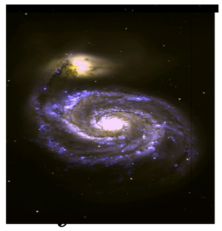

"PHOTOIONIZATION AND RECOMBINATION OF Ne IV AND EXCITATION OF NeV IN NEBULAR PLASMAS"

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Observation of Ne V lines: Orion Nebula - Birthplace of Stars

[Composed by images from Spitzer & Hubble]

• ∼ 1500 Lyr away, closest cosmic cloud to us
• Center bright & yellow gas - illuminated ultraviolet (UV) radiation
Images: Spitzer - Infrared (red & orange) C rich molecules - hydrocarbons, Hubble - optical & UV (swirl green) of H, S
• Small dots - infant stars; over 1000 young stars
• Shows low ionization lines of C, N, O, Ne, Fe

Observation of Ne V Lines:

PLANETARY NEBULAE - Endpoint of a Star

PNe: Final stage of a Star [PNe K 4-55 below]

- **Condensed central star: very high T $\sim$ 100,000 K (>> T $\leq$ 40,000 K - typical star)**
- **Envelope: thin gas radiatively ejected & illuminated by central star radiation: red (N), blue (O)**
- **Lines of low ionization states - low ρ & low T**
- **Their chemical enrichment is therefore a chronometer of the life of the universe itself.**

Ultra Luminus Infrared Galaxy (ULIRG)

ULIRG: IRAS-19297-0406

- **ULIRG - emits more than 10^{11} solar luminosities in IR (as stars are born), heavily dust obscured**
- **Only far-infrared photons escape from absorption and are observed at high redshift (by SPITZER, HERSCHEL, SOFIA) which provides information on chemical evolution of the galaxy.**

ELECTRON-IMPACT EXCITATION (EIE)

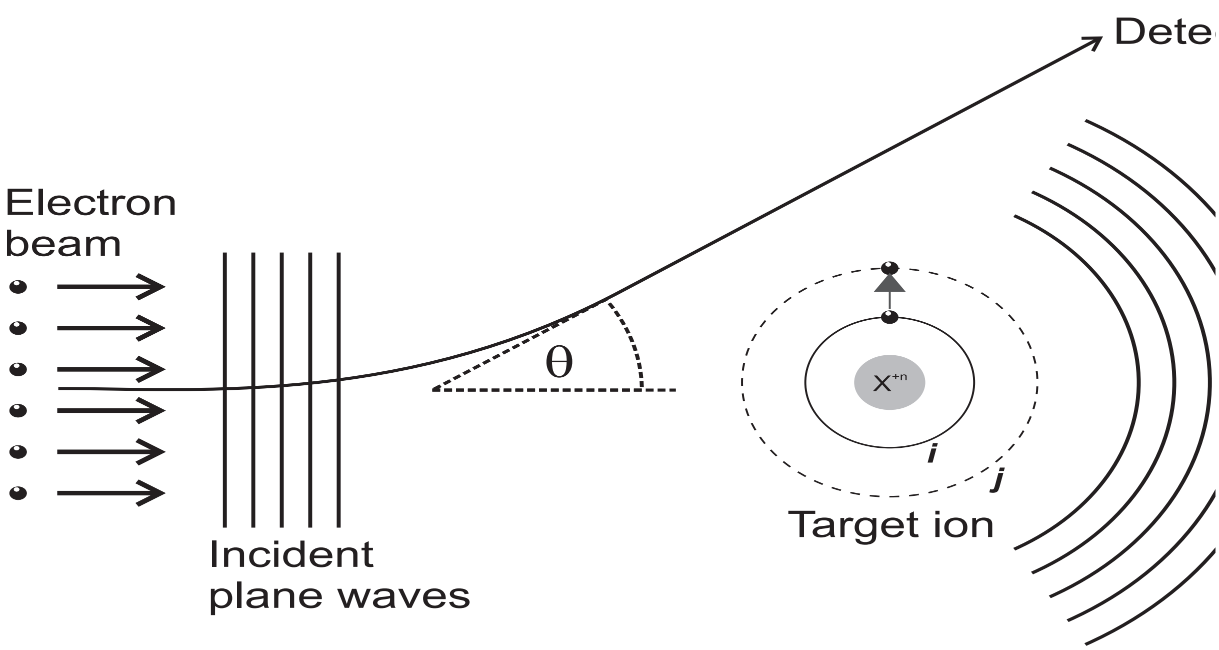
The most common source of these radiation is collsion:

$$\mathbf{e} + \mathbf{X}^{+\mathbf{Z}} \rightarrow \mathbf{e}' + \mathbf{X}^{+\mathbf{Z}*} \rightarrow \mathbf{e}' + \mathbf{X}^{+\mathbf{Z}} + \mathbf{h}\nu$$

ii) Via Autoionization (AI) (2-steps):

$$\epsilon + \mathbf{X}^{+\mathbf{Z}} \rightleftharpoons (\mathbf{X}^{+\mathbf{Z}-\mathbf{1}})^{**} \rightleftharpoons \begin{cases} \epsilon + \mathbf{X}^{+\mathbf{Z}} & \text{AI} \\ X^{+Z-1} + h\nu & \text{DR} \end{cases}$$

AI state $[(\mathbf{X}^{+\mathbf{Z}-\mathbf{1}})^{**}]$ $(10^{14}/s)$ results in a resonance



- **- A photon emits as the excitation decays**

- forms a diagnostic, often forbidden, emission line

- the scattered electron shows features with energy

- **Atomic quantity:** ***Collision Strength (Ω)***
- **Common in low T, low ρ astrophysical plasmas, such as, in Orion Nebula, Planetary Nebulae (PNe)**

PHOTOIONIZATION & ELECTRON-ION RECOMBINATION

i) Direct Photoionization (PI) (1-step):

$$\mathbf{X^{+Z} + h\nu \leftrightarrow X^{+Z+1} + \epsilon}$$

Inverse: Radiative Recombination (RR)

ii) Via Autoionization (AI) (2-steps):

$$\epsilon + \mathbf{X^{+Z}} \rightleftharpoons (\mathbf{X^{+Z-1}})^{**} \rightleftharpoons \begin{cases} \epsilon + \mathbf{X^{+Z}} & \text{AI} \\ X^{+Z-1} + h\nu & \text{DR} \end{cases}$$

AI state $[(\mathbf{X^{+Z-1}})^{**}]$ results in a resonance
Inverse: Dielectronic Recombination (DR)

