Mapping Oxygen in the Universe

Very deep spectroscopy of planetary nebula NGC7009

The rich optical recombination spectrum and new atomic data

Xuan Fang

Department of Astronomy, Peking University

Collaborators: Xiao-Wei Liu (KIAA, PKU),
Peter Storey (UCL)
Ian McNabb (KIAA, PKU)

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Outline

- Background
- New atomic data
  - Effective recombination coefficients for the N II and O II recombination spectra
- Very deep spectroscopy of NGC7009
  - The rich optical recombination spectrum
  - Plasma diagnostics and abundance determinations
- Summary

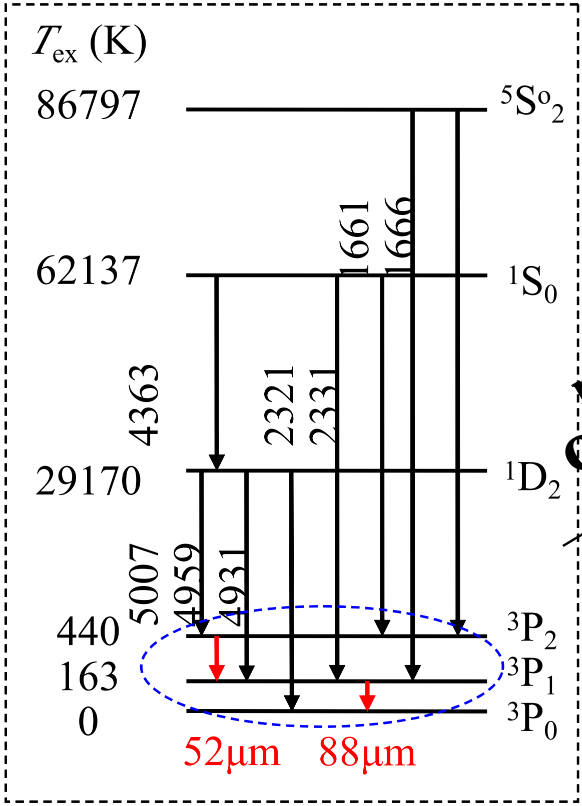
Background

- Photoionized Nebulae
  - Planetary nebulae (PNe), H II regions, broad and narrow emission line regions AGNs, etc.
  - Study of PNe
    - An ideal lab for studying atomic physics, radiative transfer
    - daynamics, stellar evolution
  - The distribution and production of elements in galaxies
  - Chemical evolution of galaxies and the universe

Background

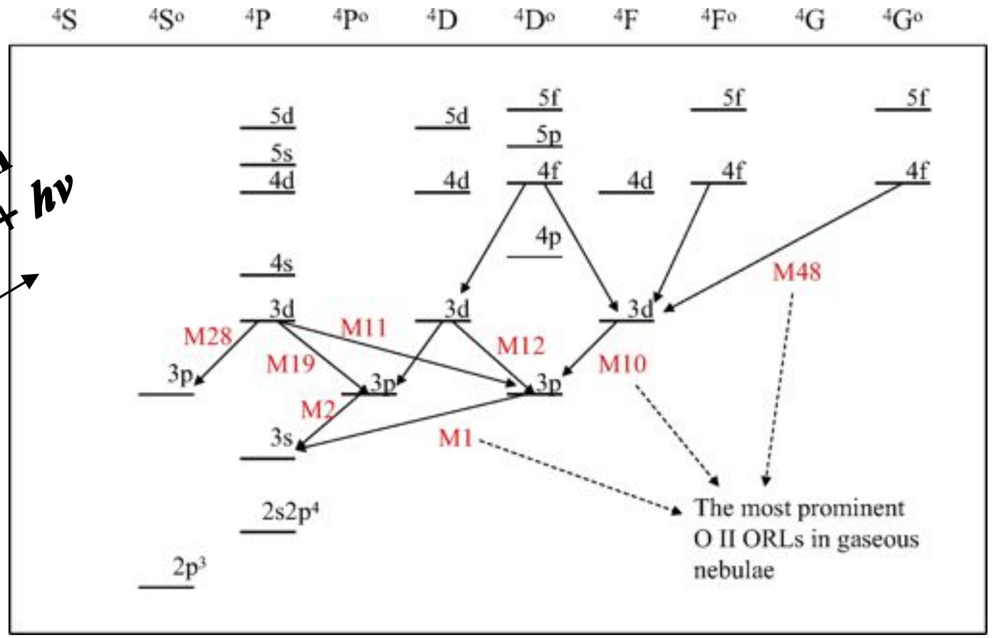
- Spectroscopy of PNe
  - Collisionally excited lines (CELs): $j_\nu = T_e^{-1/2}\exp(-E_{ex}/kT_e)$
  - Optical recombination lines (ORLs): $j_\nu = T_e^{-\alpha}, (\alpha \sim 1)$

[O III] $2p^2$, $2s2p^3$



recombination
$O^{2+} + e^- \rightarrow O^{+} + h\nu$

Grotrian diagram of O II



Background

- Basic problems in nebular astrophysics
  - X^{i+}/H(ORLs) > X^{i+}/H(CELs), where X is the C, N, O, and Ne ions
    Abundance discrepancy factor **adf** = X^{i+}(ORLs)/X^{i+}(CELs)
  - T_e(CELs) > T_e(H I Balmer jump)
    First observed by M.Peimbert (1967)

- The discrepancies are real
  - Measurement errors?
  - Reddening corrections?
  - Line blending?
  - Contamination of ORLs by other atomic processes (e.g. fluorescence, charge-transfer reactions)?
  - Inaccuracy of atomic data?

Background

- Explanations to the discrepancies
  - T_e fluctuations and/or N_e inhomogeneities (Peimbert 1967, 1971; Rubin 1989; Viegas & Clegg 1994)
  - Recently: κ-distribution of electrons (Nicholls et al. 2012)
  - The bi-abundance model (Liu et al. 2000): A cold (< 1000 K), metal-rich plasma component in PNe (probably also in H II regions)

- The bi-abundance model
  - CELs are from hot ionized gas, ORLs from the cold, metal-rich plasma
  - Well explains the wide ranges of observations
  - What are the astrophysical origins of the cold inclusions?
  - First need to know T_e, N_e, X/H, mass, etc.

Background

- The need for atomic data
  - Effective recombination coefficient is defined by

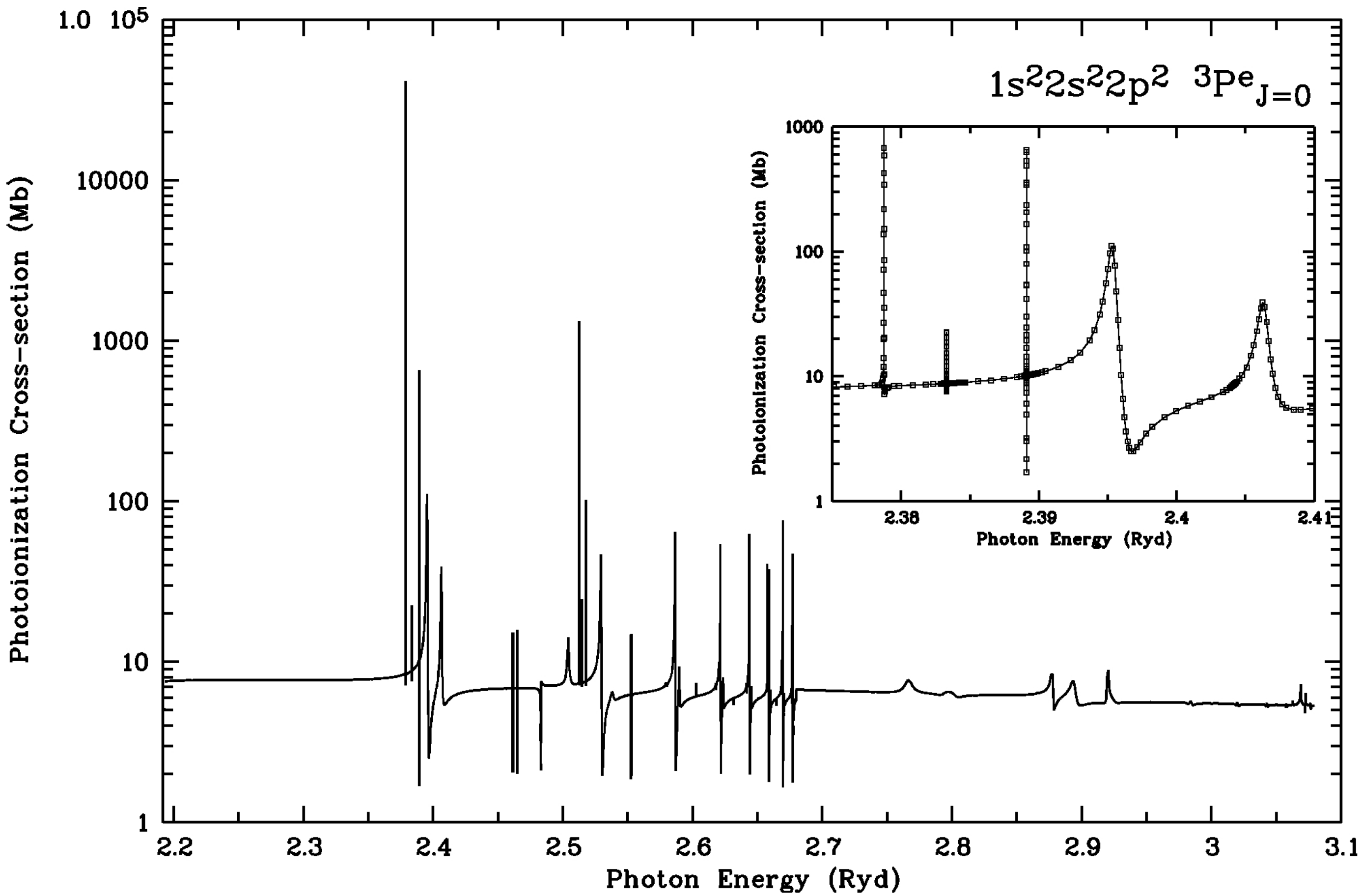
    $Emissivity = \alpha_{eff}(\lambda)\ h\nu\ N_{+}\ N_{e}$ [ergs cm^{-3} s^{-1}]
  - Classic work on C II, N II, O II, and Ne II:
    - Escalante & Victor (1990), Péquignot et al. (1991), Storey (1994), Davey et al. (2000), Kisielius et al. (1998), Kisielius & Storey (2002), etc.
  - No N_e-diagnostics tools fully based on heavy-element ORLs at the moment
  - The old effective recombination coefficients were all calculated for 5000 - 20000 K
  - If the cold, metal rich compoent does exist, the atomic data need to be calculated down to low-T_e areas (< 1000 K)

Atomic data

- *ab initio* calculations
  - The N^{2+} and O^{2+} targets are generated by SUPERSTRUCTURE
  - Radial wave functions are caluclated by AUTOSTRUCTURE
  - R-matrix calculations:
    - Energy levels, oscillator strengths, and phtoionization cross-sections
    - All calculations are in the **intermediate coulping** (IC) scheme
  - The photoionization cross-section calculations
    - Adaptive energy mesh is used (Kisielius & Storey 2002)
    - Resonances as narrow as $\sim 10^{-10}$ Ryd are resolved
    - Recombination coefficients are integrated from the photoionization cross-sections
    - Traditional OP methods based on the quantum defect mesh or fixed-step energy mesh are not adequate for narrow resonances

Atomic data

- E.g. photoionization cross-sections of the N^+ $2p^2$ $^3P_0$ level



Effective recombination coefficients

Fang, Storey & Liu (2011)

- Atomic processes considered in level population calculations
  - Bound-bound radiative transitions

    $$X^{+i}(a) \rightarrow X^{+i}(b) + h\nu$$

  - Bound-free: photoionization and radiative recombination

    $$X^{+i+1}(a) + e^{-} \rightarrow X^{+i}(b) + h\nu$$

  - Dielectronic recombination and autoionization

    $$X^{+i+1}(a) + e^{-} \Leftrightarrow X^{+i}(a^{**}) \rightarrow X^{+i}(b) + h\nu$$

  - Collisions:
    - Collisional excitation and de-excitation by e^-, H^+, He^+ and He^{++}

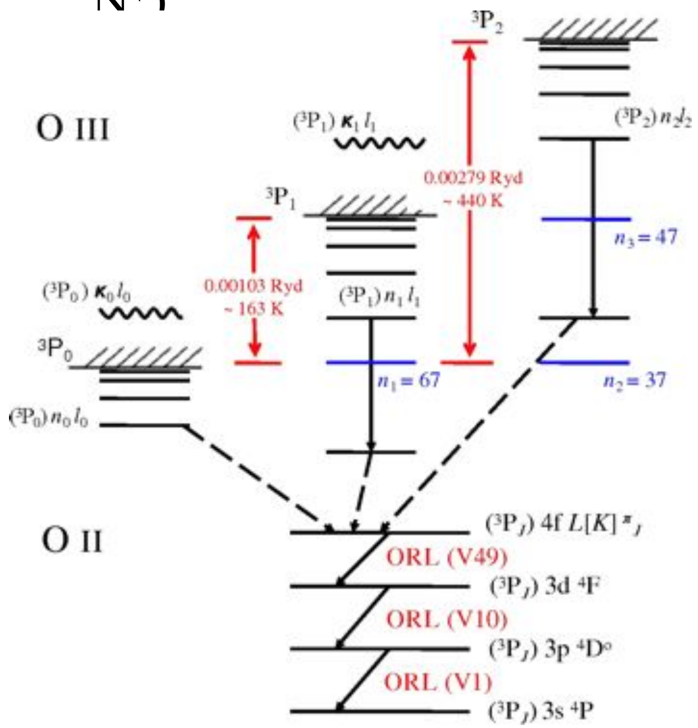
      $$X^{+i}(a) + c(k^2) \leftrightarrow X^{+i}(b) + c(k'^2)$$

