"Abundances of Elements in Nebulae and Chemical Evolution of the Universe"

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APS April Meeting 2013
Denver, Colorado
April 13-16, 2013
*Support: DOE, NSF, Ohio Supercomputer Center
INTRODUCTION

• I will discuss about infrared to optical photons from ionized gaseous nebulae
• These nebulae are associated with the birth of stars and the end point of stellar evolution
• Their elemental abundances, chemical enrichment are therefore related to chronometer of the life of the universe itself
• Radiation from Ultra-Luminous infrared galaxy (ULIRG) gives the information of the chemical evolution of the universe
• Will present study of Ne V lines as detected from these objects
Abundance of Elements 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
Abundance of Elements

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 $\rho$ & low $T$
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 collision:

\[ e + X^{+Z} \rightarrow e' + X^{+Z*} \rightarrow e' + X^{+Z} + h\nu \]

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

\[ \epsilon + X^{+Z} \leftrightarrow (X^{+Z-1})^{**} \leftrightarrow \begin{cases} \epsilon + X^{+Z} & \text{AI} \\ X^{+Z-1} + h\nu & \text{DR} \end{cases} \]

AI state \[ (X^{+Z-1})^{**} \] \[ (10^{14}/s) \] 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: \( \text{Collision Strength (}\Omega\text{)} \)
- Common in low T, low \( \rho \) astrophysical plasmas, such as, in Orion Nebula, Planetary Nebulae (PNe)
EIE: Infrared Lines of Ne V

Ne V transitions (forbidden) in the lowest levels of ground configuration: $1s^22s^22p^2 \left( ^3P_{0,1,2}, ^1D_2, ^1S_0 \right)$

- Collisionally Excited Lines (CEL):
  $$e + X^+ \rightarrow X^{++} \rightarrow X^+ + h\nu$$
Determination of Abundance:

- The intensity of a CEL of ion $X_i$

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

$q_{ba}$ - EIE rate coefficient in cm$^3$/sec.

The abundance, $n(X)/n(H)$ with respect to H

$$I(X_i, \lambda_{ba}) = \left[ \frac{h \nu}{4 \pi} A_{ba} \sum_j N_j(X_i) \frac{n(X_i)}{n(X)} \right] \left[ \frac{n(X)}{n(H)} \right] n(H)$$
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THEORY:

Breit-Pauli R-matrix (BPRM) Method

Wave Function in Close-Coupling Approximation is an expansion with excited core states:

\[ \Psi_E(e + \text{ion}) = A \sum_i^N \chi_i(\text{ion})\theta_i + \sum_j c_j \Phi_j(e + \text{ion}) \]

\( \chi_i \rightarrow \) Target ion wavefunction, \( \Phi_j \rightarrow \) correlation functions
\( \theta_i \rightarrow \) interacting electron wavefunction (continuum or bound)

- Resonant Structures - manifested through channel couplings
- Table: Levels and energies ($E_t$) of Ne V in total wave function expansion
- Comparison of calculated energies with observed energies in NIST compilation

<table>
<thead>
<tr>
<th>Level</th>
<th>$J_t$</th>
<th>$E_t$(Ry) NIST</th>
<th>$E_t$(Ry) SS</th>
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<tr>
<td>1</td>
<td>1s$^2$2s$^2$2p$^2$(3P)</td>
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<td>0.0</td>
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<tr>
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<td>0.0030391</td>
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<tr>
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<tr>
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<tr>
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<td>0 4.74472</td>
<td></td>
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</tbody>
</table>
Total wave function is obtained solving:
\[ H\Psi = E\Psi \]

R-matrix method is used to solve the Schrodinger eq.

The scattering matrix \( S_{SL\pi}(i, j) \) is obtained from the wave function phase shift. The EIE collision strength is

\[ \Omega_{SL\pi} = \frac{1}{2}(2S + 1)(2L + 1)|S_{SL\pi}(i, j)|^2 \]

The effective collision strength \( \Upsilon(T) \) is the Maxwellian averaged collision strength:

\[ \Upsilon(T) = \int_0^\infty \Omega_{ij}(\epsilon_j)e^{-\epsilon_j/kT}d(\epsilon_j/kT) \quad (2) \]

The excitation rate coefficient \( q_{ij}(T) \) is

\[ q_{ij}(T) = \frac{8.63 \times 10^{-6}}{g_i T^{1/2}}e^{-E_{ij}/kT}\Upsilon(T) \text{ cm}^3\text{s}^{-1} \quad (3) \]
ELECTRON IMPACT EXCITATIONS (EIE)

Ne V Collision strengths $\Omega$(EIE) (Dance et al, submitted):

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

**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
Ne V Collision strengths $\Omega$(EIE) (Dance et al, submitted):

- Rydberg series of resonances in the near-threshold $\Omega(EIE)$ for $2p^{2}(^{3}P_{0} - ^{3}P_{1})$ of 24 $\mu$m 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 $\gamma(T_e)$ (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: $2p^2(3P^0 - 1D^2)$ (3301Å), $2p^2(3P^0 - 1S^0)$ (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 strengths, 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.
Ne V OPTICAL LINE RATIOS AT NEBULAR $\rho$ & T DIAGNOSTICS

- Comparison: Blended O line ratio $(3346+3426)/2973$ vs T at $n_e = 10^3$ cm$^{-3}$
- Closer agreement due to systematic differences in rate coefficients.
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. A precise delineation of these resonance structures has a significant effect on the mid-IR 14/24 μm line emissitivities

4. Forbidden optical collision strengths are generally in good agreement with previous works

5. New features indicate better agreement with observation, and hence should improve Ne abundance calculations