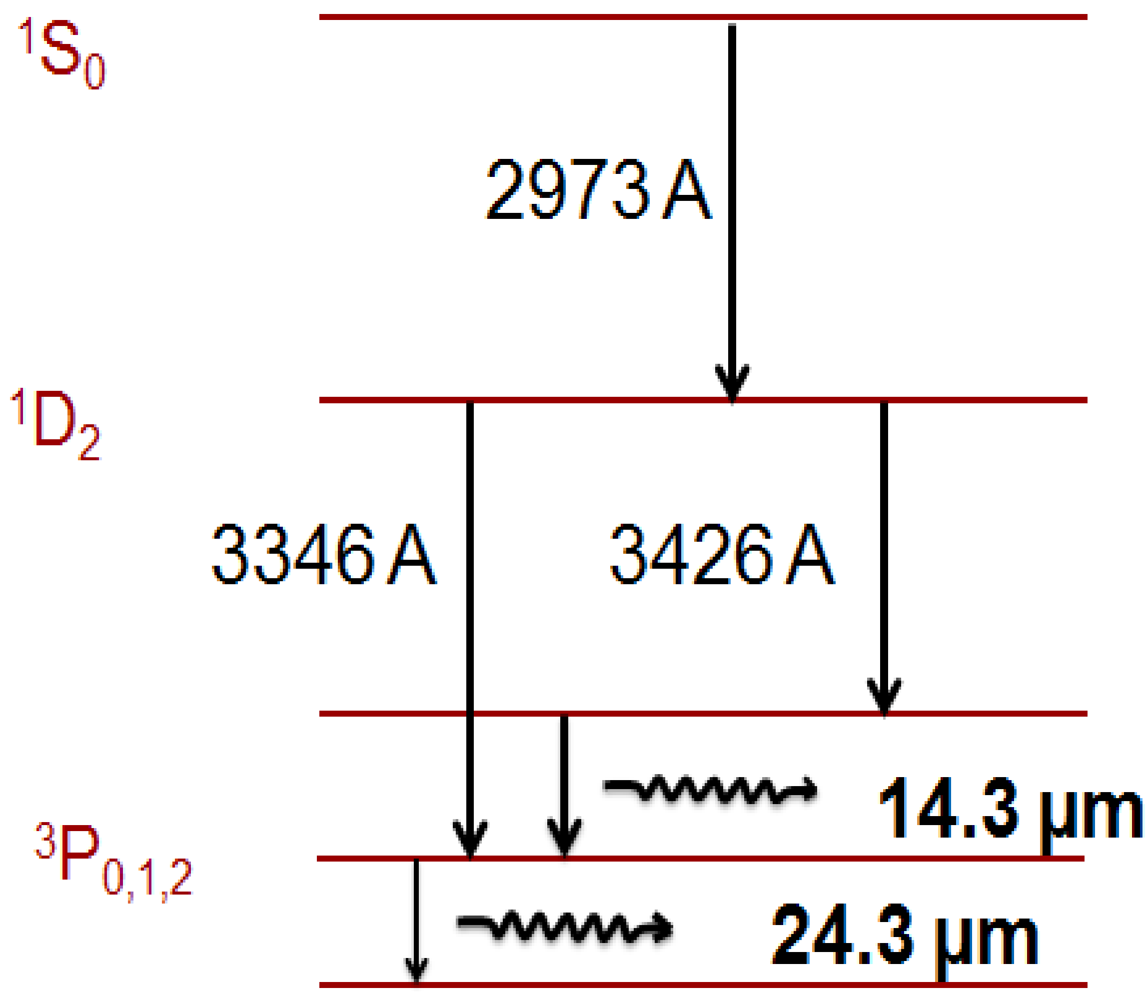
- **Spectral lines are produced by photoionization and by electron-ion recombination**

iv) PHOTO-EXCITATION:

$$\mathbf{X^{+Z} + h\nu \leftrightarrow X^{+Z*}}$$

EIE: Infrared Lines of Ne V

Ne V transitions (forbidden) in the lowest levels of ground configuration: $1s^2 2s^2 2p^2$ ($^3P_{0,1,2}, ^1D_2, ^1S_0$)



- **Collisionally Excited Lines (CEL):**

$$e + X^+ \rightarrow X^{+*} \rightarrow X^+ + h\nu$$

Determination of Abundance:

- **The intensity of a CEL of ion X_i**

$$\mathbf{I_{ba}(X_i, \lambda_{ba}) = \left[\frac{h\nu}{4\pi} n_e n_{ion}\right] q_{ba}} \qquad (1)$$

$\mathbf{q_{ba}}$ - EIE rate coeffcient in cm^3/sec.

The abundance, $\mathbf{n(X)/n(H)}$ with respect to H

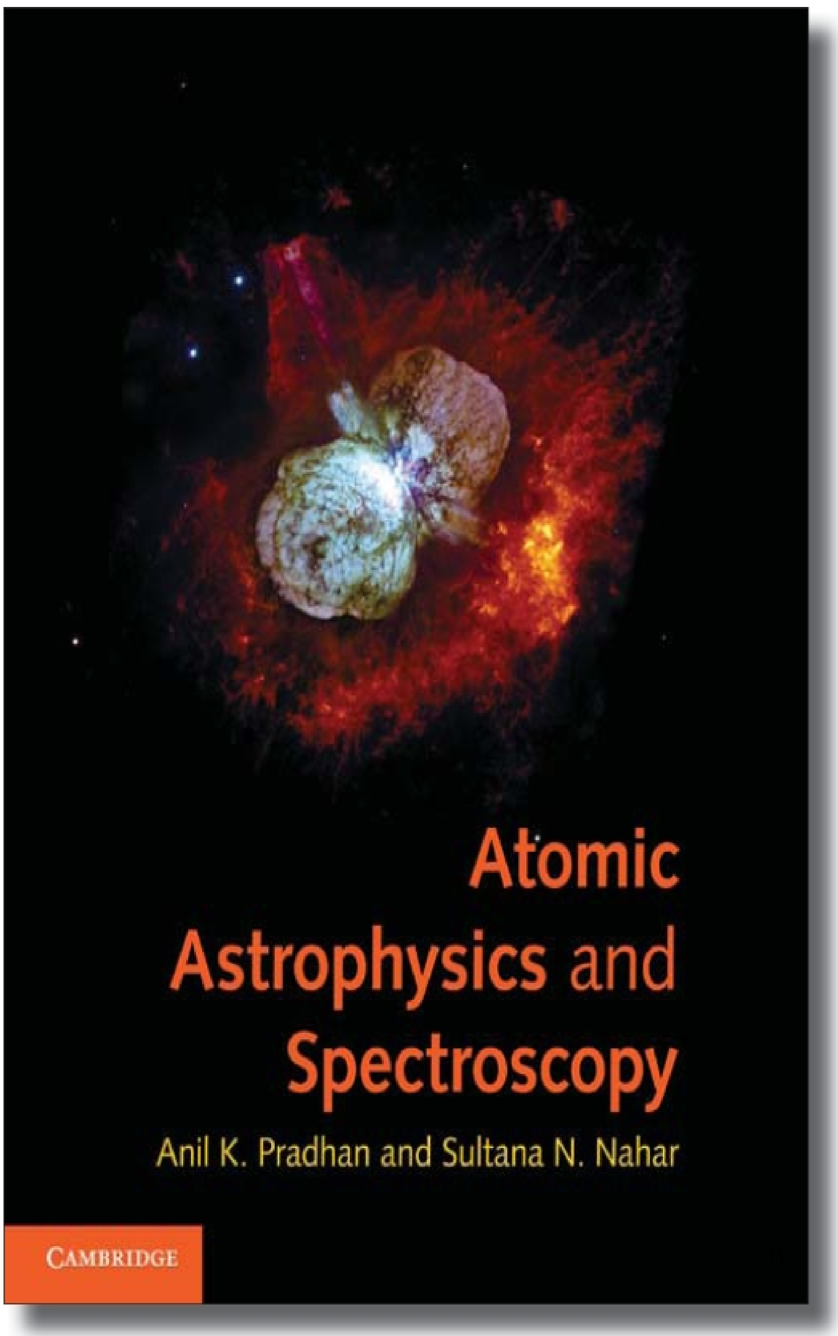
$$\mathbf{I(X_i, \lambda_{ba}) = \left[\frac{h\nu}{4\pi} A_{ba} \frac{N(b)}{\Sigma_j N_j(X_i)} \frac{n(X_i)}{n(X)}\right] \left[\frac{n(X)}{n(H)}\right] n(H)}$$