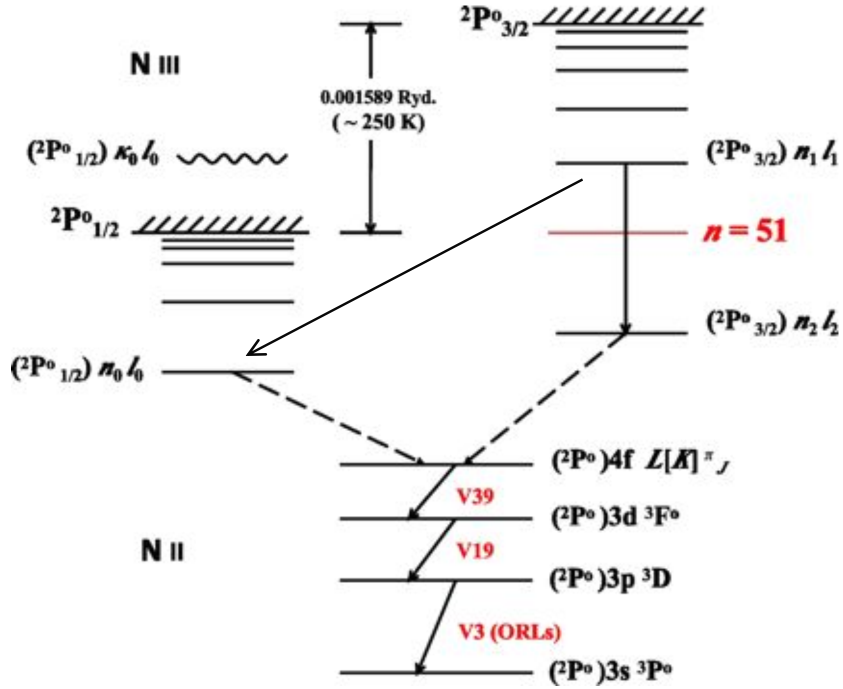
    - Collisional ionization and three-body recombination

      $$X^{+i}(a) + e^{-} \leftrightarrow X^{+i}(b) + e^{-} + e^{-}$$

Effective recombination coefficients

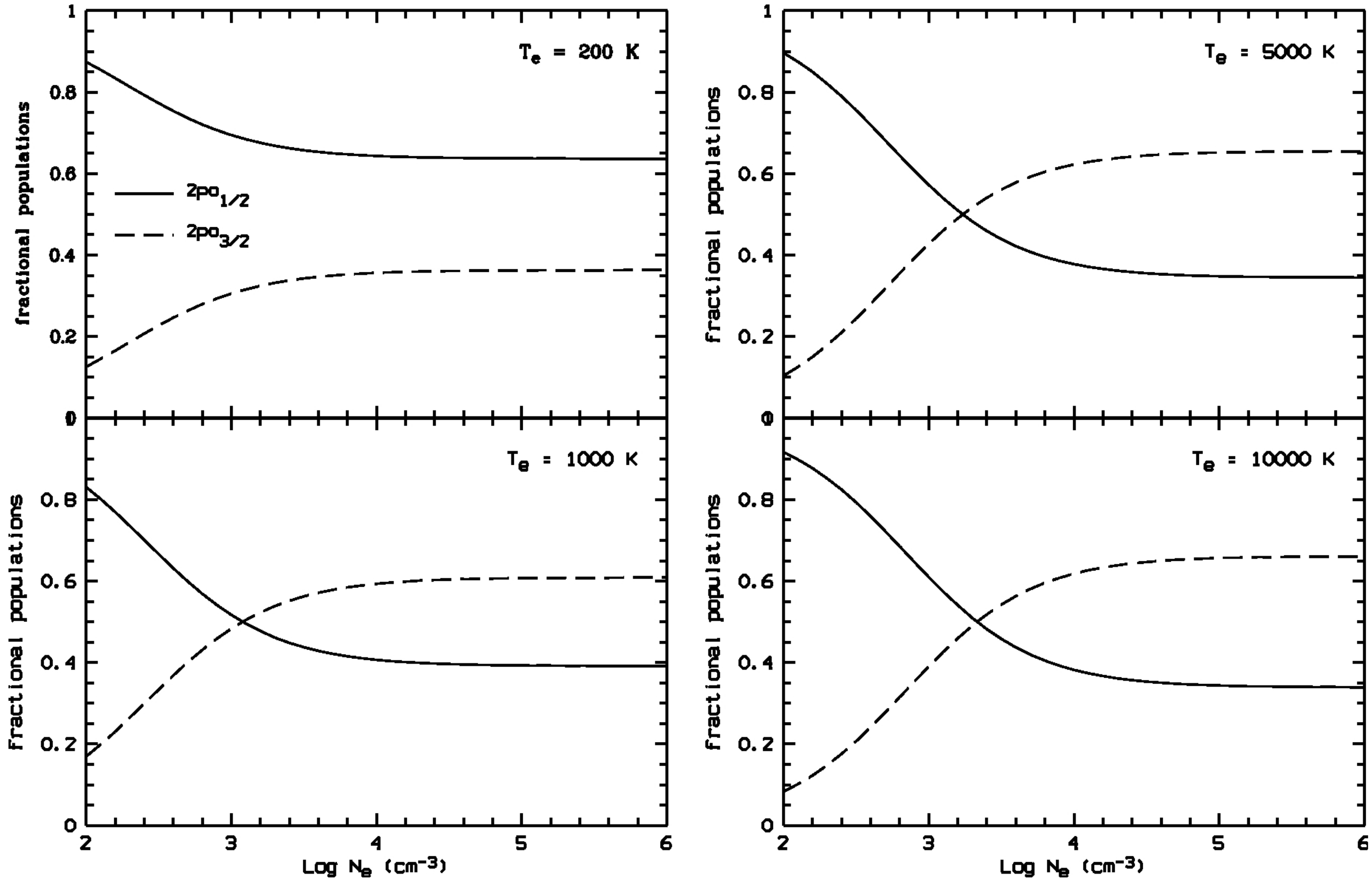
- Dielectronic recombination
  - High-T_e dielectronic recombination (occurs through high-n states (n≈100), only important for T_e's above 15000 K)
  - Low-T_e dielectronic recombination (occurs through near-threshold resonances)
  - Dielectronic recombination at very low T_e (e.g. ≲250 K in the case of N^+)





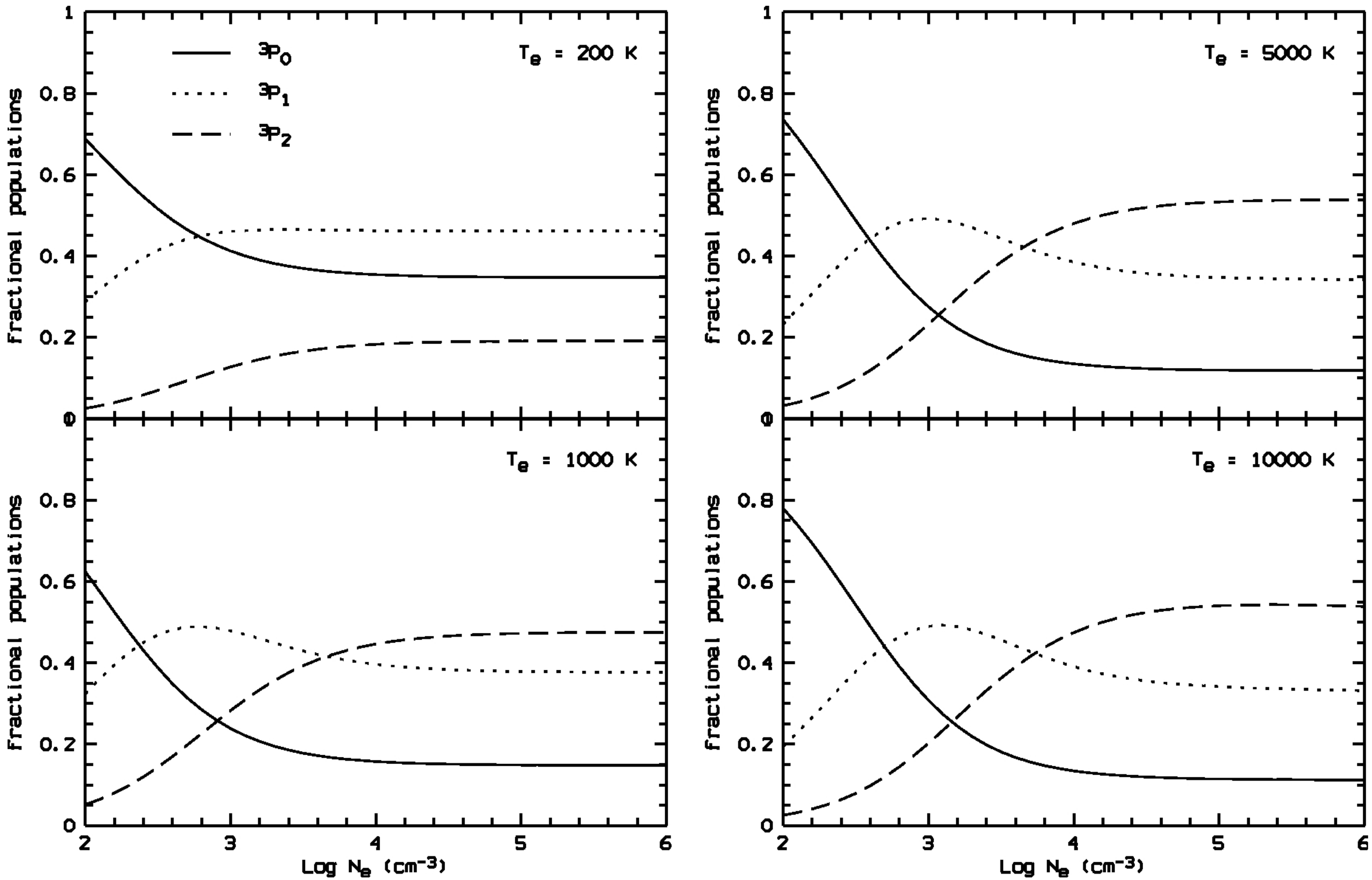
Effective recombination coefficients

- Relative populations of the recombining ion N^{2+} $^2P^o_{1/2}$ and $^2P^o_{3/2}$



Effective recombination coefficients

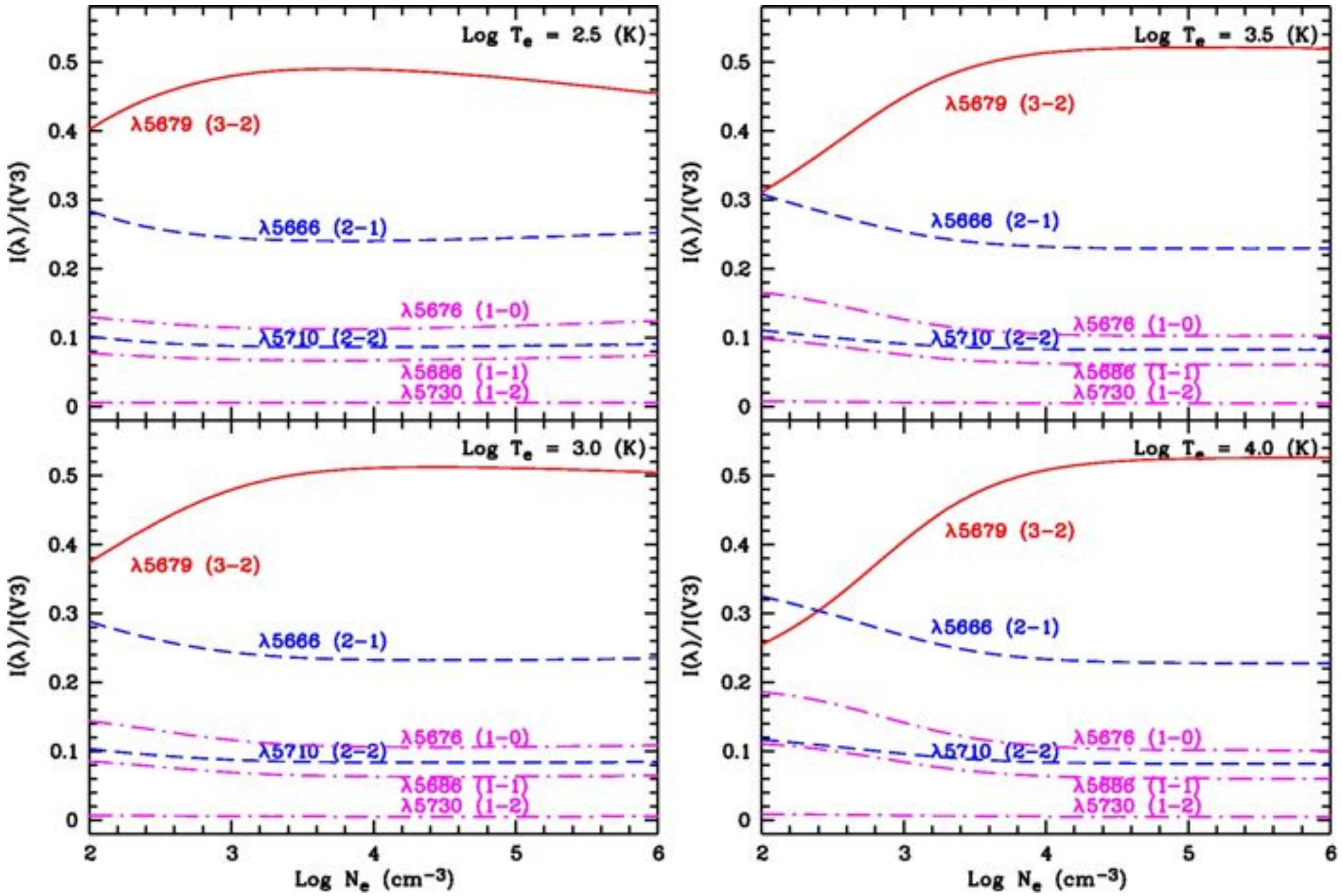
- Relative populations of the recombining ion O^{2+} $^3P_0$, $^3P_1$ and $^3P_2$



Effective recombination coefficients

- N II Multiplet V3: 2p3p ^3D - 2p3s $^3P^o$

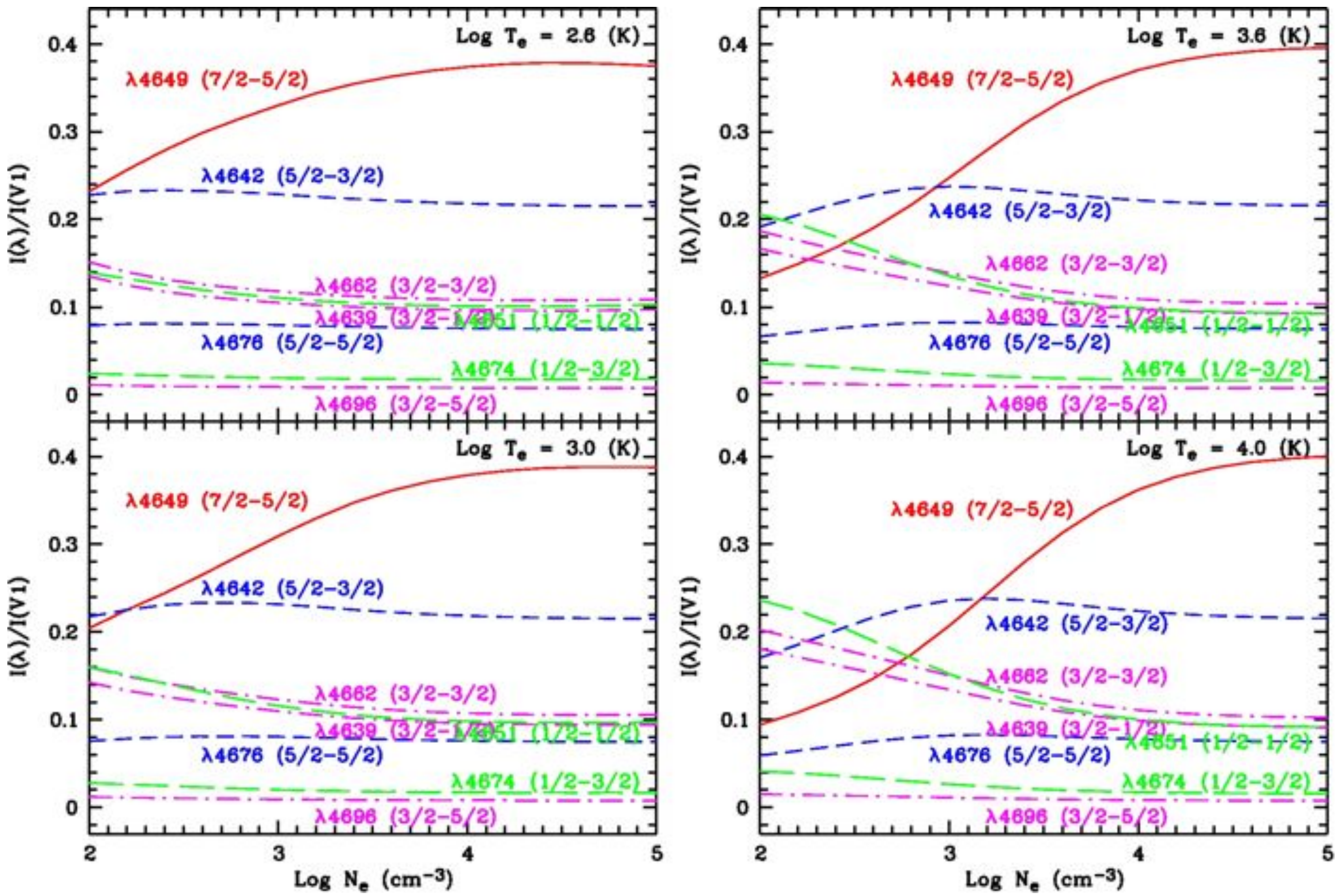
Fang, Storey & Liu (2011)



