*: resolution of solar O ‘paradox’

- From studies thus far, the (forbidden-line) heavy element content of PN and H II regions does not seem to have been seriously underestimated.

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Conclusions: Relevance to ISM evolution

CNONe ORLs from H II regions under the 'Dual-Abundance' paradigm:

- H-poor clumps: Evidence for incomplete small-scale ISM homogenization ?
  (cf. Supernova-driven models by de Avillez & Mc Low 2002)

- Probes of small-scale ISM chemical inhomogeneities arising from supernova explosions (e.g. Tenorio-Tagle 1996) or *other* 'polluting' sources?

- Spatially-resolved observations and dedicated coupled hydro/radiative transfer (e.g. Lim & Mellema 2003; O'Dell, Henney & Ferland 2005) + photoionization models (Ercolano et al 2005 - 3D dustyMOCASSIN) needed to further investigate origins and fate of H-poor inclusions in nebulae