- **Similarly abundance can obtained from emissivity intensity of a REL:**

$$\epsilon(\lambda_{\mathbf{pj}}) = \left[\mathbf{N_e N(X^+) h\nu_{pj}}\right] \alpha_{\mathbf{eff}}(\lambda_{\mathbf{pj}}) [\mathrm{arg\ cm^{-1} s^{-1}}]$$

THEORY:
Breit-Pauli R-matrix (BPRM) Method

Atomic processes & Theory: Explained in, e.g.
"Atomic Astrophysics and Spectroscopy"
(Pradhan and Nahar, Cambridge U press, 2011)



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Close-Coupling Approximation for Wave Function

Wave Function: Expansion with excited core states

$$\Psi_E(e+ion) = A\sum_{i}^{N}\chi_i(ion)\theta_i + \sum_j c_j\Phi_j(e+ion)$$

- Resonant Structures - via channel couplings
- Ψ_E(Ne IV): Levels and energies (E_t) of Ne V

	Level	J_t	E_t(Ry)(NIST)	E_t(Ry)(SS)
1	$1s^22s^22p^2(^3P)$	0	0.0	0.
2	$1s^22s^22p^2(^3P)$	1	0.003758	0.0030391
3	$1s^22s^22p^2(^3P)$	2	0.010116	0.011366
4	$1s^22s^22p^2(^1D)$	2	0.276036	0.30391
5	$1s^22s^22p^2(^1S)$	2	0.582424	0.57413
6	$1s^22s2p^3(^5S^o)$	2	0.8052	0.71604
7	$1s^22s2p^3(^3D^o)$	3	1.60232	1.62957
8	$1s^22s2p^3(^3D^o)$	2	1.60296	1.62932
9	$1s^22s2p^3(^3D^o)$	1	1.60316	1.62929
10	$1s^22s2p^3(^3P^o)$	2	1.89687	1.92363
11	$1s^22s2p^3(^3P^o)$	1	1.89687	1.92340
12	$1s^22s2p^3(^3P^o)$	0	1.89719	1.92328
13	$1s^22s2p^3(^1D^o)$	2	2.46556	2.59326
14	$1s^22s2p^3(^3S^o)$	1	2.54576	2.64956
15	$1s^22s2p^3(^1P^o)$	1	2.76854	2.88988
16	$1s^22p^4(^3P)$	2	3.76063	3.86076
17	$1s^22p^4(^3P)$	1	3.76778	3.86807
18	$1s^22p^4(^3P)$	0	3.77085	3.87155
19	$1s^22p^4(^1D)$	2		4.13816
20	$1s^22p^4(^1S)$	0		4.74472

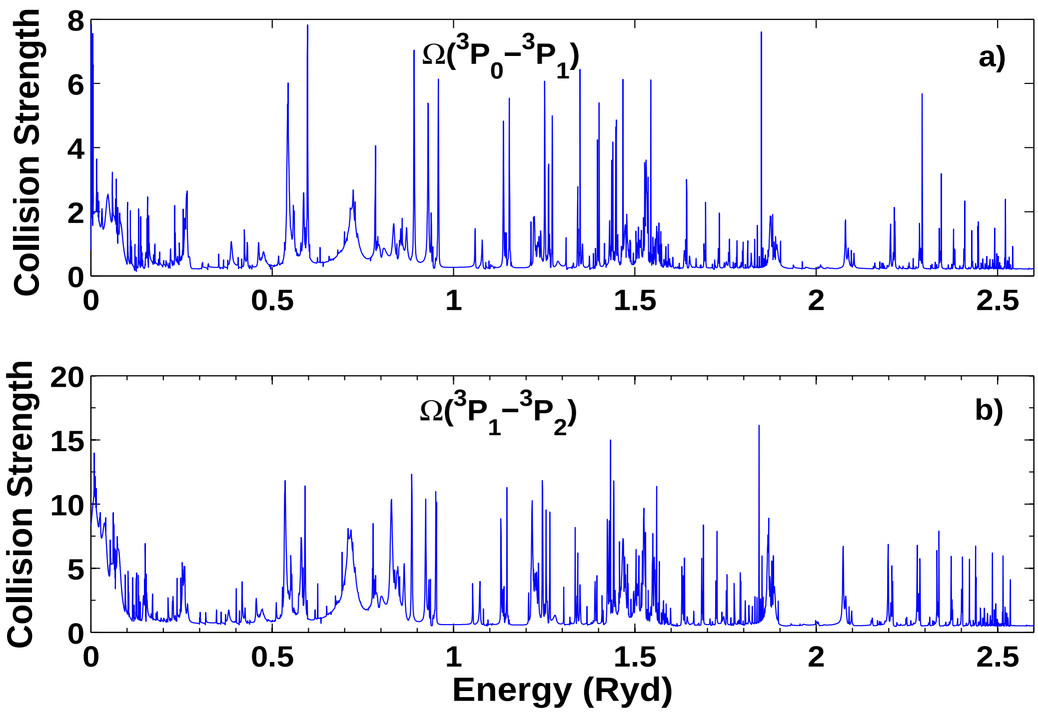
ELECTRON IMPACT EXCITATIONS (EIE)

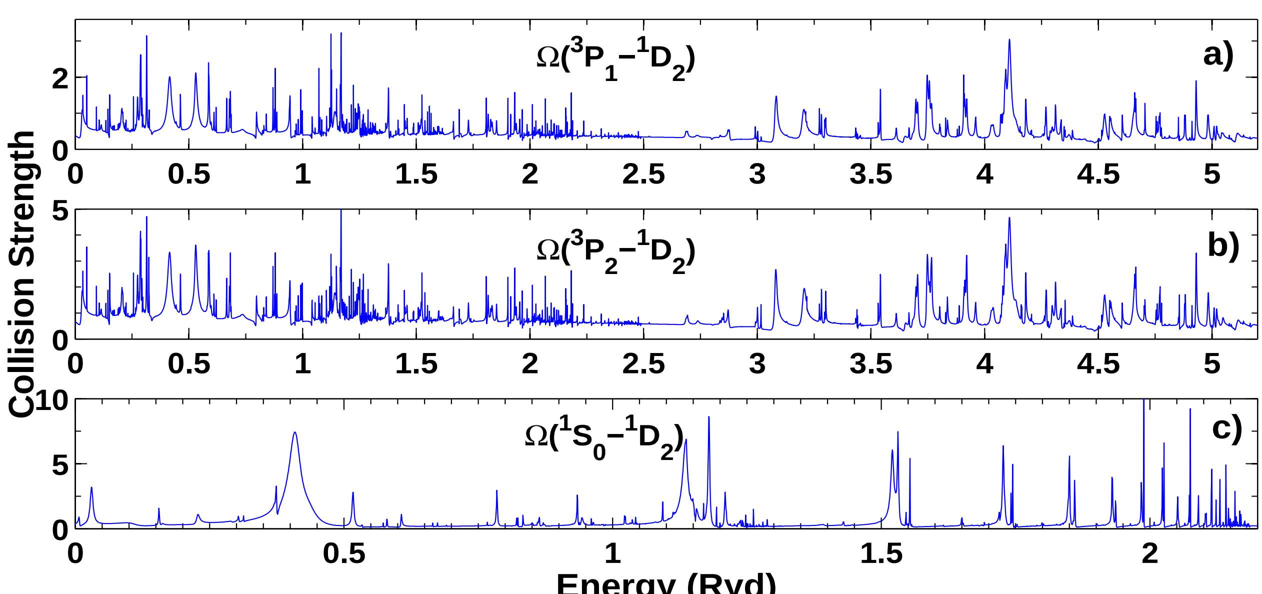
Ne V Collision strengths **Ω(EIE)** (Dance et al, submitted):