Effective recombination coefficients

- O II Multiplet V1: 2p23p $^4D^o$ - 2p23s ^4P

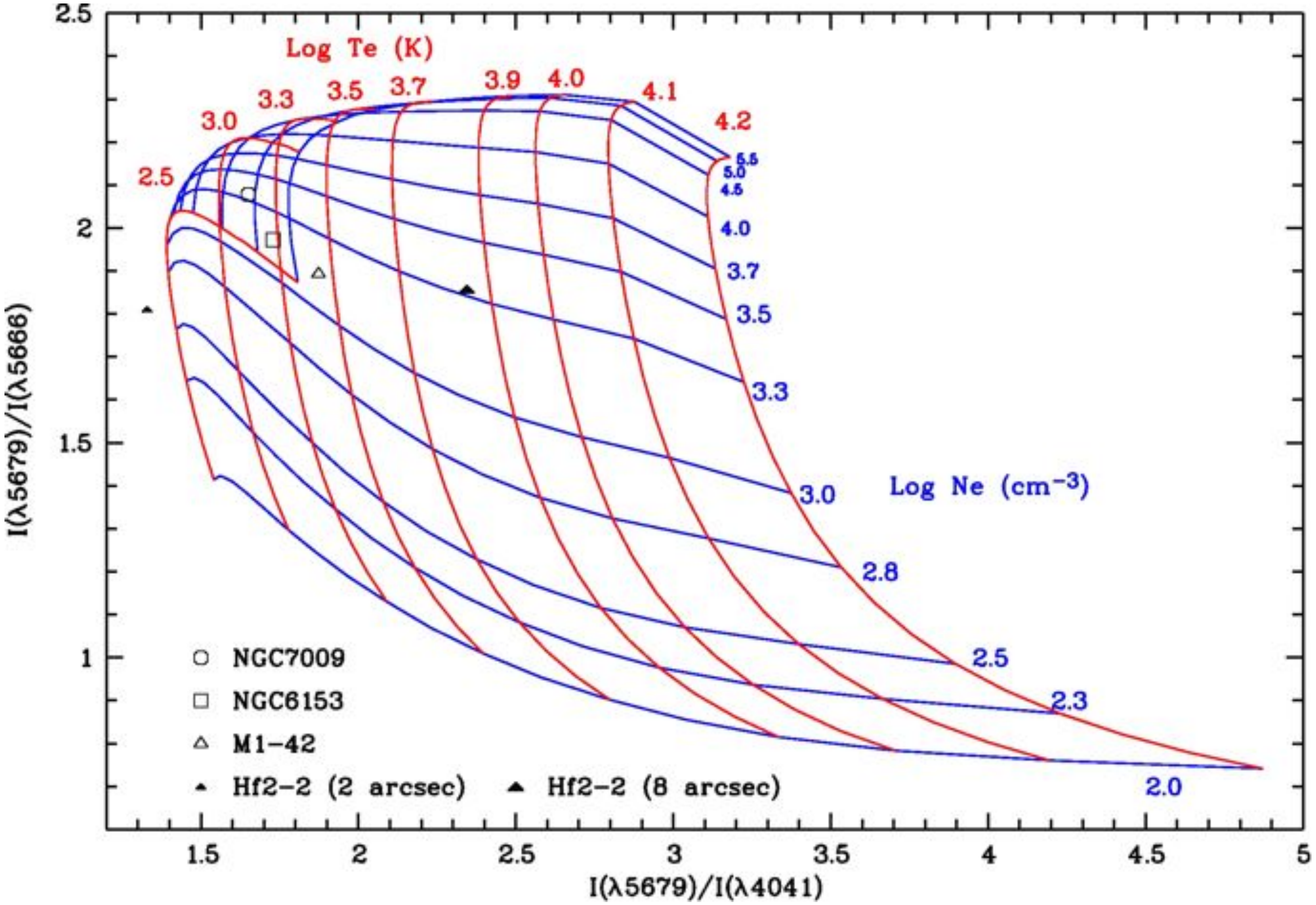
Storey, unpublished



Effective recombination coefficients

Applications to plasma diagnostics

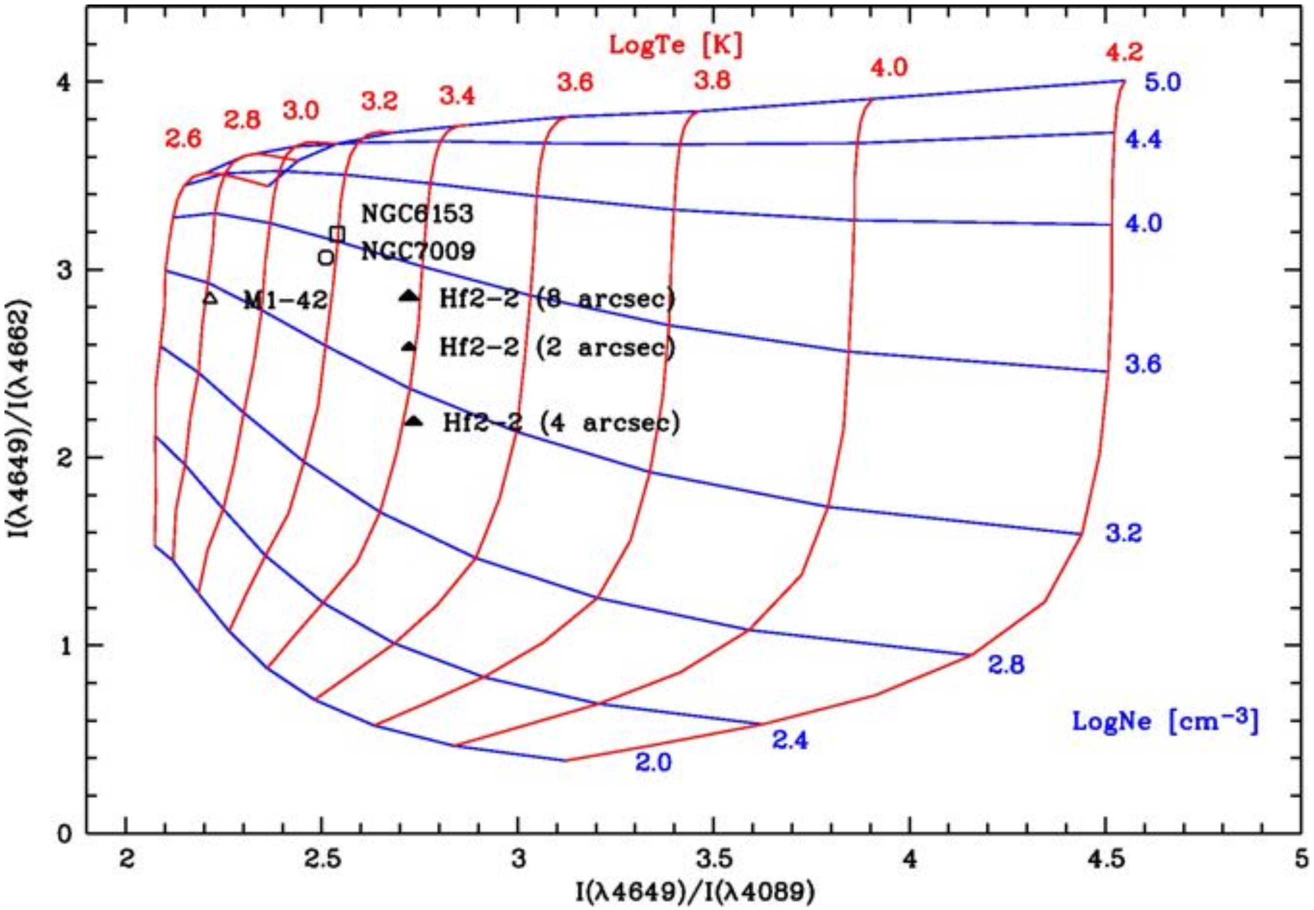
- Plasma diagnostics using the N II ORL ratios
  - Based on the recent intermediate coupling calculations of Fang, Storey & Liu (2011)



Effective recombination coefficients

Applications to plasma diagnostics

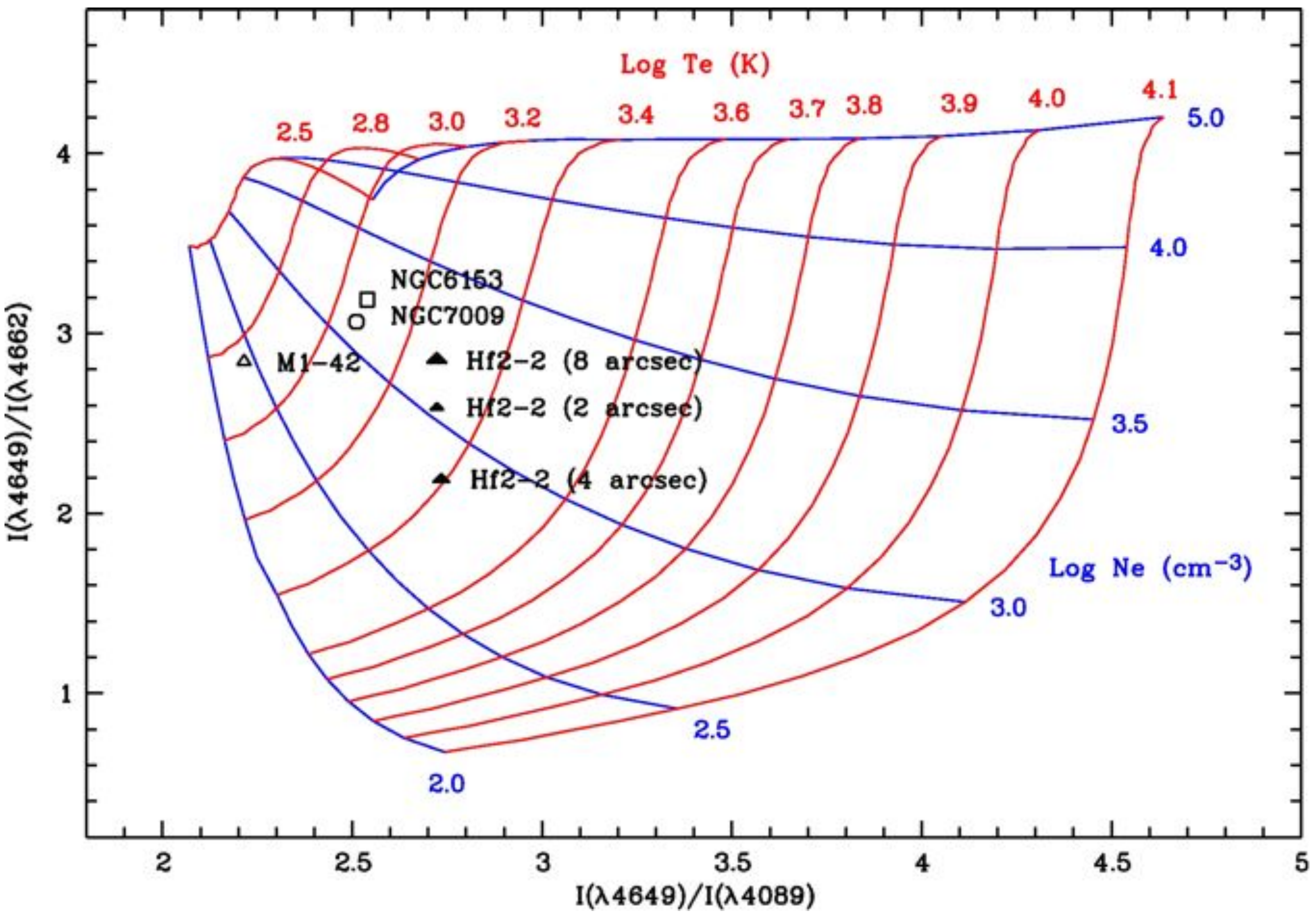
- Plasma diagnostics using the O II ORL ratios
  - Based on the new intermediate coupling calculations of Storey (private communications)



Effective recombination coefficients

The old O II data (before 2007)

- Plasma diagnostics using the O II ORL ratios
  - Based on the j-j coupling calculations of Bastin & Storey (2006)

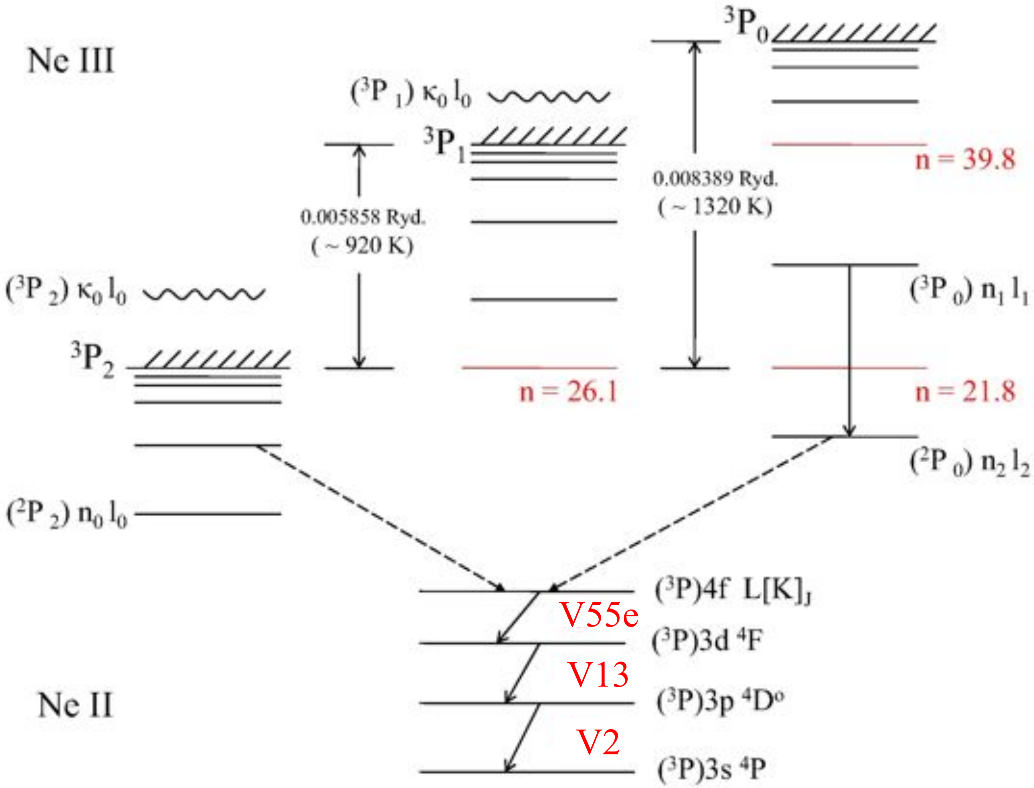


Effective recombination coefficients

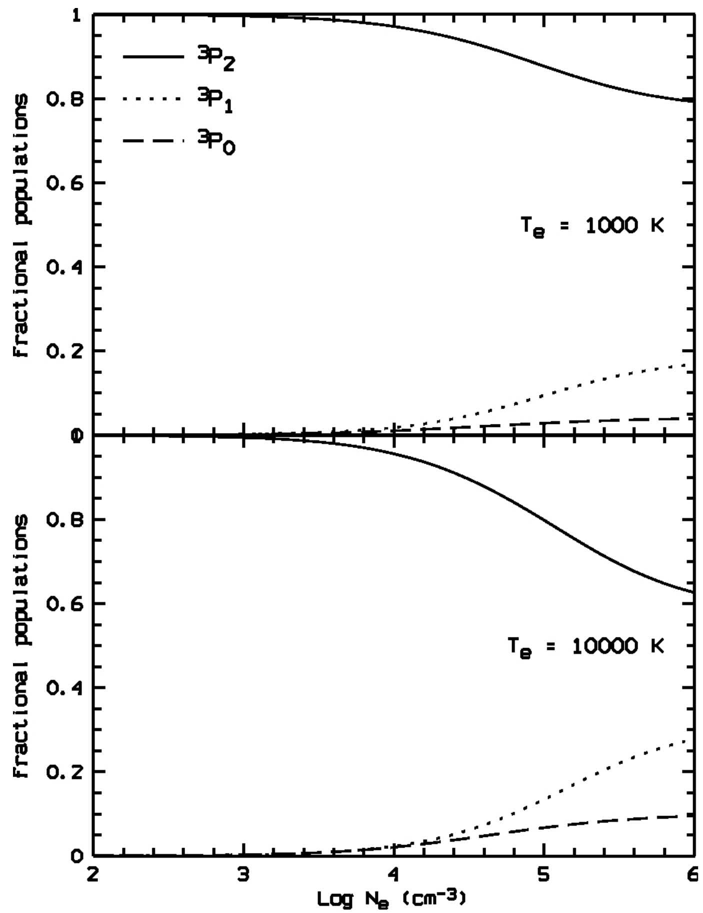
What about Ne II?

