Classification of Emission-line Spectra: The Presentation

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CLASSIFICATION PARAMETERS FOR THE EMISSION-LINE SPECTRA OF EXTRAGALACTIC OBJECTS

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An investigation is made of the merits of various emission-line intensity ratios for classifying the spectra of extragalactic objects. It is shown empirically that several combinations of easily-measured lines can be used to separate objects into one of four categories according to the principal excitation mechanism: normal H II regions, planetary nebulae, objects photoionized by a power-law continuum, and objects excited by shock-wave heating. A two-dimensional quantitative classification scheme is suggested.

Key words: H II region—Seyfert galaxies—quasars—spectral classification
Significance of the paper

The achievement of the paper is the construction of a quantitative classification scheme for emission-line extragalactic objects. The foundation of the construction is built upon distinguishing the excitation mechanism of the line-emitting gas. The classification categories are:

- photoionization by main sequence O and B stars
  - H II regions
- photoionization by power-law continuum sources
  - Seyfert 1, Seyfert 2 and narrow-line radio galaxies
- shock-wave heating
  - LINERS (low-ionization nuclear emission-line region)
- extremely hot O stars
  - Planetary nebulae
Sections

I. Introduction

II. The Data Base

III. A Search for Useful Intensity Ratios

IV. Toward a Quantitative Classification Scheme

V. Discussion

VI. Summary
Objects of Interest

- Normal H II regions
- Planetary nebulae
- Objects photo ionized by power-law continuum
- Objects excited by shock-wave heating

(a) ESO 97-G13 from Hubble
(b) M87 in X-ray from Chandra

†hint: this is an ISM class
Emission-lines used for diagnostics

Transition lines

<table>
<thead>
<tr>
<th>[O II] 3727</th>
<th>[O I] 6300</th>
<th>Hβ 4861</th>
</tr>
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<tbody>
<tr>
<td>[O III] 5007</td>
<td>[N II] 6584</td>
<td>Hα 6563</td>
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</table>

\[\lambda_{\text{O II}} = 3727, \quad \lambda_{\text{O I}} = 6300, \quad \lambda_{\text{H}\beta} = 4861, \quad \lambda_{\text{O III}} = 5007, \quad \lambda_{\text{N II}} = 6584, \quad \lambda_{\text{H}\alpha} = 6563\]
Reddening Corrections

- To achieve our goal we will need to correct line strengths for reddening.
- Use the Whitford (1958) reddening law, parameterized by Miller and Mathews (1972)

\[
\left(\frac{\lambda_1}{\lambda_2}\right) \equiv \log\left[\frac{I(\lambda_1)}{I(\lambda_2)}\right]_{obs} + C_1 \log\left[\frac{I(H\alpha)}{I(H\beta)}\right]_{obs} - C_2. \quad (1)
\]
Corrected Intensity Ratios

- Intrinsic intensity is related to the reddened intensity by
  \[ I(\lambda) = F(\lambda) \times 10^c f(\lambda) \]
  
  - \( f(\lambda) \) is the reddening function defined as \( \delta m_\lambda / \delta m_\beta \)
  - \( \delta m_\lambda \) is the renormalized magnitude extinction given by \( \Delta m_\lambda + m_R \)
  - \( \Delta m_\lambda \) is the magnitude extinction shown by Whitford, parameterized by Miller for 3,200–11,000 Å (\( \lambda^{-1} \) in \( \mu m^{-1} \))

  \[
  \Delta m_\lambda = \begin{cases} 
  .74\lambda^{-1} - .34, & \lambda^{-1} \geq 2.29\mu m^{-1}; \\
  .43\lambda^{-1} + .37, & \lambda^{-1} < 2.29\mu m^{-1}.
  \end{cases}
  \]

- \( c \) is the extinction parameter defined as \( \log(I(H\beta)/F(H\beta)) \)
- Use \( H\alpha/H\beta \) intrinsic ratio of 2.86 (case B, \( T_e = 10^4 \) K, \( N_e = 10^2 \) )
- Note that these are reasonable for H II regions and planetary nebulae, but application to other excitation methods unassured\(^\dagger\)

\(^\dagger\) However, the scheme still discriminates without a reddening correction

\(^\dagger\) collisional excitation and self-absorption affect intrinsic Balmer decrement
Compared Ratios

- No single intensity ratio fully discriminates excitation processes
- Focus on \((\lambda 3727/\lambda 5007)\) due to its strength and excitation sensitivity
  - O III and O II have photoionization potentials of 13.62 and 35.12eV
- Secondary ratios used are: \((\lambda 5007/\lambda 4861)\), \((\lambda 6584/\lambda 6563)\) and \((\lambda 6300/\lambda 6563)\)
- Also briefly analysis \((\lambda 5007/\lambda 4861)\) verse \((\lambda 6584/\lambda 6563)\)
Figure 1

- Plotted are planetary nebulae, H II regions and detached H II regions
- Fitted curve is to the scatter of H II regions
- Notice the tightness of the H II regions to the curve, and the planetary nebulae clearly above it
Fig. 1—The relationship between the $\lambda_{5007}/\lambda_{4861}$ and $\lambda_{3727}/\lambda_{5007}$ intensity ratios for H II regions and planetary nebulae. The intensity ratios are expressed in logarithms with reddening corrections applied as described in the text. Symbols: octagons = normal H II regions; triangles = detached extragalactic H II regions; "+" = planetary nebulae; vertical bar = upper limit on $\lambda_{5007}/\lambda_{4861}$. 
Figure 2

- Same as figure 1, but now includes power-law photoionization and shock-heating sources
- Note their departure from the H II region fit, systematically above
Fig. 2—The same as Figure 1, with the addition of objects photoionized by power laws (shown as diamonds), and shock-heated galaxies (shown as "x"s).
Now a different secondary ratio is used ($\lambda_{6584}/\lambda_{6563}$).

