$(AGN)^2$

13. Active Galactic Nuclei - Diagnostics and Physics

Week 15

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13.4 Densities and Temperatures in the Narrow-Line Gas

- The “narrow” emission lines observed in Seyfer 2 and narrow-line radio galaxies
  - They are much the same as those observed in H II regions and planetary nebulae, except that in the AGNs the range of ionization is considerably greater.
  - Not only [O II], [O III], [N II], [Ne III] are observed, but also [O I], [N I], [Ne V], [Fe VIII], [Fe X].
  - [S II], which is relatively low stage of ionization (10.4 eV), is generally much stronger in the AGNs.
  - Permitted lines of H I, He I, and He II are moderately strong.
  - These narrow lines are emitted by highly-ionized gas, with roughly “normal” abundances of the elements.
  - The standard nebular diagnostic methods may be used to analyze it.
- NLRG Cyg A
  - is a particularly well-studied example. Table 13.2 shows its measured line intensities.
  - The measured H I Balmer-line relative strengths do not fit the recombination predictions. The observed Balmer decrement is steeper that the calculated recombination decrement, just as it is in H II regions.

- Extinction - Balmer decrement
  - was calculated from the Balmer decrement, to give the best overall fit with the recombination decrement for $T = 10^4\,\mathrm{K}$, $n_e = 10^4\,\mathrm{cm}^{-3}$.
  - The result is $E(B-V) = 0.69 \pm 0.04$, using the standard reddening law.

    More weight has been given to the Hγ/Hβ and Hδ/Hβ ratios.

    The dust extinction corrected value of Hα/Hβ is 3.08, slightly lager than the recombination value of 2.85.

    This increase is real; it results from a **contribution due to collisional excitation of Hα** (Section 11.5).
  - Cyg A is near the galactic equator in the sky. Therefore, some of $E(B-V)$ is due to duet within our Galaxy. Observations of elliptical galaxies near Cyg A indicate that about half its extinction arises within our Galaxy, and the other half in Cyg A itself.

Observed and calculated relative line fluxes in Cyg A

Ion	λ (Å)	Relative Fluxes Measured	Relative Fluxes Corrected	Crab Nebula	Photoionization Model
Hδ	4101	0.17	0.28	0.31	0.26
Hγ	4340	0.32	0.46	0.61	0.47
Hβ	1.00	1.00	1.00	1.00	1.00
Hα	6563	6.61	3.08	3.28	2.85

Table 13.2
Observed and calculated relative line fluxes in Cyg A

Ion	λ (Å)	Relative Fluxes Measured	Relative Fluxes Corrected	Crab Nebula	Photoionization Model
[Ne V]	3346	0.14	0.38	—	0.12
[Ne V]	3426	0.36	0.95	0.46	0.34
[O II]	3727	2.44	5.00	10.3	0.24
[Ne III]	3869	0.66	1.23	1.56	0.53
[Ne III]	3967	0.22	0.40	0.47	0.16
[S II]	4072	0.14	0.23	0.31	
Hδ	4101	0.17	0.28	0.31	0.26
Hγ	4340	0.32	0.46	0.61	0.47
[O III]	4363	0.16	0.21	0.19	0.19
He I	4471	≤ 0.07	≤ 0.09	0.28	0.02
He II	4686	0.25	0.28	0.53	0.18
Hβ	1.00	1.00	1.00	1.00	1.00
[O III]	4959	4.08	3.88	2.81	6.3
[O III]	5007	13.11	12.30	8.43	18.1
[N I]	5199	0.40	0.32	—	—
[Fe XIV]	5303	≤ 0.10	≤ 0.08	—	0.01
[Fe VII]	5721	≤ 0.10	≤ 0.06	—	0.03
[N II]	5755	0.14	0.09	0.11	—
He I	5876	0.13	0.08	0.79	0.06
[Fe VII]	6087	≤ 0.07	≤ 0.04	—	0.04
[O I]	6300	2.10	1.10	1.20	1.24
[O I]	6364	0.69	0.35	0.33	0.41
[Fe X]	6375	0.10	0.05	—	0.07
[N II]	6548	3.94	1.90	1.56	0.29
Hα	6563	6.61	3.08	3.28	2.85
[N II]	6583	13.07	6.15	4.69	0.86
[S II]	6716	3.65	1.66	5.00	
[S II]	6731	3.29	1.51	—	
[Ar III]	7136	0.64	0.25	0.38	—
[O II]	7325	0.35	0.13	0.50	—
[Ar III]	7751	0.13	0.043	—	—