- The Ne II calculations

Schematic figure showing the low-temperature dielectronic recombination of Ne II through the autoionization levels between the Ne^{2+} $^3P_2$, $^3P_1$, and $^3P_0$ thresholds:

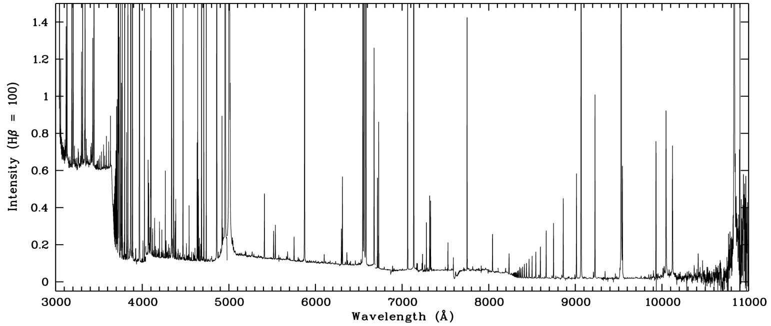


The relative populations of the Ne^{2+} $^3P_2$, $^3P_1$, and $^3P_0$ levels as a function of N_e:

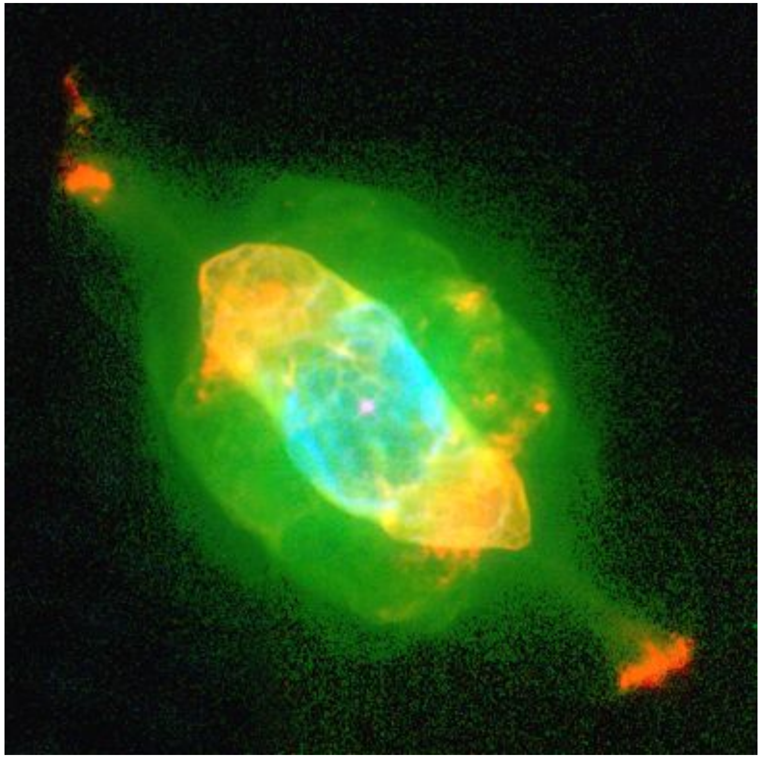


Very deep spectroscopy of NGC7009
Observations

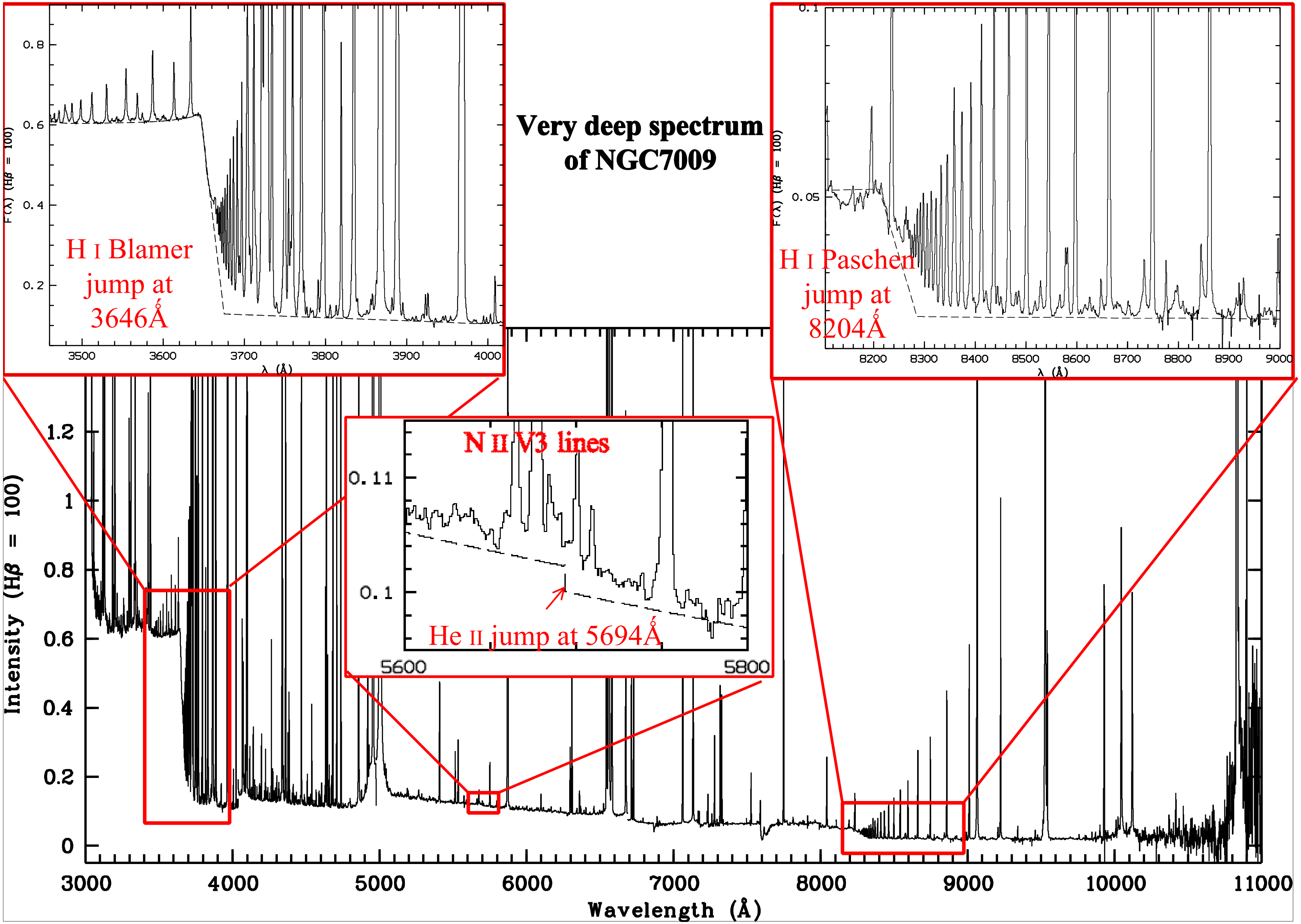
- The bright Saturn nebula NGC7009
  - A medium excitation PN
  - Distance: 0.86 kpc
  - Rich in emission lines, especially the ORLs of O II **(e.g. Wyse 1942; Aller & Kaller 1964; Barker 1983; Liu et al. 1995)**
  - ESO 1.52m, WHT 4.2m
  - 3000-11000Å; high resolution
  - The best quality in 3000-6000Å



HST/WFPC2 image of NGC7009:



Credit: Bruce Balick (University of Washington), Jason Alexander (University of Washington), Yervant Terzian (Conell University), etc. (http://www.spacetelescope.org/images)

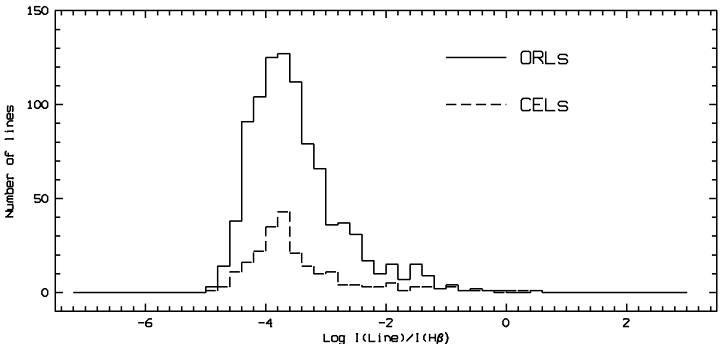


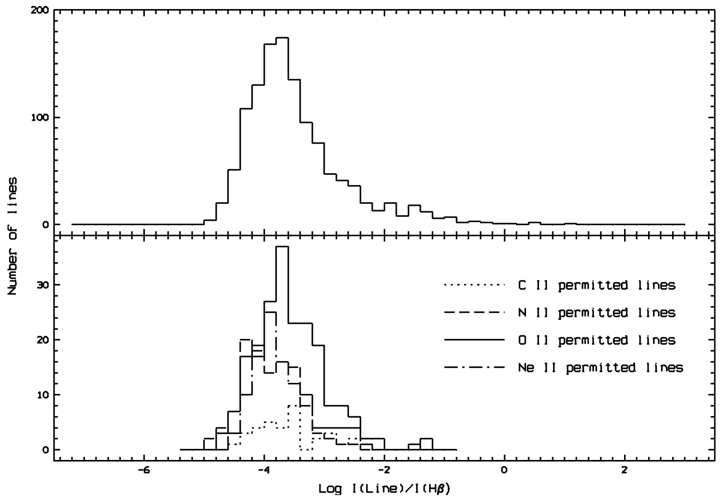
Very deep spectrum
of NGC7009
H I Blamer
jump at
3646Å
H I Paschen
jump at
8204Å
N II V3 lines
He II jump at 5694Å
Intensity (Hβ = 100)
Wavelength (Å)
F(λ) (Hβ = 100)
λ (Å)

Very deep spectroscopy of NGC7009

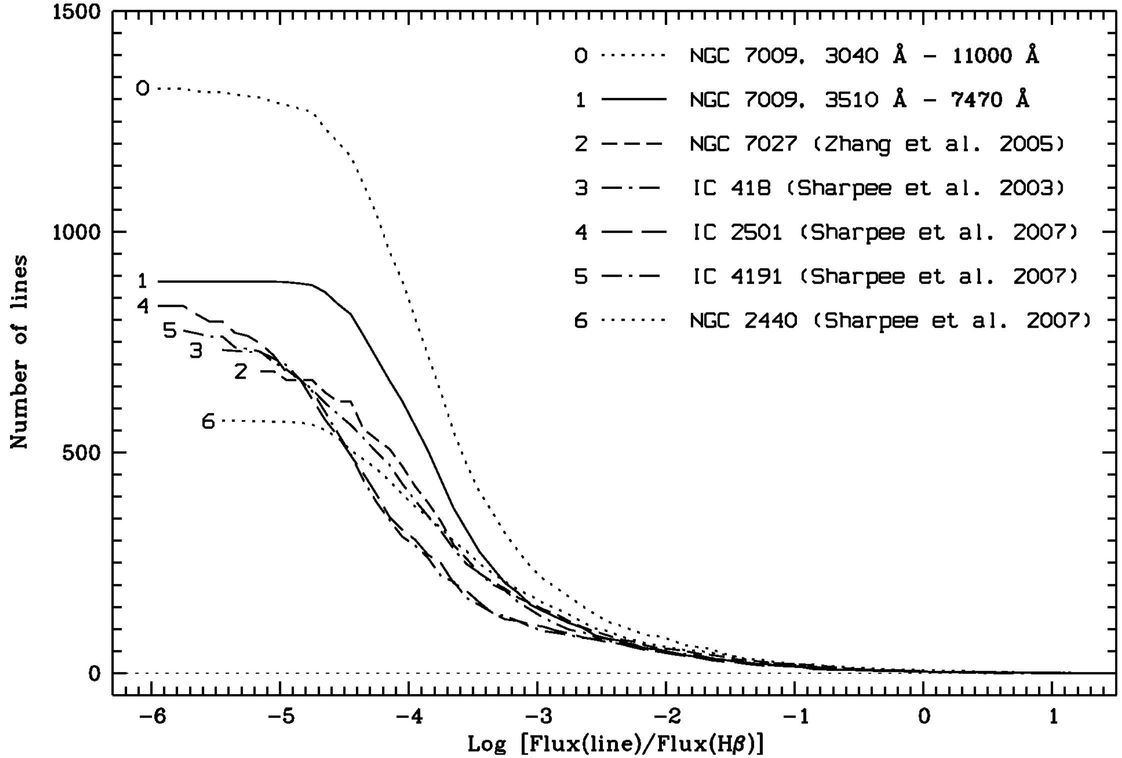
Observations

- Rich optical recombination lines in NGC7009
  - Gaussian profile fitting was used to deblend lines





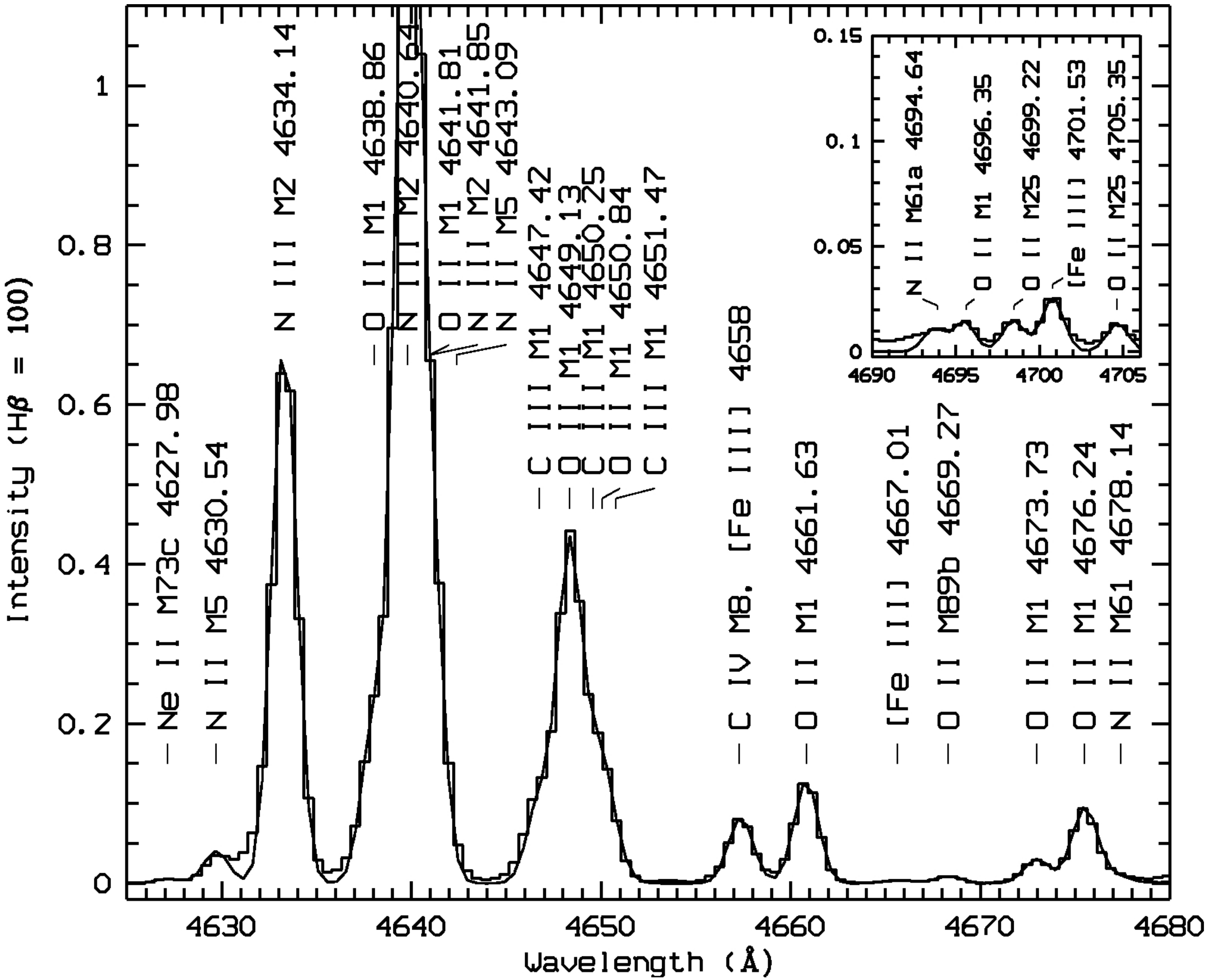
Cumulative curve of emission lines:



Very deep spectroscopy of NGC7009

The rich optical recombiantion spectrum

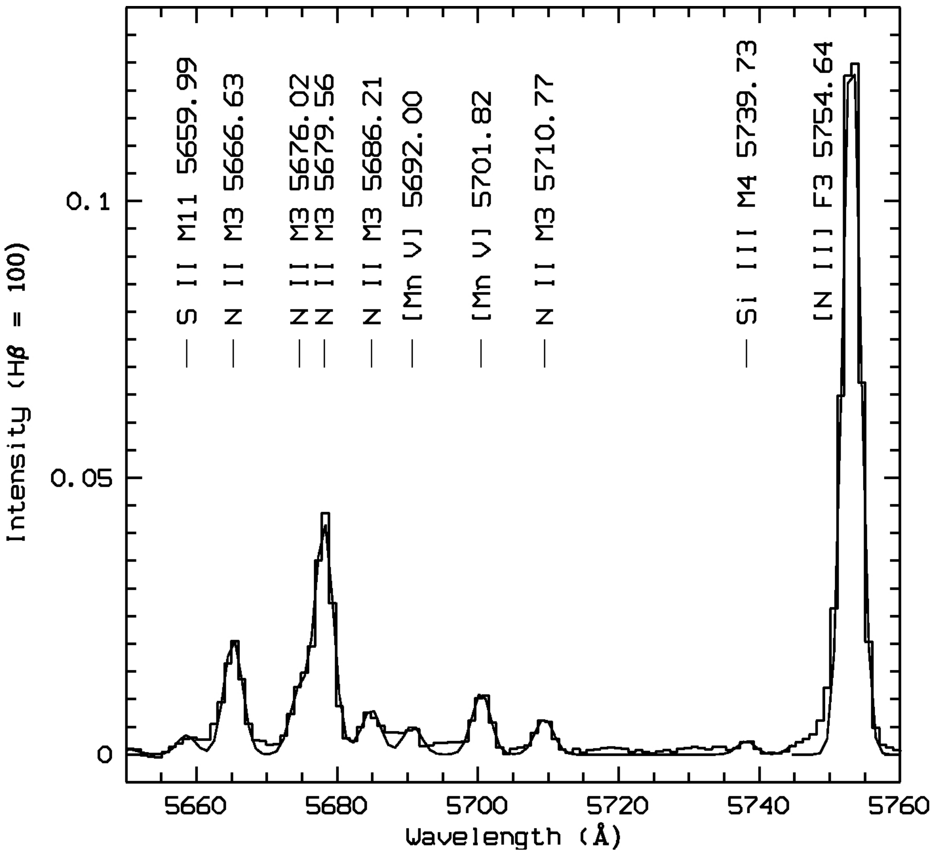
- The O II V1 multiplet



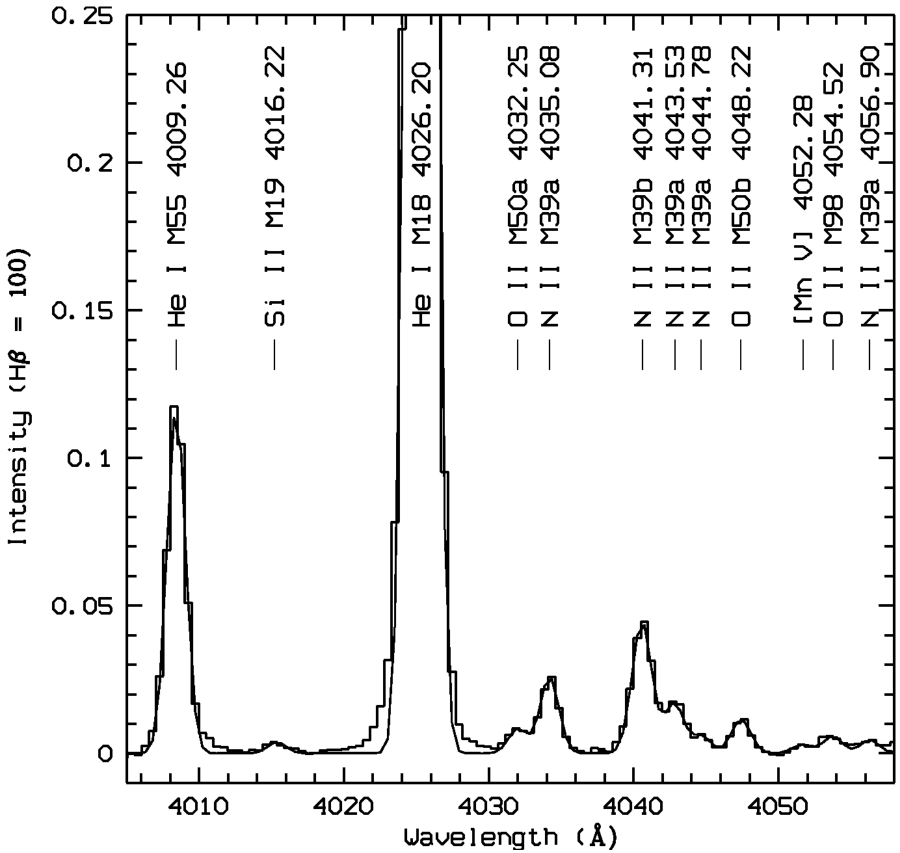
Very deep spectroscopy of NGC7009

The rich optical recombiantion spectrum

- The N II V3 multiplet



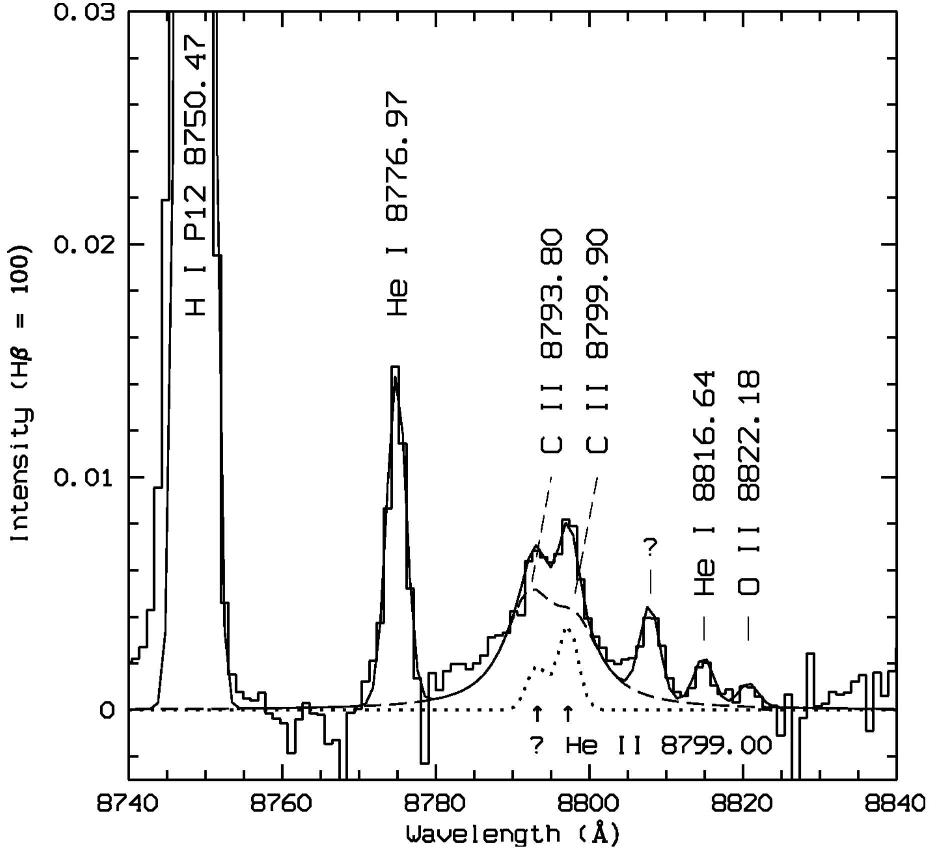
- The N II 4f-3d transitions



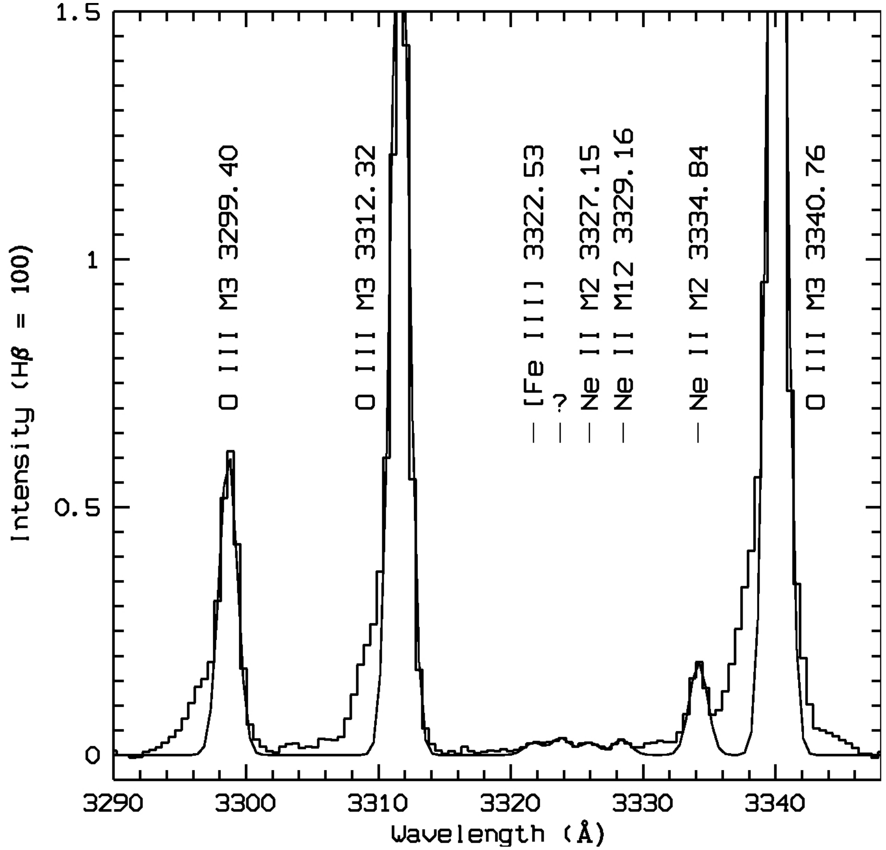
Very deep spectroscopy of NGC7009

The rich optical recombiantion spectrum

- C II V28.01
  2s2p(^{3}P^o)3d ^{2}F^o -2s2p(^{3}P^o)3p ^{2}D



- Ne II V2 2p^{4}3p ^{4}D^o - 2p^{4}3s ^{4}P

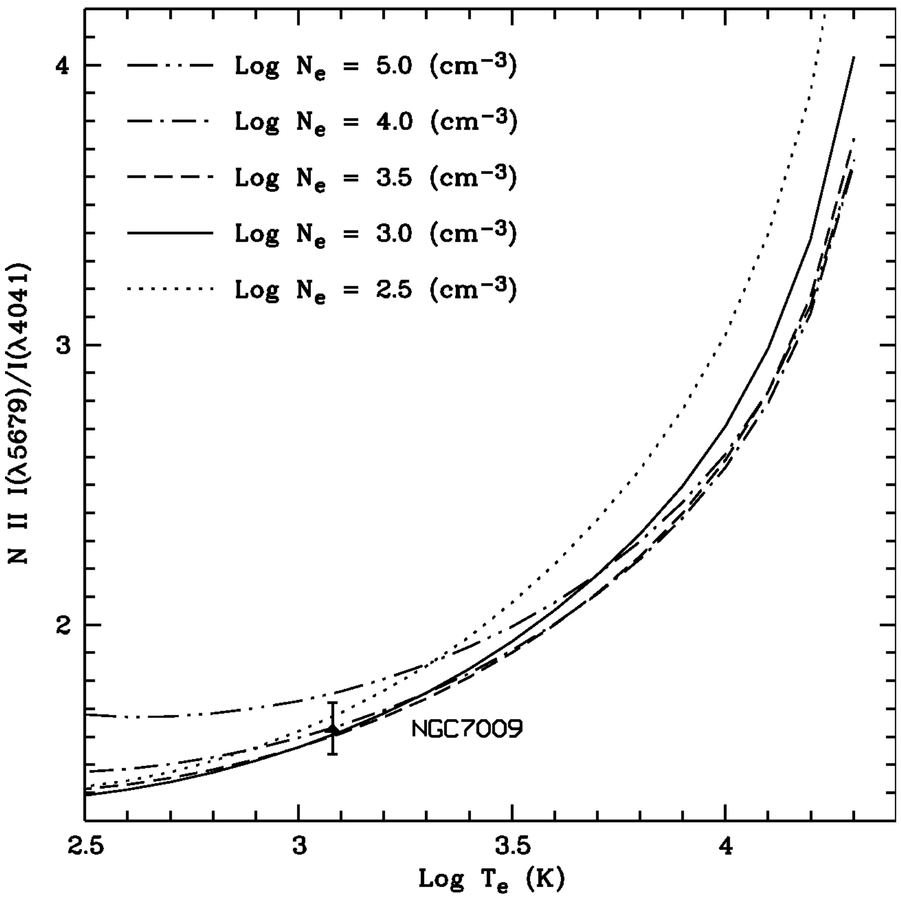


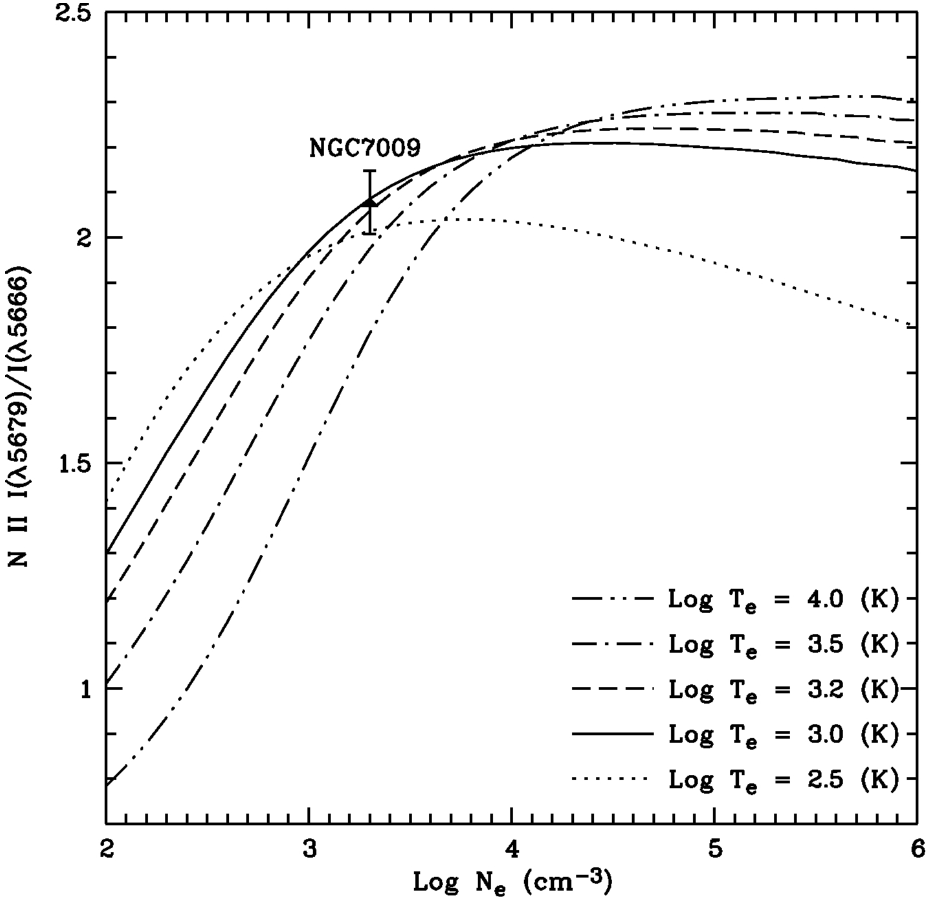
Very deep spectroscopy of NGC7009

Plasma diagnostics using ORLs

- T_e and N_e from the N II optical recombination lines
  - N_e(λ5679/λ5666) ≈ 2000-3200 cm^{-3}
  - T_e(λ5679/λ4041) ≈ 1200+/-200 K