Top: Forbidden IR transitions $2p^2(^3P_0 - ^3P_1)$ (24μm) and $2p^2(^3P_1 - ^3P_2)$ (14μm),

Bottom: Forbidden optical transitions $2p^2(^3P_1 - ^1D_2)$ (3346Å), $2p^2(^3P_2 - ^1D_2)$ (3426Å), and $2p^2(^1S_0 - ^1D_2)$ (2973Å)

- Resonances at near threshold energy seen for the first time

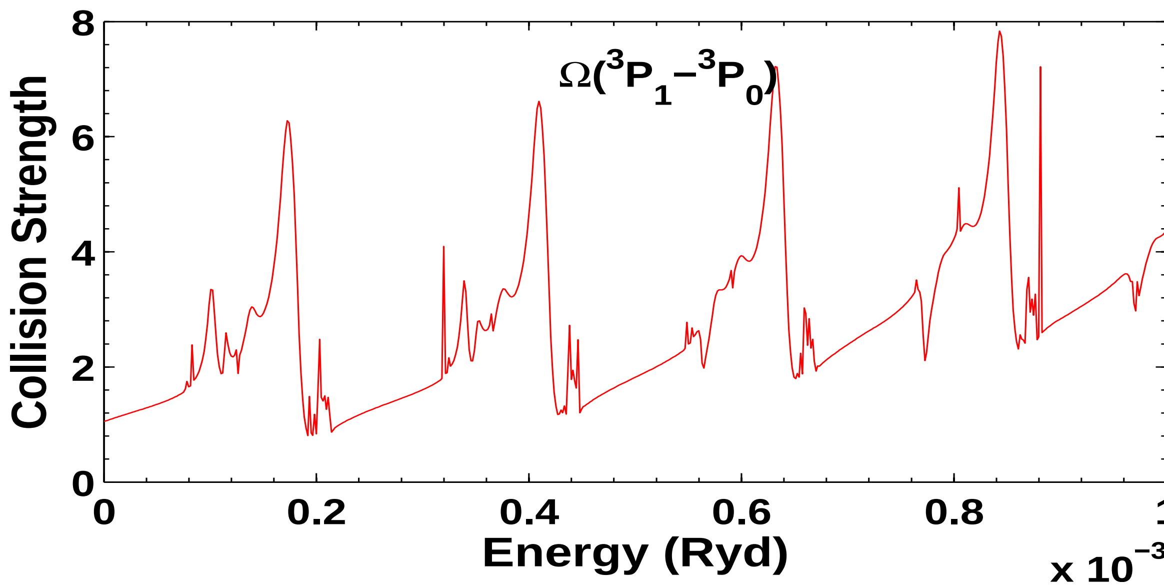




RYDBERG SERIES OF RESONANCES IN EIE

Ne V Collision strengths Ω(EIE) (Dance et al, submitted):

- **Rydberg series of resonances in the near-threshold $\Omega(EIE)$ for 2p^2($^3P_0 - ^3P_1$) of 24 μm FIR line. Fully resolved at a fine energy mesh of 10^{-6} Ryd**
- **Resonant features not seen before**

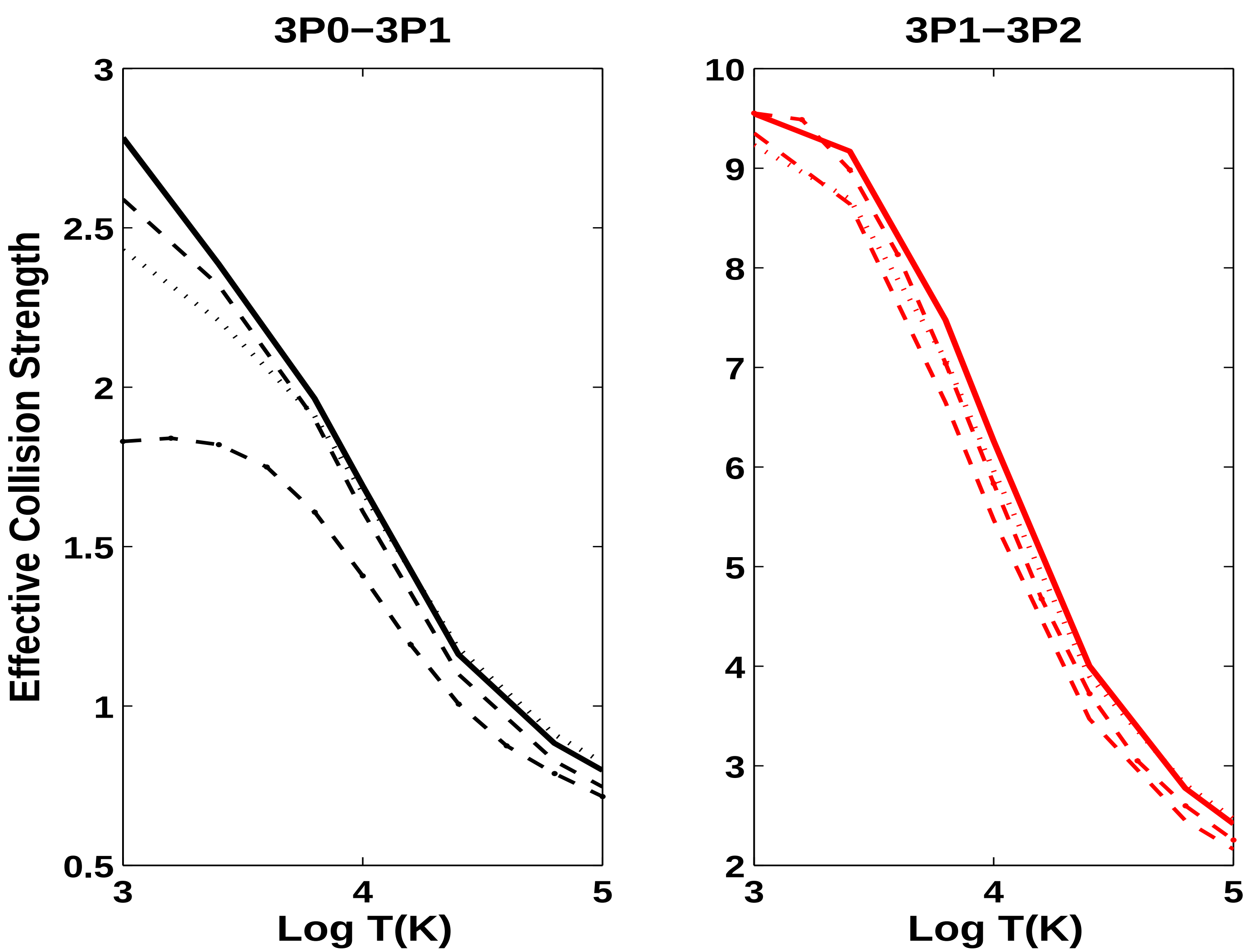


EFFECTIVE COLLISION STRENGTHS: Ne V

Comparison: **Effective collision strengths $\Upsilon(T_e)$ (EIE) :**

IR: $2p^2(^3P_0 - ^3P_1)$ ($24\mu m$), $2p^2(^3P_1 - ^3P_2)$ ($14\mu m$)