- Using one mean extinction law is an extreme oversimplification.
  - Optical properties
    - The Balmer-line method used to correct the measured line intensities of the spectra of H II regions in other galaxies, starburst galaxy nuclei, and ANGs is the same as the one applied in our Galaxy.
    - The extinction law has been derived from our Galaxy within approximately 1 kpc of the Sun.
    - The properties of the dust would no doubt depend on the physical conditions and past history of the regions.
  - Not Extinction but Attenuation
    - The reddening law was derived from measurements of stars, for which extinction occurs both by absorption and scattering all along the line of sight.
    - However, in AGNs, dust absorbs and scatters light, and scattering not only removes photons from the beam toward the observer, it also add photons to it that were originally going in other directions.
    - In spherically symmetric systems, scattering within the line-emitting region has no effect, only the absorption effect would occur.
  - Clumpiness
    - In nearly all observed nebulae, the gas and dust have clumpy, irregular distributions.
  - Using one extinction law is an extreme oversimplification. The only justification is that at present we do not have sufficient information on the observed strengths of emission lines from AGNs.

- Diagnostic information on the physical conditions in the ionized gas in Cyg A.
  - Temperature
    - [O III] (λ4959 + λ5007)/λ4363 = 77 gives $T = (1.5 \pm 0.1) \times 10^4$ K in the [O III] emitting region in the low-density limit ($n_e < 10^4\,\mathrm{cm^{-3}}$) or lower temperature at higher electron density.
    - [N II] (λ6548 + λ6583)/λ5757 = 89 corresponds to $T = 1.0 \times 10^4$ K in the low-density limit.
  - Density
    - [O III] λ3729/λ3726 is a good electron-density diagnostic in H II regions and PNe. However, this ratio cannot be applied in AGNs because their line widths are comparable to or larger than the separation of the two lines (2.8Å, corresponding to ~ 300 km $\mathrm{s^{-1}}$).
    - [S II] λ6716/λ6731 = 1.10 corresponds to $n_E = 3 \times 10^2\,\mathrm{cm^{-3}}$ at $T = 1.0 \times 10^4$ K, or to $n_e = 4 \times 10^2\,\mathrm{cm^{-3}}$ at $T = 1.5 \times 10^4$ K.
    - [S II] emission arises in a less highly ionized region outside the [O III] emitting zone. Thus, the electron density derived from this ratio is not representative of the entire ionized volume. But, it seems unlikely that $n_e > 10^4\,\mathrm{cm^{-3}}$.
  - Abundances
    - Assumes (1) T = 8,500 K for the [S III], [O I], and [N II] emitting regions, (2) T = 12,000 K for H I, He II, and He II, (3) T = 15,000 K for [O III] and [Ne III], (4) T = 20,000 K for [Ne V] and [Fe VII]

- The derived ionic abundances are shown in Table 13.3.
- With a rough allowance for unobserved stages of ionization, these ionic abundances give the approximate elemental abundances shown in Table 13.4.
- Table 13.4 shows that Cyg A has approximately the same composition as in our Galaxy and other observed galaxies with H II regions or starburst nuceli.
- H is the most abundant element; He is less abundant by a factor of ~ 10; O, Ne, N, and C are the most abundant heavy elements.
- Fe is underabundant, which can be understood as due to depletion onto grains, suggesting the existence of dust within the ionized gas.
- These abundances are useful as a starting point for model calculations based on a more specific physical model.

Table 13.3

Relative ionic composition of Cyg A emission-line region

Ion	Abundance	Ion	Abundance
H^+	10^4	O^0	1.9
He^+	5.7×10^2	O^+	1.7
He^{++}	2.4×10^2	O^{++}	1.5
N^0	0.37	Ne^{++}	0.45
N^+	0.88	Ne^{+4}	0.16
		Fe^{+6}	≤ 0.008

Table 13.4

Approximate elemental abundances in Cyg A emission-line region

Element	Abundance	Element	Abundance
H	10^4	Ne	1
He	10^3	S	0.3
N	1	Fe	≤ 0.1
O	4		

- Similar observational data are available for many other NLRGs and Seyfert 2 galaxies.
- Table 13.5 gives a list of mean values of T and n_e determined from the best fits to [O III], [N II], [O II], [S II], and [O I] line ratios in Seyfert 2 and NLRGs.