(Fang et al. 2012, in preparation)



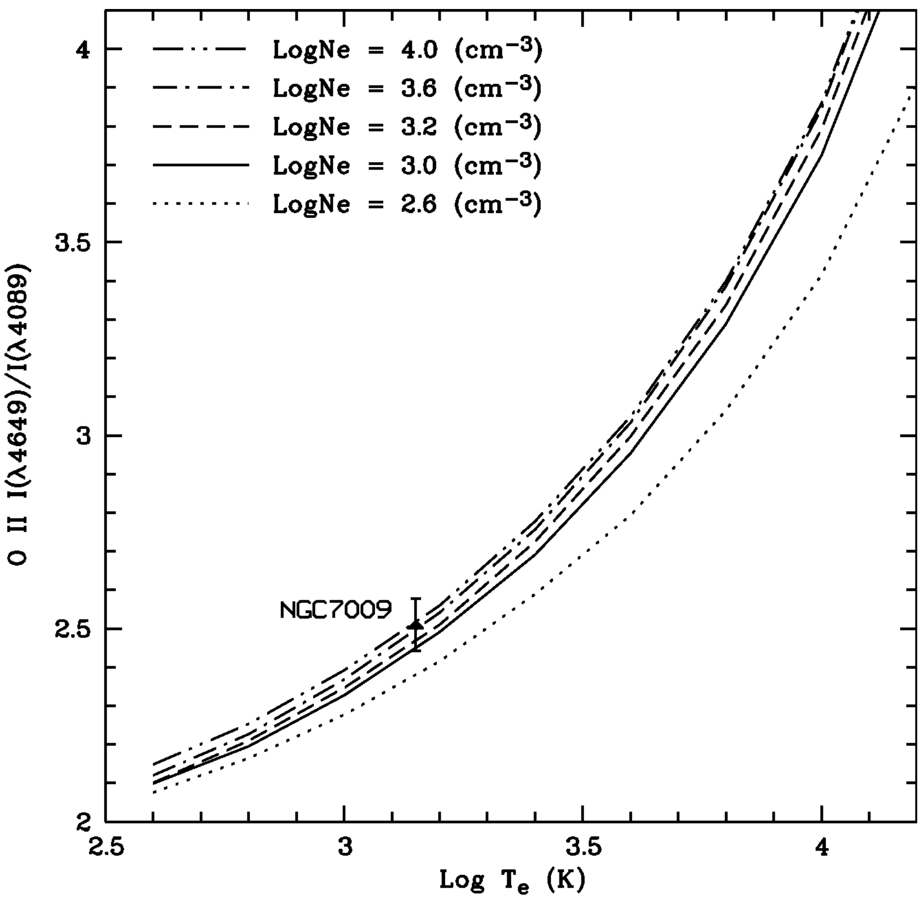


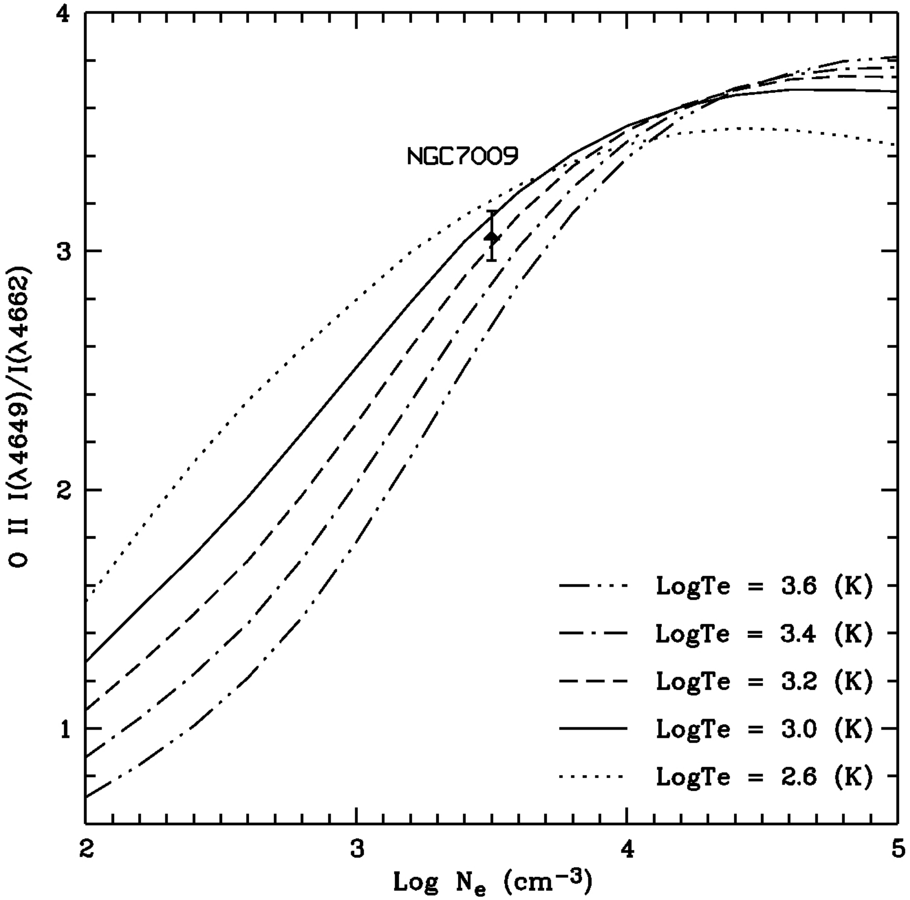
Very deep spectroscopy of NGC7009

Plasma diagnostics using ORLs

- T_e and N_e from the O II optical recombination lines
  - $N_e(\lambda 4649/\lambda 4662) \approx 3000\text{-}4000\ cm^{-3}$
  - $T_e(\lambda 4649/\lambda 4089) \approx 1300+/-300$ K

(Fang et al. 2012, in preparation)





Very deep spectroscopy of NGC7009

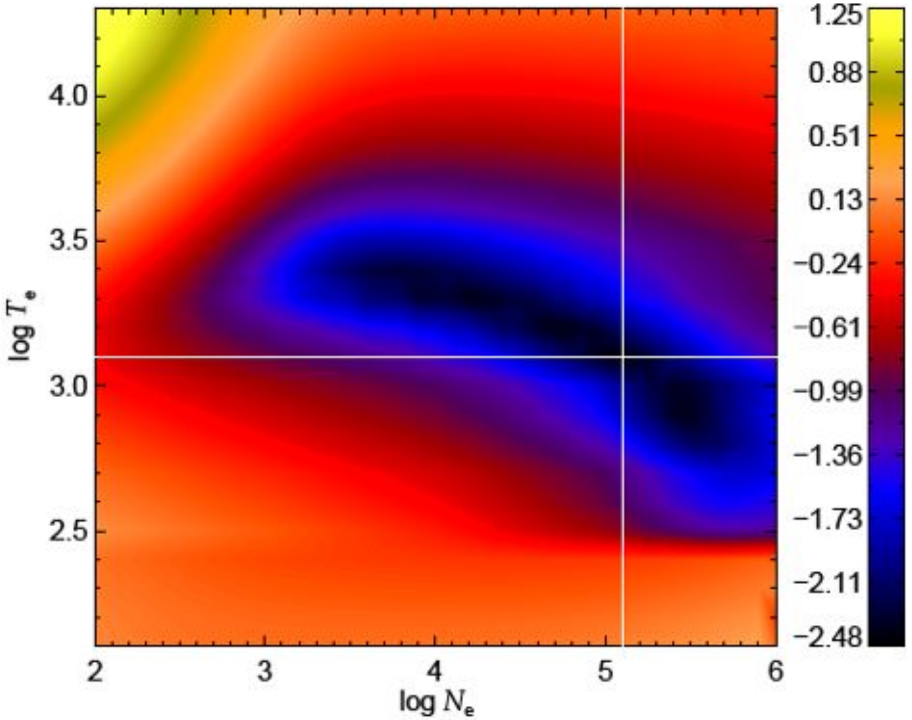
Plasma diagnostics using ORLs (another method)

- T_e's and N_e's from the N II and O II ORLs
  - Several ORLs are used simultaneously to confine T_e and N_e
  - The residuals:

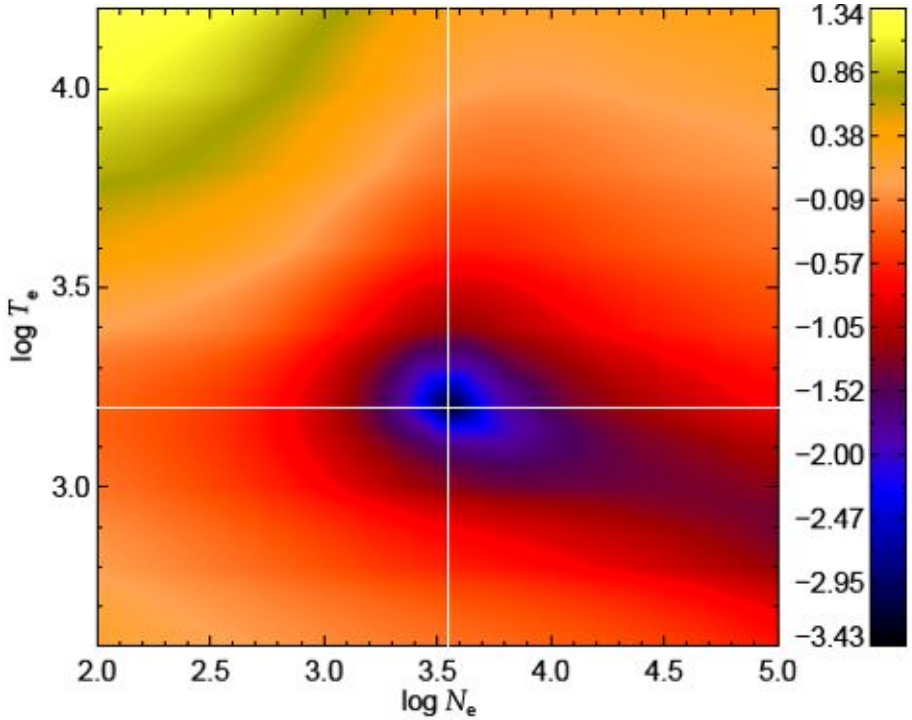
$$\chi^2 = \sum_{i=1}^{n} \left(\frac{I_{observed}(\lambda_i) - I_{predicted}(\lambda_i)}{I_{predicted}(\lambda_i)} \right)^2$$

(McNabb et al. 2012, in preparation)

N II:
λλ5679 (V3), 5666 (V3), 4041 (V39b), 4035 (V39a)



O II:
λλ4662 (V1), 4649 (V1), 4089 (V48a), 4087 (V48c)

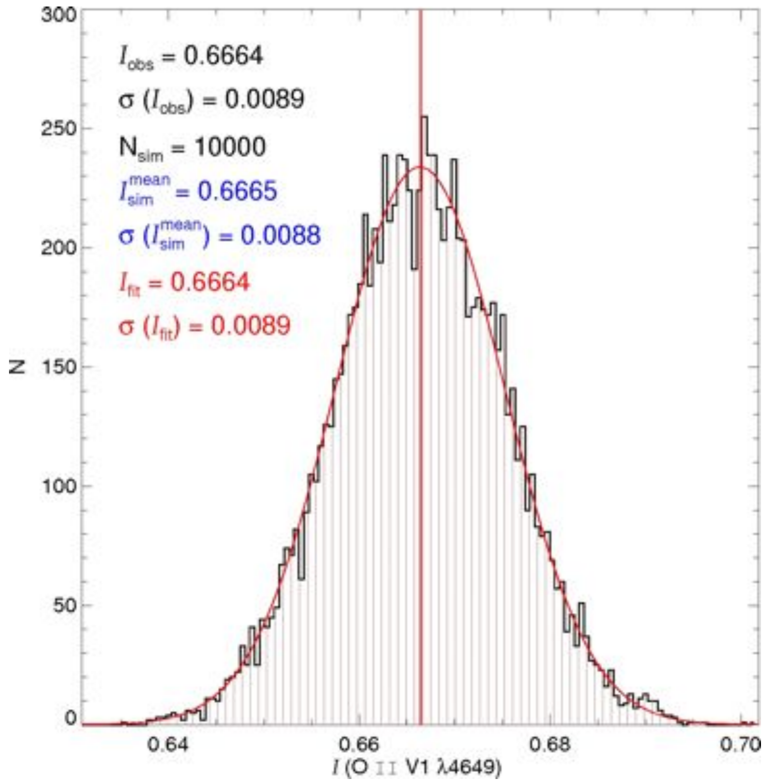


Very deep spectroscopy of NGC7009

Plasma diagnostics using ORLs (another method)

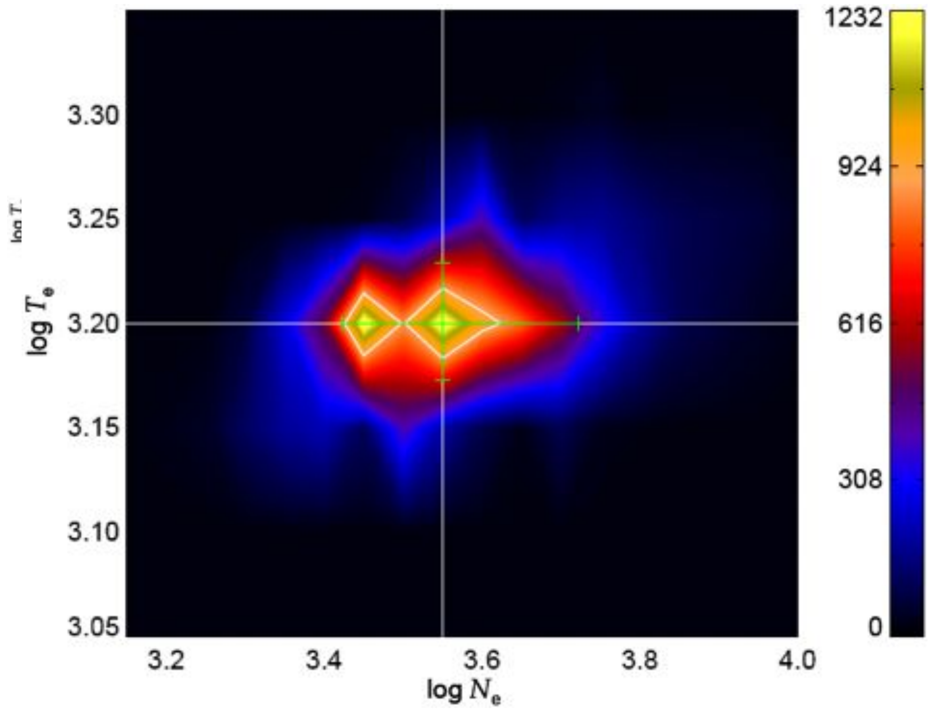
- T_e's and N_e's from the N II and O II ORLs
  - Error estimate: randomly generate 10000 numbers for each line flux
  - The random numbers are assumed to be in Gaussian distribution
  - Each set of randomly generated flux gives a T_e and N_e