- **Solid curves (present), dotted curves (non-relativistic, Lennon & Burke 1994); dash-dot & dashed curves (BPRM and ICFT, Griffin & Badnell 2000), available at $T_e > 1000$ K**
- **Present enhancements (IR, 20%, 10%) are due to high resolution resonances at near threshold energy**

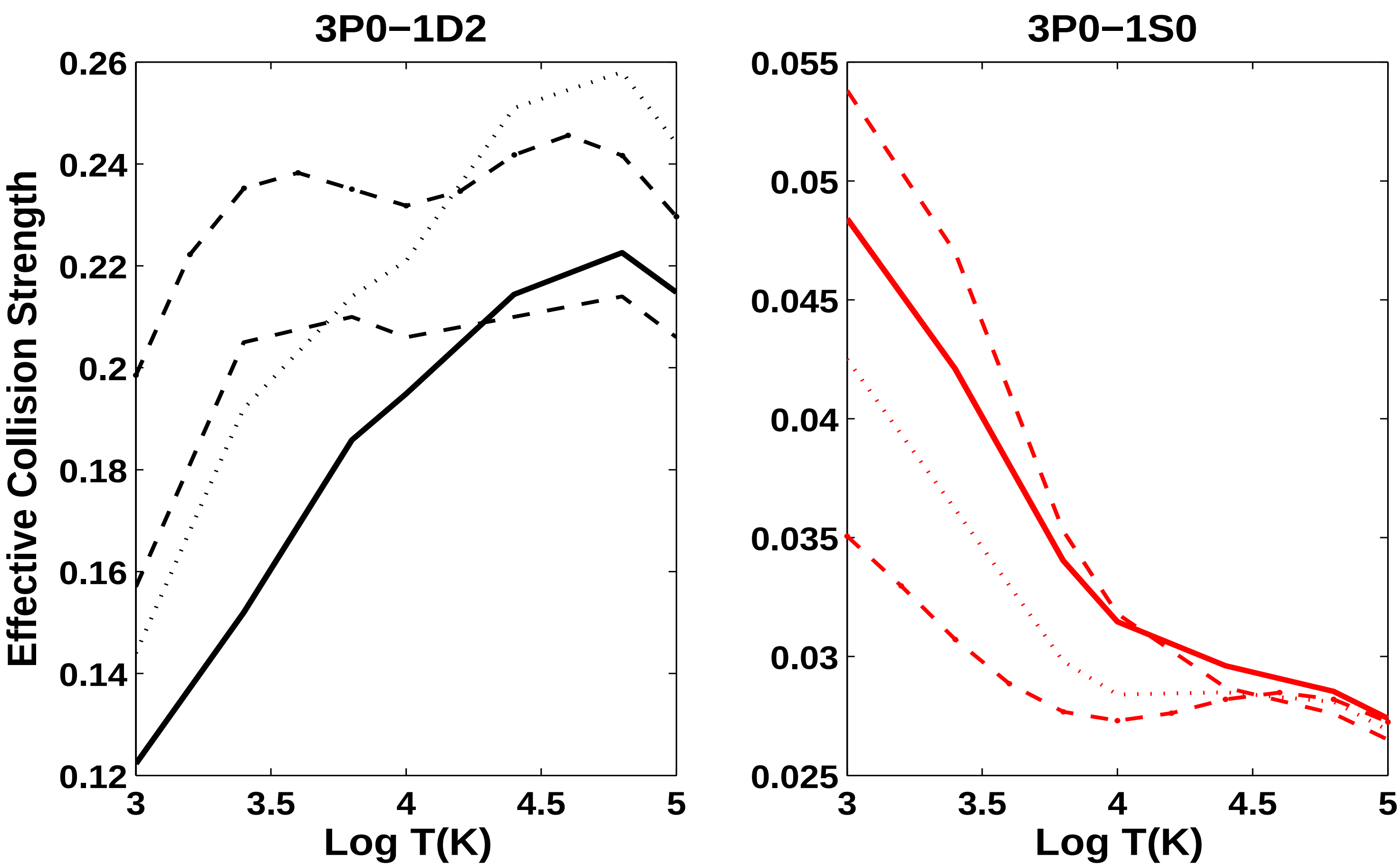


EFFECTIVE COLLISION STRENGTHS: Ne V

Comparison: Effective collision strengths $\Upsilon(T_e)$:

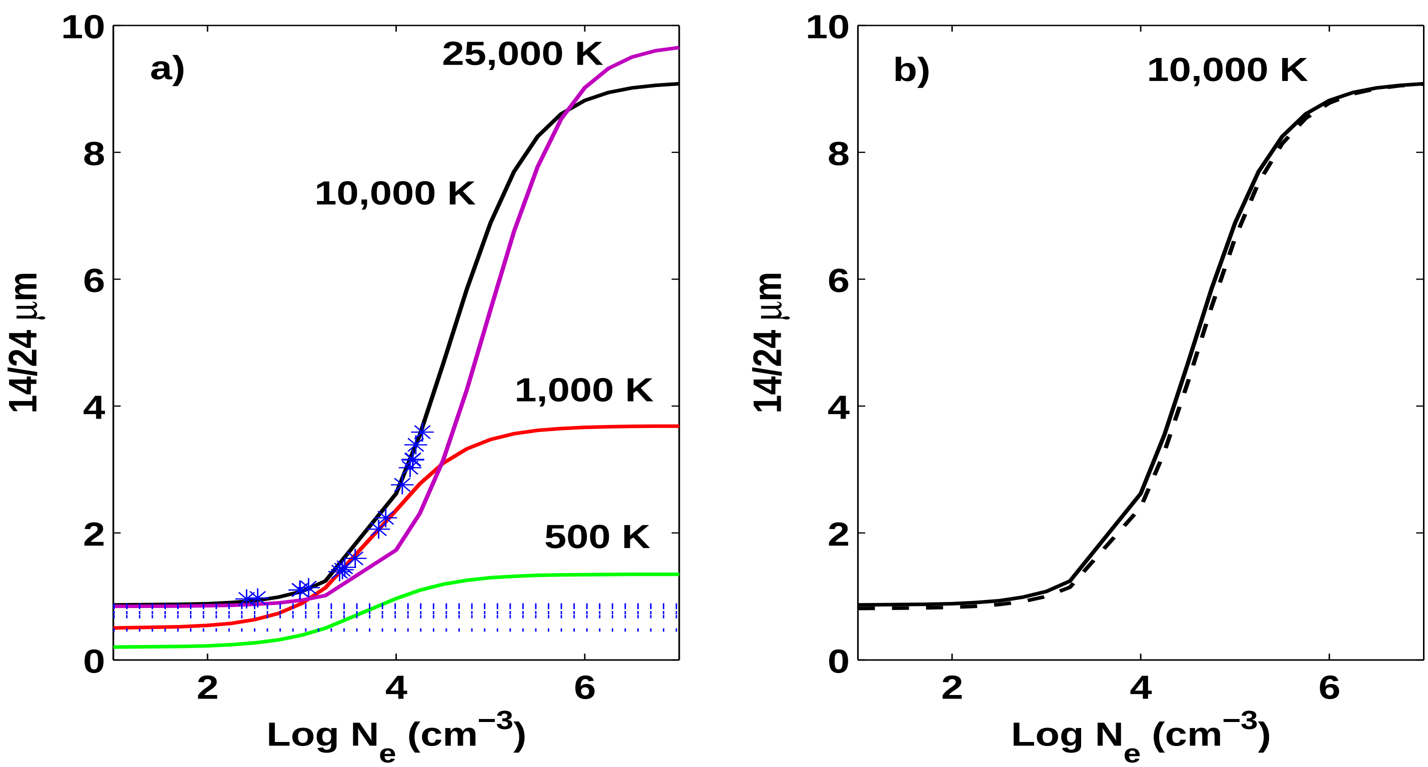
O: $2p^2(^3P_0 -^1 D_2)$ (3301Å), $2p^2(^3P_0 -^1 S_0)$ (1560Å)