[Table 13.5] Mean temperatures, electron densities, and extinctions in Seyfert 2 and NLRGs

Galaxy	log T (K)	log n_e (cm^{-3})	$E(B-V)$
Mrk 3	4.1	3.5	0.50
Mrk 34	4.1	3.2	0.30
Mrk 78	4.0	3.2	0.72
Mrk 198	4.1	2.6	0.24
Mrk 348	4.2	3.3	0.41
3C 33	4.1	2.9	0.38
3C 98	4.3	3.6	0.68
3C 327	4.3	3.2	0.43
3C 433	4.2	2.4	0.58

13.5 Photoionization

- Photoionization is the main ionization mechanism.
  - The temperature in the ionized gas in Cyg A and other NLRGs and Seyfert 2 galaxies $\sim 1-2\times10^4$ K.
  - In some Seyfert 2s and NLRGs, [O III] ($\lambda4959 + \lambda5007$)/$\lambda4363$ is smaller, indicating higher temperature (up to $T \approx 5\times10^4$ K in some objects) and $n_e < 10^4\,\mathrm{cm}^{-3}$, or $T \approx 1-2\times10^4$ K and higher densities (up to $n_e \approx 10^7\,\mathrm{cm}^{-3}$).
  - These results strongly indicate that the main source of energy input is by photoionization.
  - **Under photoionization conditions, there is no direct relationship between gas temperature and degree of ionization.**
  - The radiative cooling by collisionally excited line radiation increases rapidly with increasing temperature, and this tends keep temperature $T \approx 1-2\times10^4$ K over a wide range of input ionization radiation spectra.
- Shock-wave heating?
  - **Under pure shock-wave (or collisional) heating, there is a direct relationship between temperature and degree of ionization**, and the [O III] lines would be radiated mostly at $T > 5\times10^4$ K.
  - In actual cases of shock-wave heating, pre-heating ahead of the shock front due to photoionization by radiation from the very hot gas close to the front. In this case, the [O III] emitting zone in shock gas always has $T > 3\times10^4$ K.
- The observations indicates that photoionization is operative in all (or most) AGNs, since the [O III] line ratios cannot be caused by collisional ionization.

- Ionization source with "Hard" spectrum
  - This simple analysis strongly implies that photoionization is the main energy-input mechanism.
  - However, it is clear that the main source of the radiation cannot be hot stars, as in H II regions and PNe. Radiation from such stars will not produce the wide range of ionization observed in NLRG and Seyfert 2 AGNs (emission lines of low stages [O I] and [S II[, and high stages [Ne V] and [Fe VII])
  - What is required is a source with a much "harder" spectrum, that extends even further into the UV than the spectra of central stars of PNe, some of which have effective temperature up to $T = 2 \times 10^5$ K.
  - High-energy photons ($h\nu > 100$ eV) produce **high ionization (up to Ne^{+4}, Fe^{+6}, and even Fe^{+9}) near the source**, and **a long, partially-ionized "transition zone"** in which H^0 and H^+, O^0, and S^+ all coexist, and strong [O I] and [S II] lines can be collisionally excited.
  - The width of this transition zone is roughly one mean free path of an ionizing photon,

$$l = \frac{1}{n(\mathrm{H}^0)\sigma_\nu^{\mathrm{pi}}(\mathrm{H}^0)}$$

    Since both $n(\mathrm{H}^0)$ and the mean frequency of the remaining photons vary rapidly with distance, the mean free path also varies rapidly.

    The higher the energy of the photons present, the longer their mean free path is, and the larger the transition zone is.

- Spectral Energy Distributions (SEDs) of AGNs
  - A featureless continuum, extending across a broad range wavelengths, is observed in AGNs. The form of the SED in the optical-UV region approximately fits a power law:

$$L_\nu = C\nu^{-\alpha}, \text{ typically with } \alpha \approx 1 - 2.$$

  - In Cyg A, the "observed" continuum has $\alpha = 3.8$. But, if it is corrected for the same amount of extinction as derived from the Balmer decrement, this becomes $\alpha = 1.6$.
  - If this spectrum extended to high energies, its can explain the observed Cyg A line spectrum.