(McNabb et al. 2012, in preparation)



O II:

λλ4662 (V1), 4649 (V1), 4089 (V48a), 4087 (V48c)

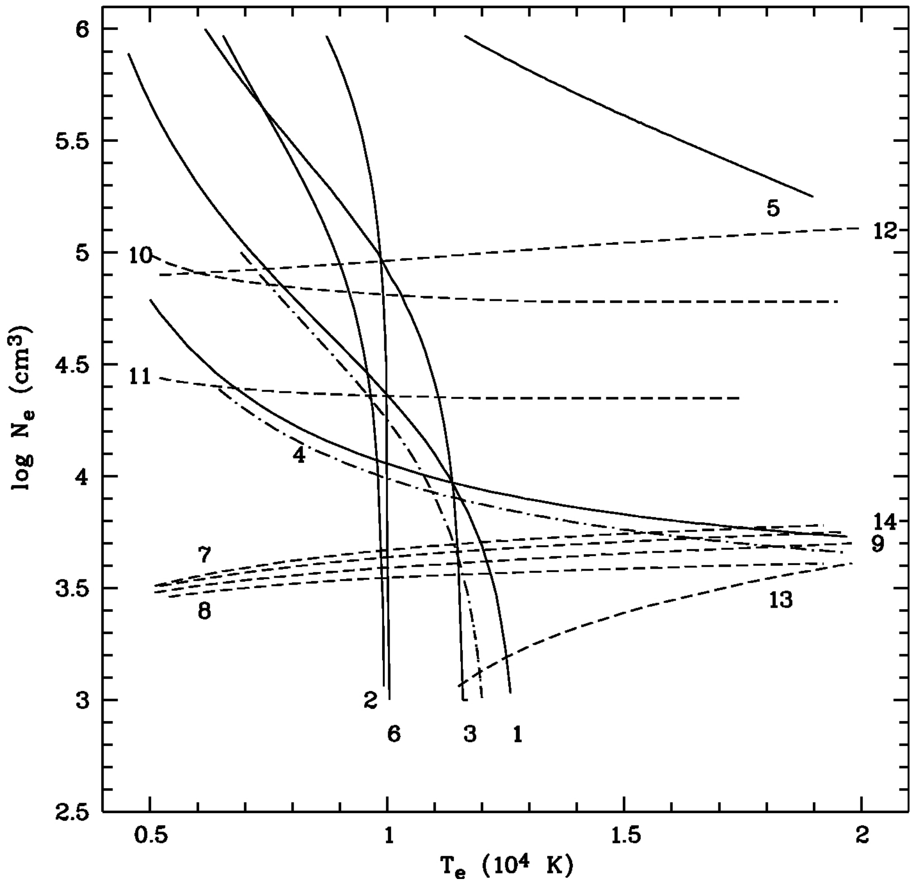


Very deep spectroscopy of NGC7009

Plasma diagnostics

- Plasma diagnostics based on CELs

		T_e (K)
1.	[N II] (6584+6548)/5754	10781
2.	[O III] (4959+5007)/4363	10940
3.	[S III] (9531+9069)/6412	11500
4.	[O II] (7320+7330)/3729	9850
5.	[O I] (6300+6363)/5577	-
6.	[Ar III] 7135/5192	10050
		N_e (cm^{-3})
7.	[Ar IV] 4740/4711	4890
8.	[Cl III] 5537/5517	3600
9.	[S II] 6731/6716	4100
10 - 13.	[Fe III] line ratios	>22000
14.	[O II] 3726/3729	4720

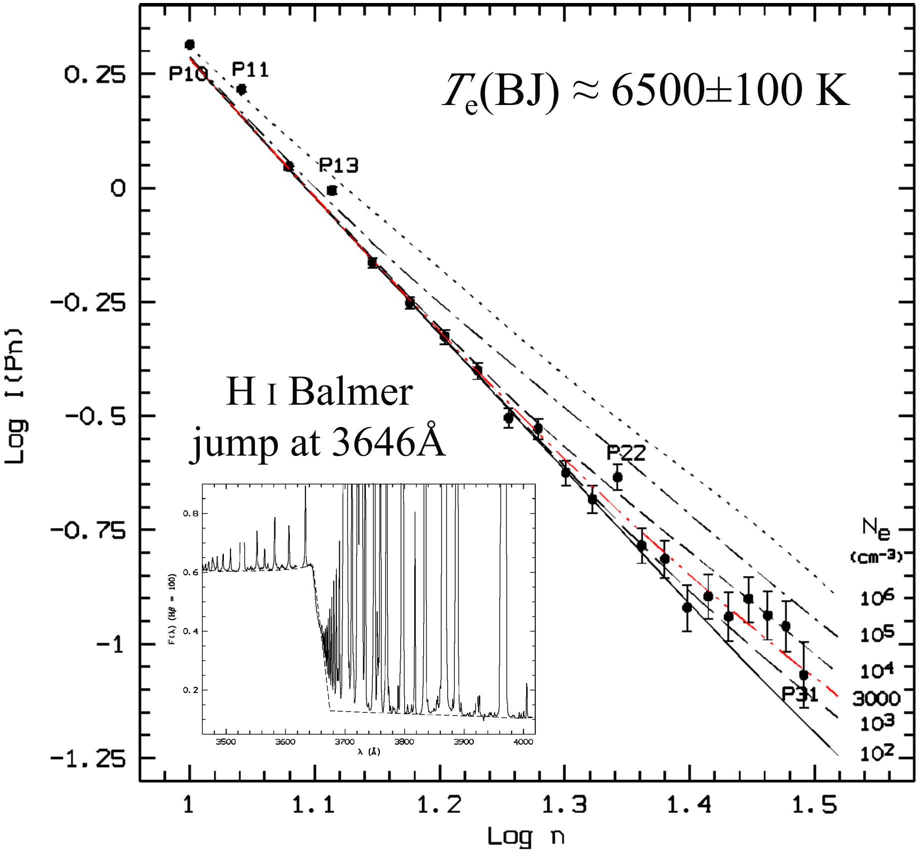


Very deep spectroscopy of NGC7009

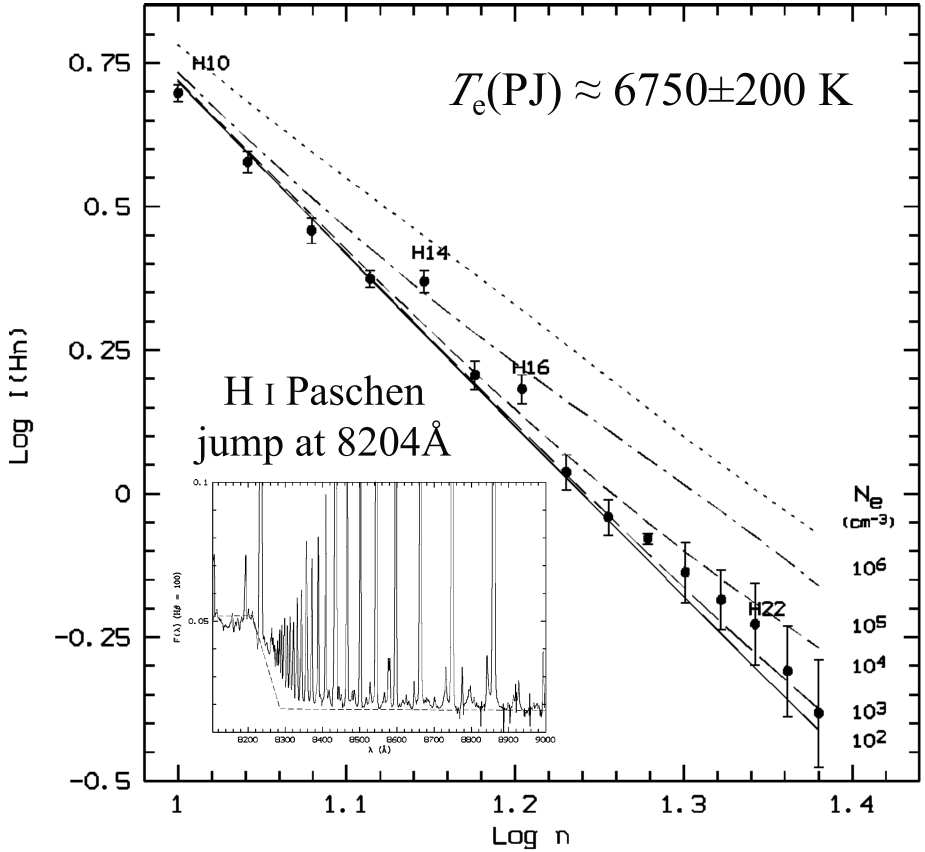
Plasma diagnostics

- T_e's and N_e's from the H I recombination spectrum
  - T_e(H I Balmer jump) ≈6500K; T_e(H I Paschen jump) ≈6750K

N_e(Balmer Decrements) ≈ 3000 cm^{-3}



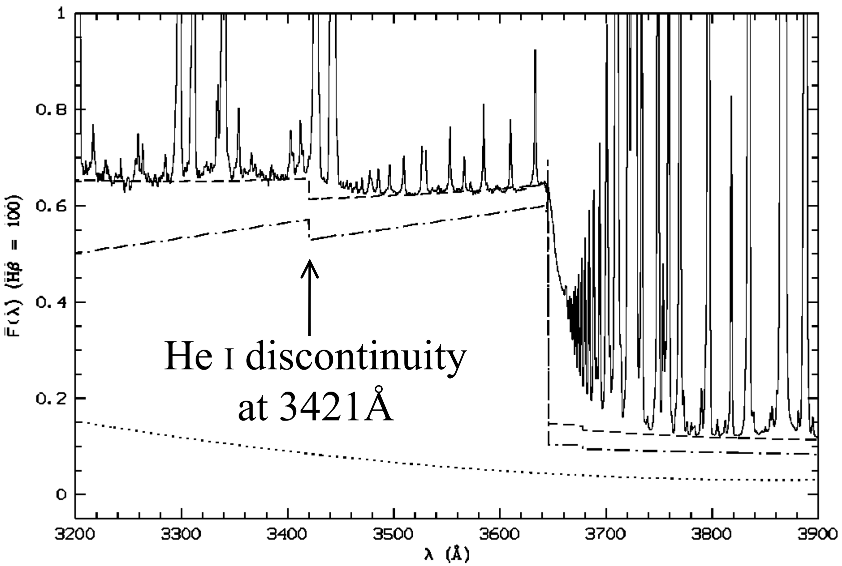
N_e(Paschen Decrements) ≈ 1000 – 3000 cm^{-3}



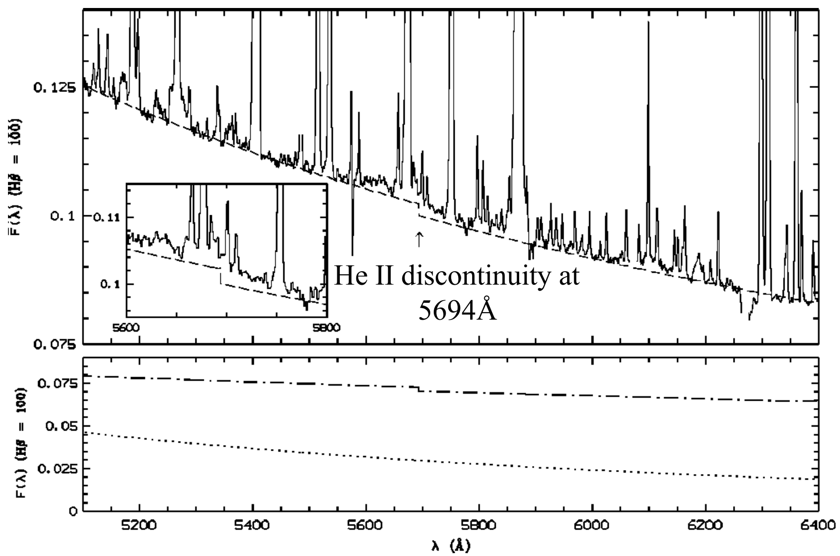
Very deep spectroscopy of NGC7009
Plasma diagnostics

- T_e's from the He I and He II recombination spectra
  - T_e(He I λ7281/λ6678) ≈ 5100 K (most reliable, adopted)
  - The He I discontinuity at 3421Å yields a temperature ~7800 K
  - The He II discontinuity at 5694Å yields a temperature ~ 11000 K

The He I discontinuity at 3421Å
(recombination to 1s2p $^3P^o$)



The He II discontinuity at 5694Å
(recombination to the n=5 level)