- Solid curves (present), dotted curves (non-relativistic, Lennon & Burke 1994); dash-dot & dashed curves (BPRM and ICFT, Griffin & Badnell 2000), available at $T_e > 1000$ K



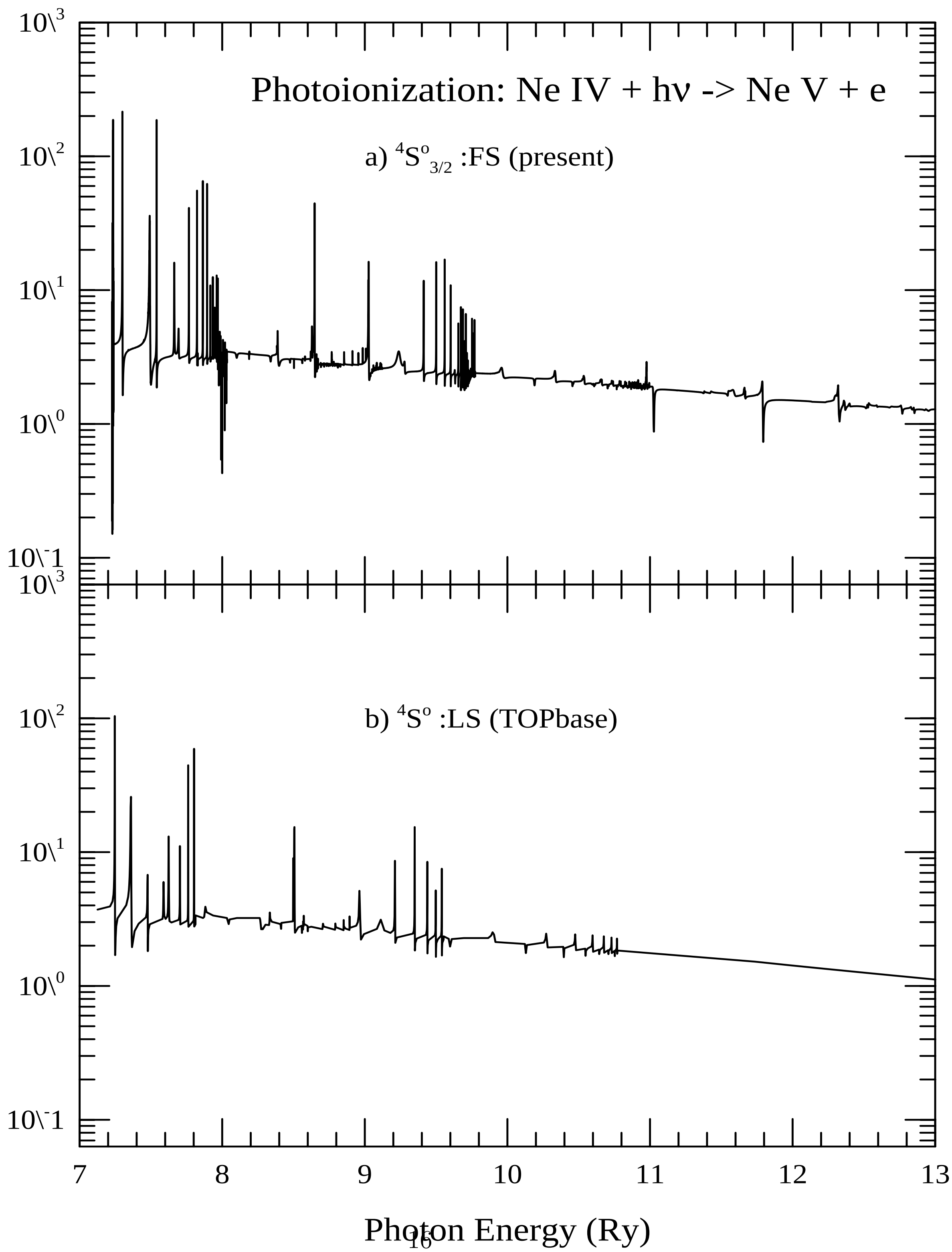
Ne V LINE RATIOS: NEBULAR ρ & T DIAGNOSTICS

- **Comparison:** IR 14/24 μm line emissivity ratios: a) Solid curves (present) at different T, Asterisks (observed from PNe at T = 10,000 K with assigned densities, Rubin 2004), Dotted curves (observed line ratios, outside typical nebular T-ρ range except at low T, Rubin 2004), b) Solid (present), dash (collision stengths, Lennon & Burke 1994)
- Better agreement with observed emissivity ratios at T = 10,000 (10 PNe) and 500 K (anomalously low, 11 PNe)
- Closer agreement due to *systematic* differences in rate coefficients.



COMPARISON OF PHOTOIONIZATION CROSS SECTION (σ_{PI}) OF GROUND STATE OF Ne IV:

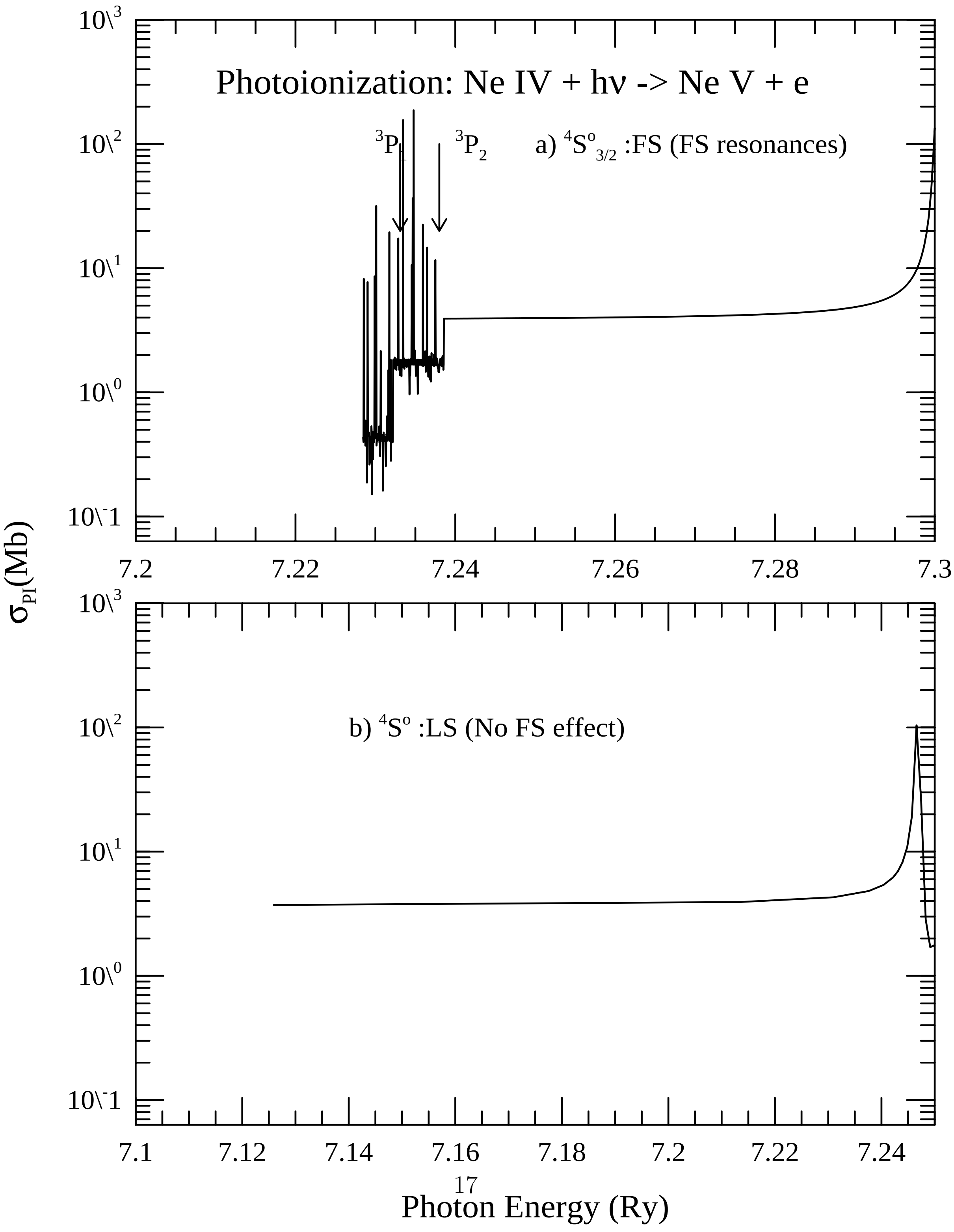
- **Top: Present BPRM, Bottom: LS coupling (TOPbase)**
- **Similar except additional weak resonances in BPRM**