Again four separate excitations can be readily discriminated.
Fig. 3—The relationship between the (λ6584/λ6563) and (λ3727/λ5007) intensity ratios. The symbols have the same meanings as in Figures 1 and 2. Almost all of the upper limits (indicated by vertical bars) are for planetary nebulae.
Secondary ratio used: \((\lambda 6300 / \lambda 6563)\)

Best comparative ratios to discriminate H II regions from LINERS and Seyfers

Because of presence of O I in the later two and absences in H II regions

Still need resolution of high ionization verse low ionization to break the degeneracies within O I detection
Fig. 4—The relationship between the (λ6300/λ6563) and (λ3727/λ5007) intensity ratios. The symbols have the same meanings as in Figures 1 and 2.
New abscissa. \((\lambda_{5007}/\lambda_{4861})\) verse \((\lambda_{6584}/\lambda_{6563})\)

- Good since line ratios are close and reddening correction less important
- Bad since sensitive to N/O abundance (same for figure 3 \((\lambda_{6584}/\lambda_{6563})\) verse \((\lambda_{3727}/\lambda_{5007})\))

- Fitted model line \((\lambda_{5007}/\lambda_{4861}) = \log(4.2 - 9.4I(\lambda_{6584})/I(\lambda_{6563}))\)

- Close to Draine (18.12) & (18.13) solving for \(\xi\) in (18.13) and substituting in (18.12)
  - In LLD for \(T_4 = .8\) and solar abundance†
    \((\lambda_{5007}/\lambda_{4861}) = \log(5.0 - 7.1I(\lambda_{6584})/I(\lambda_{6563}))\)

† with 20% of O tied up in silicates
FIG. 5—The relationship between the ($\lambda$5007/$\lambda$4861) and ($\lambda$6584/$\lambda$6563) intensity ratios. The symbols have the same meanings as in Figures 1 and 2.
Scheme quantification

- We have seen it is possible to qualitatively classify excitation mechanism from line strengths
- Now we to combine all this information to quantify the scheme
- Model H II regions after Searle’s (1971) work
  - high-ionization inner zone with $\text{He}^+$ and $\text{O}^{++}$
  - low-ionization butter zone with $\text{He}^0$, $\text{O}^+$, and $\text{N}^+$
- With a quasi-analytic H II region equation in hand we can now compute “excitation differences,” $\Delta E(\lambda_1/\lambda_2)$
Excitation Differences

\[ \Delta E(\lambda_{5007}/\lambda_{4861}) = (\lambda_{5007}/\lambda_{4861}) + \log(0.32 + x) - 0.44. \quad (2) \]

\[ \Delta E(\lambda_{6584}/\lambda_{6563}) = 1/2[(\lambda_{6584}/\lambda_{6563}) - \log(x/(x + 1.93))] + 0.37. \quad (3) \]

\[ \Delta E(\lambda_{6300}/\lambda_{6563}) = 1/5[(\lambda_{6300}/\lambda_{6563}) + 2.23]. \quad (4) \]

Averaging all the weighted information together we defined \( \langle \Delta E \rangle \)

\[ \langle \Delta E \rangle = 1/3[\Delta E(\lambda_{5007}/\lambda_{4861}) + \Delta E(\lambda_{6584}/\lambda_{6563}) + \Delta E(\lambda_{6300}/\lambda_{6563})]. \quad (5) \]
H II regions are scattered around \( \langle \Delta E \rangle = 0 \), with a standard deviation of \( \sigma = 0.064 \).

We see planetary nebulae all fall within another space, except for 6 which fall into the H II region.

- Authors suggest misclassification or unusually cool stars for planetary nebulae.
- Unfortunately they do not name the systems and cannot be trivially answered 30 years later.
FIG. 8—The relationship between $\langle \Delta E \rangle$ (the average of the individual $\Delta E$ indices) and the $\langle \lambda 3727/\lambda 5007 \rangle$ intensity ratio for planetaries and H II regions. Symbols: same as in Figure 1.
Figure 9

- Power-law photoionization zone classified as
  - $-1.3 < \frac{\lambda3727}{\lambda5007} < 0$ and $\langle \Delta E \rangle > .19$

- Shock-heated zone classified as
  - $\frac{\lambda3727}{\lambda5007} \geq 0$ and $\langle \Delta E \rangle > .19$
FIG. 9—The same as Figure 8, except showing objects photoionized by power laws (indicated by diamonds) and shock-heated galaxies ("+" symbols). A few individual galaxies discussed in the text are indicated by name.