Very deep spectroscopy of NGC7009

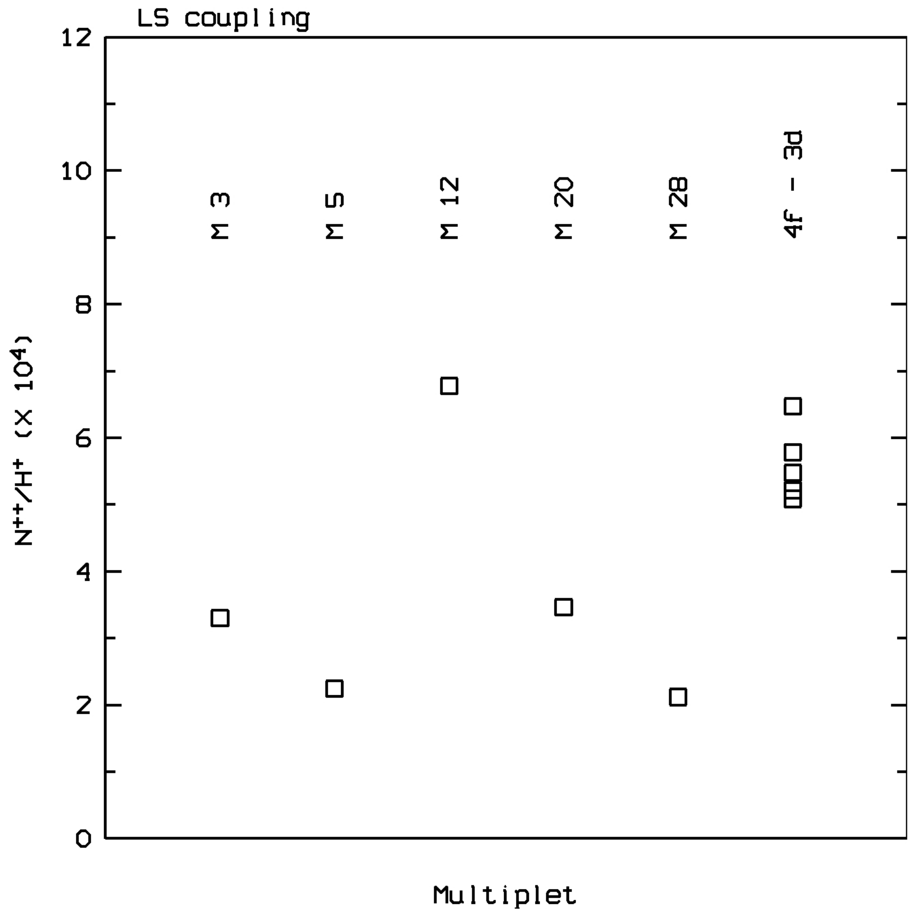
Summary of plasma diagnostics

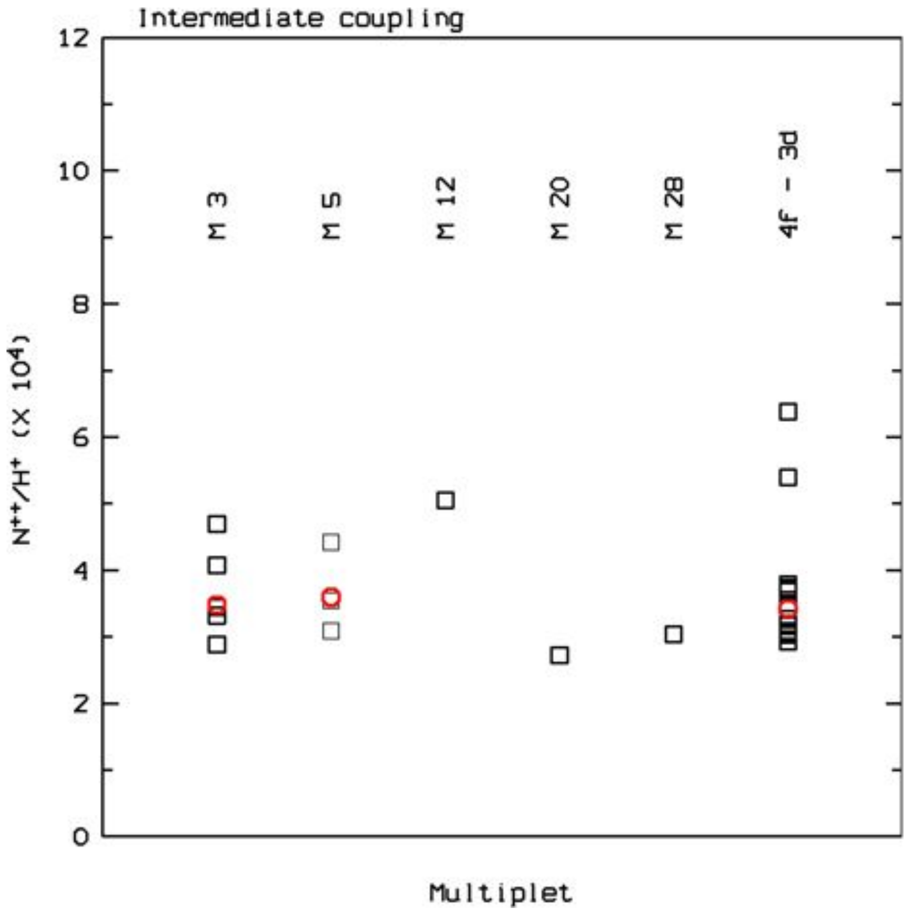
- T_e(CELs) ≈ 10^4 K
- T_e(H I Balmer jump) ≈ 6500 K
- T_e(He I λ7281/λ6678) ≈ 5100 K
- T_e(N II λ5679/λ4041) ≈ 1200 K
- T_e(O II λ4649/λ4089) ≈ 1400 K
- T_e(CELs) ≥ T_e(H I) ≥ T_e(He I) ≥ T_e(N II, O II ORLs)
- T_e(N II ORLs) ~ T_e(O II ORLs)
- N II and O II ORLs are emitted from the low-T_e area

Ionic abundances from ORLs

- N^{2+}/H^{+}

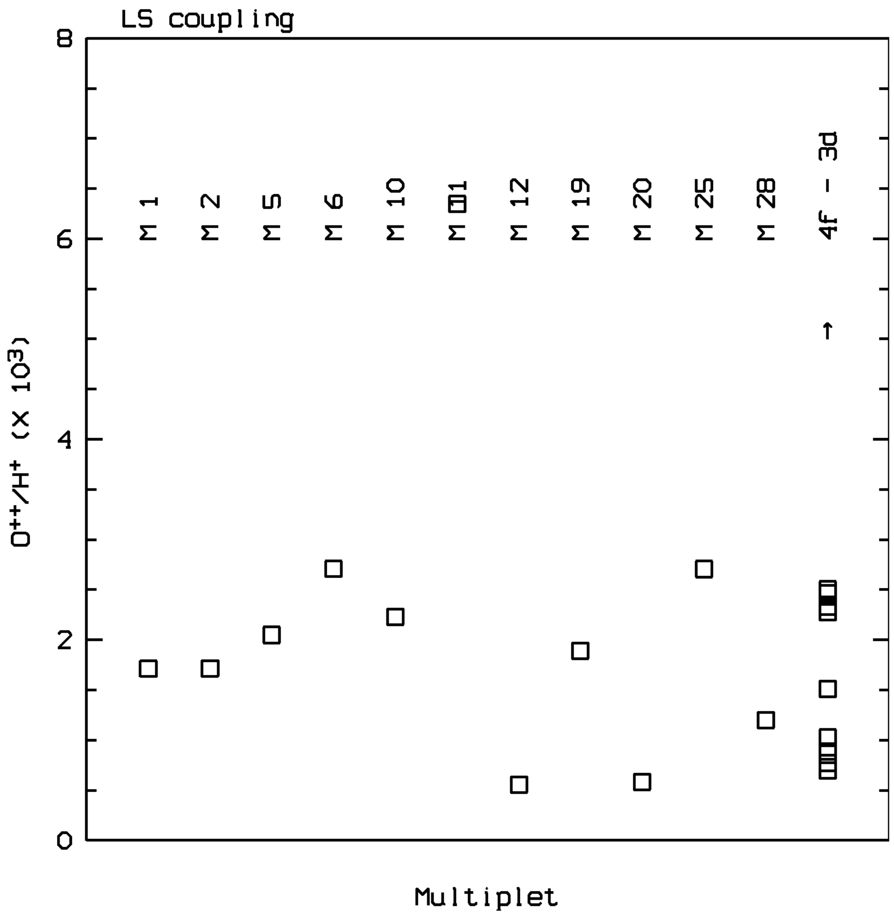
$$\frac{X^{+i+1}}{H^{+}} = \frac{\alpha_{eff}(H\beta)}{\alpha_{eff}(\lambda)} \frac{\lambda}{4861} \frac{I(\lambda)}{I(H\beta)}$$

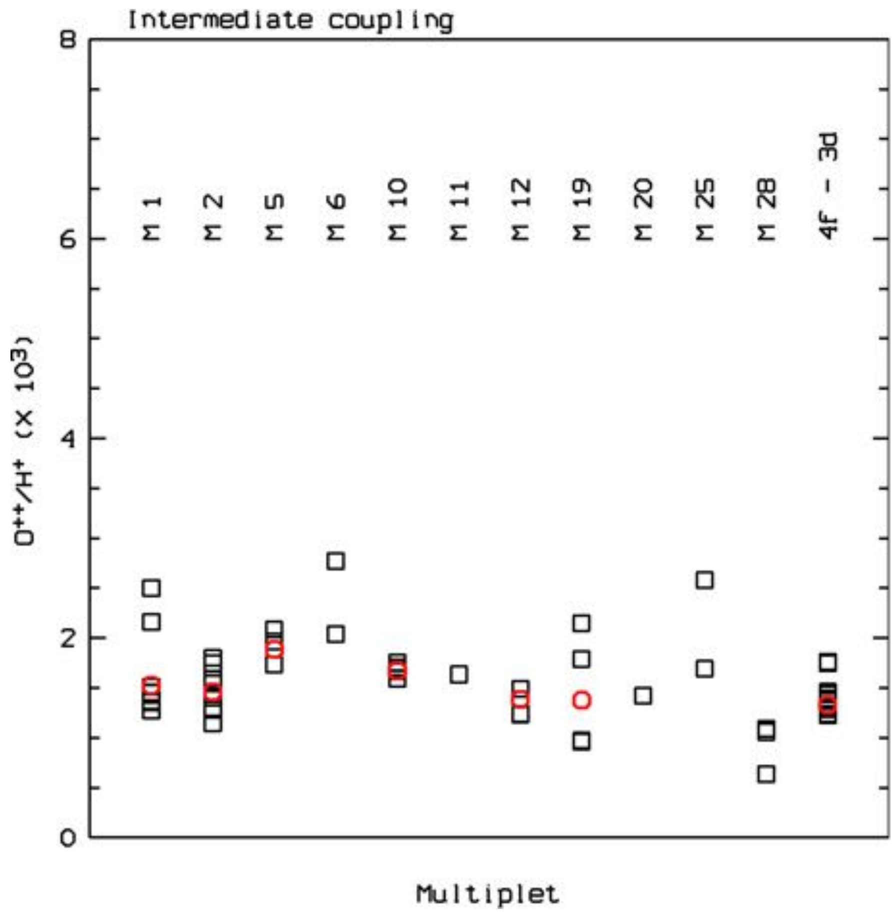




Ionic abundances from ORLs

- O^{2+}/H^{+}





Ionic abundances from ORLs

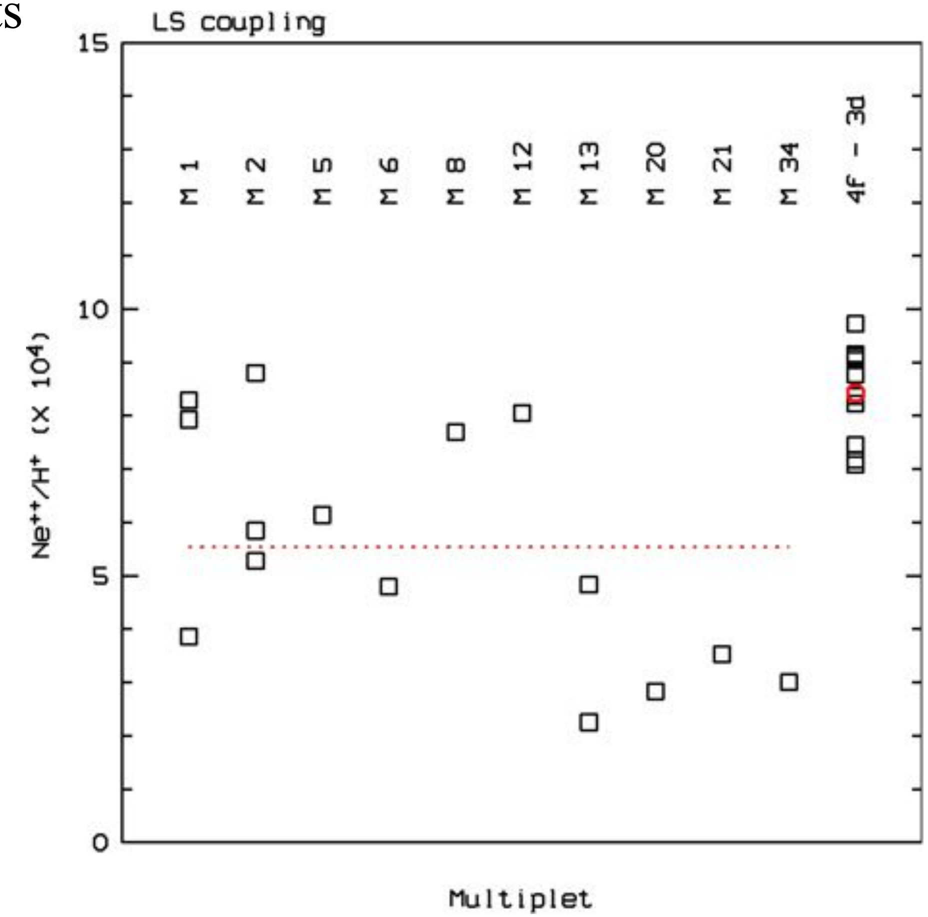
- Ne^{2+}/H^{+}
  - 3 - 3: Kisielius et al. (1998)
  - 4f - 3d: the preliminary results of Storey (unpublished)

Red dotted line: The average abundance from the 3–3 transitions.

Red circle: The average abundance from the 4f–3d transitions

$\langle Ne^{2+}/H^{+}\rangle_{3-3}$ is 0.21 dex lower than $\langle Ne^{2+}/H^{+}\rangle_{4f-3d}$.

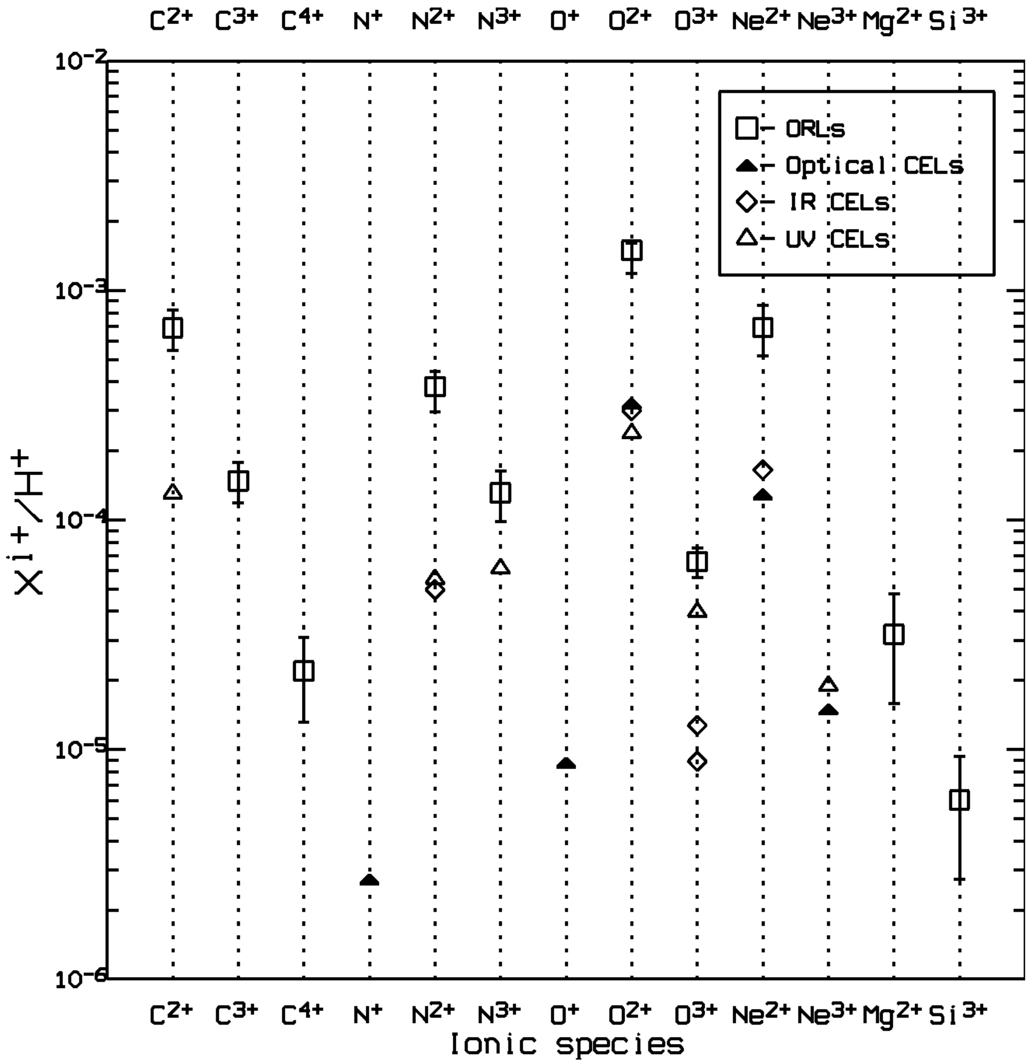
New calculations of the Ne II effective effective recombination coefficients are needed!



Comparison of ionic abundances

CELs v.s. ORLs

- Ionic abundances of heavy elements
  - adf(C^{2+}, N^{2+}, O^{2+}, Ne^{2+}) ~ 5
  - log(O/H)+12 = 8.65 +/- 0.08
  - IR and UV data are from the literatures



Summary

- New effective recombination coefficients for the N II and O II recombination spectra
  - Laying the fundation for plasma diagnostics based on heavy element ORLs in nebulae
- Very deep spectroscopy of NGC7009
  - Very rich ORLs of heavy element ions
  - Plasma diagnostics confirm the bi-abundance model:
    T_e(CELs) ≥ T_e(H I) ≥ T_e(He I) ≥ T_e(N II, O II ORLs)
  - The N II and O II ORLs yield almost the same T_e : Heavy element ORLs originate from cold regions
  - The new effective recombiantion coefficients of N II and O II are reliable
  - New calculations for Ne II are underway

Thank you!