COMPARISON OF NEAR THRESHOLD PHOTOIONIZATION OF Ne IV:

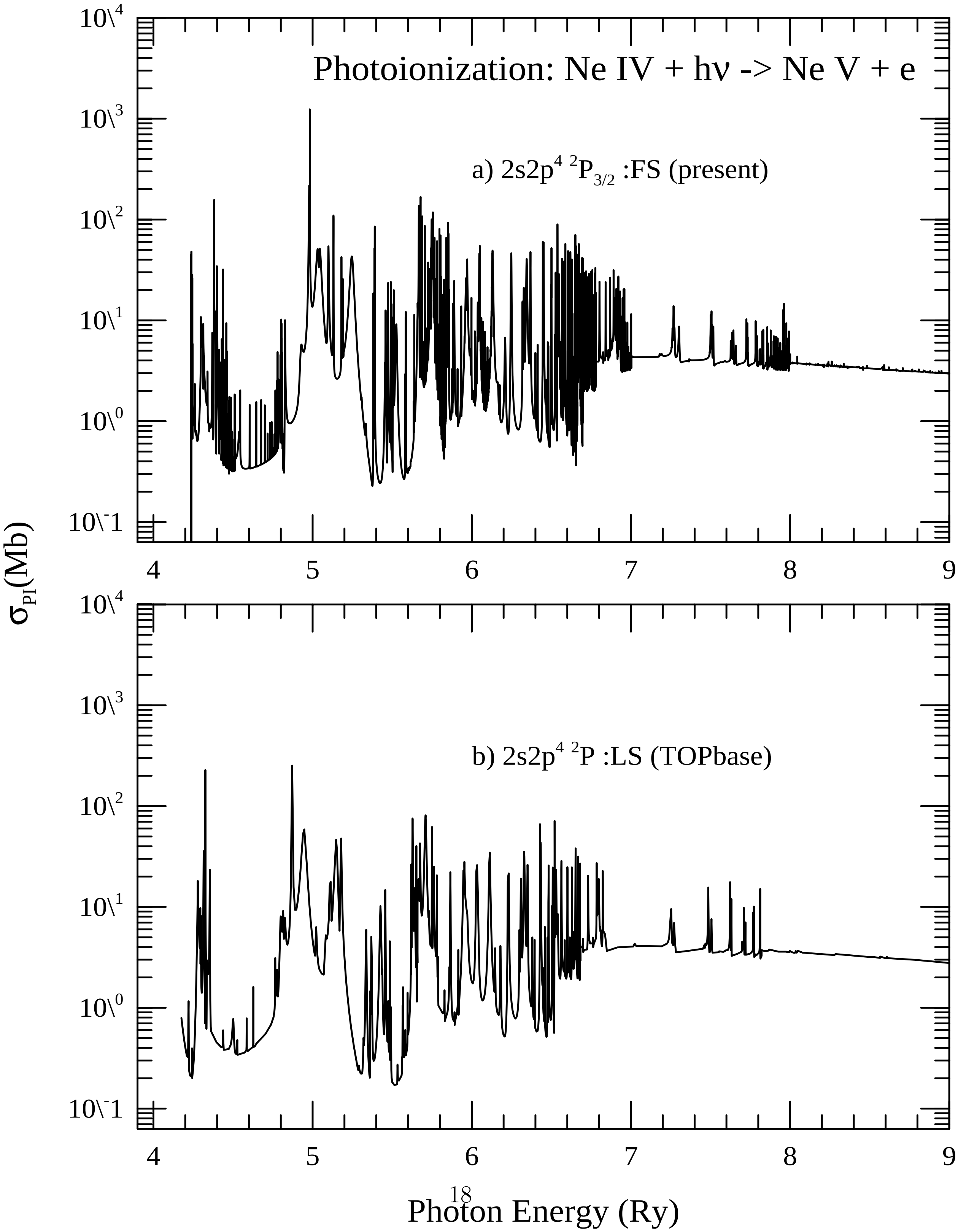
- **Top: Present BPRM, nearthreshold resonances are due to fine structure coupling.**

Bottom: They are not allowed in LS coupling (TOPbase)



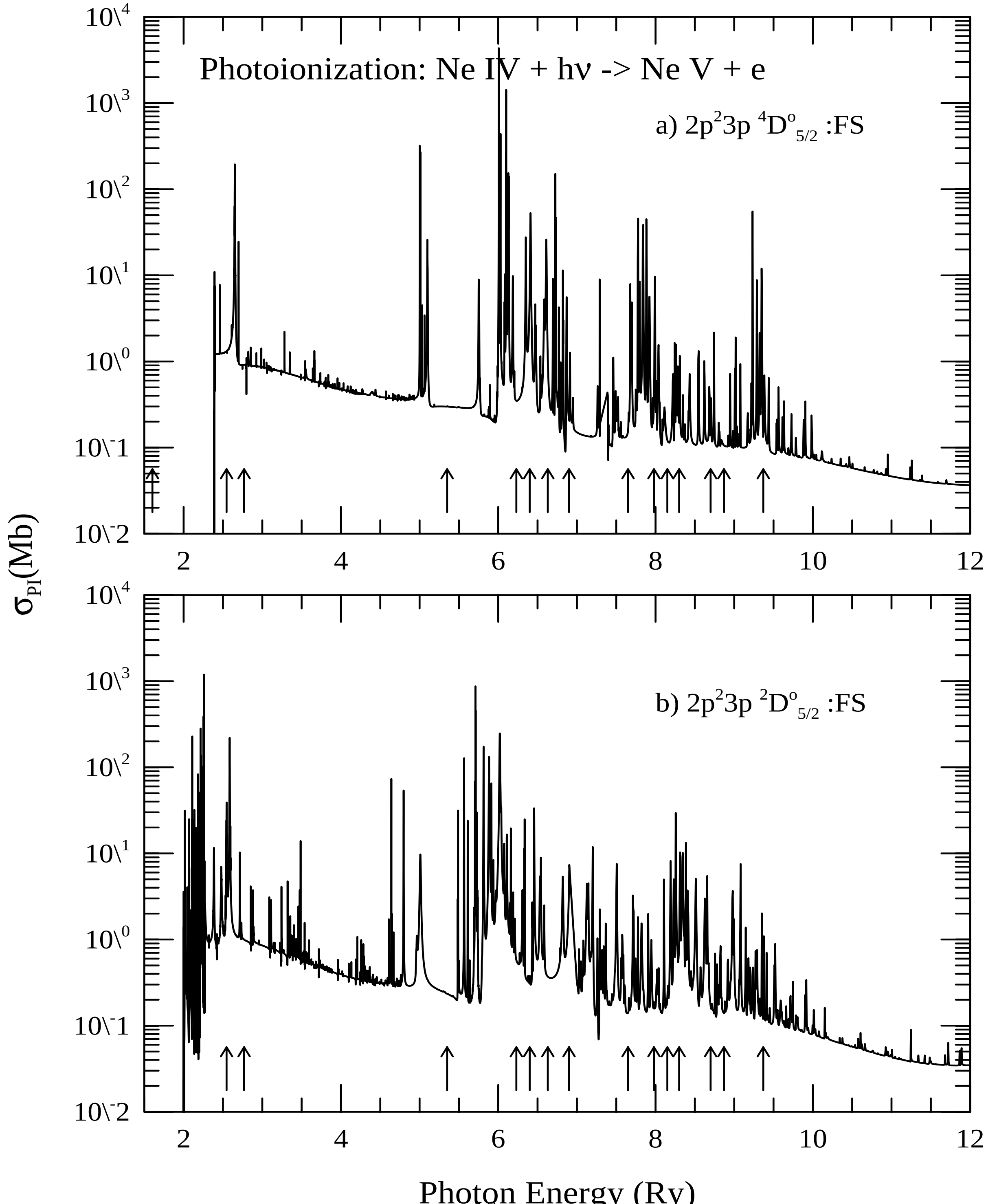
COMPARISON OF PHOTOIONIZATION (σ_{PI}) OF Ne IV: EXCITED STATES

- Top: Present BPRM, Bottom: LS coupling (TOPbase)
- Similar except in near threshold energy



SEATON RESONANCES IN PHOTOIONIZATION OF EXCITED LEVELES OF Ne IV:

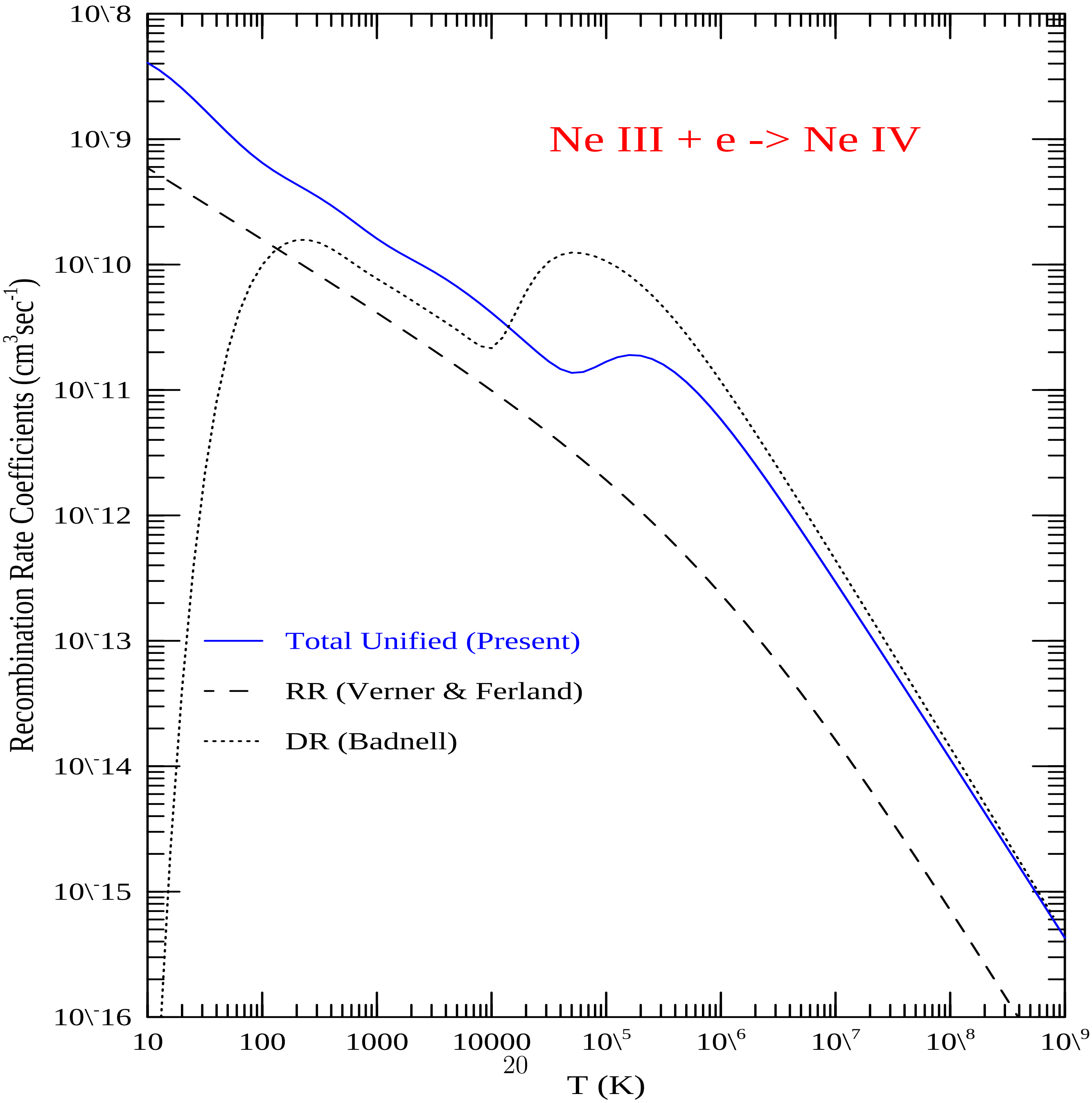
- **Seaton PEC (Photo- Excitation-of-Core) resonances appear (pointed by allows) in photoionization of excited single valence electron levels**
- **Strong and enhance the background cross section**
- **Will affect photoionization and recombination rates**



RECOMBINATION RATE COEFFICIENT OF Ne IV:

- Total unified recombination rate coefficient α_{RC} (blue)
- RR coefficient (dashed), • DR coefficient (dotted)
- i) Seaton resonances has enhanced the very low T α_{RC}, ii) low T bump is indicated both in total unified and in DR coefficient using IRA (Badnell), iii) Total high-T bump using relativistic effects is much lower than that from IRA and the peak positions are also shifted
- Will be investigated for the differences

Total Recombination Rate Coefficients Ne IV



CONCLUSION

1. **We present collision strength and line ratios of forbidden optical and far-infrared transitions in Ne V in nebular temperature and density diagnostics:**
2. **Find prominent resonant features due to fine structure effects in low energy collision cross section not studied before**
3. **New features indicate better agreement with observation, and hence should improve Ne abundance calculations**
4. **Photoionization: Threshold resonances due to fine structure effect, not allowed in LS coupling**
5. **Extensive Seaton resonances over a large energy range**
6. **Enhanced low T recombination and lower high-T peak**