A COMPARISON OF LINE INTENSITIES IN THE SPECTRA OF GALACTIC AND EXTRAGALACTIC EMISSION OBJECTS

BY

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Michael Chriss

CONTENTS

I. Introduction

The spectrograph has been used extensively in the study of the physical processes in astronomical bodies since the time of its invention by Joseph Fraunhofer , who first used it astronomically to investigate the nature of the sun. With this instrument it has been possible to identify the chemical composition of most kinds of astronomical objects by identifying the characteristic spectral lines which each element exhibits when energized. In this manner, the constituents of the atmospheres of many stars, the sun included, were discovered by measuring the wave lengths of the absorption lines produced by the cooler gases in the outer regions of the stars.

Similarly, the make-up of the luminiferous clouds of gas, which inhabit the plane of the Milky Way and which show up as tenuous wisps and rings of light on direct photographs, can also be inferred by examination with the spectrograph. From these objects, however, are observed bright or emission lines at wave lengths characteristic of the atoms composing the gas.

It might be expected, then, that if the spectrum of an extragalactic object, i.e. another galaxy, were to be examined, the result would be a composite of the radiation of all the objects comprising the galaxy. And since the energy reaching us from other galaxies must be primarily due to its stars, a composite absorption spectrum might be expected. Indeed this proves to be the case for the majority of galaxies which have been examined spectroscopically. However, an impressive number of galaxies show certain emission lines superimposed on the composite absorption spectrum. These then are called emission galaxies or extragalactic emission objects.

As will be noted in a later section of this study, these emissions sometimes appear to be localized in bright patches in some of the nearer galaxies, but in many instances also appear to extend generally all along the entire body of other galaxies. The question arises as to whether this extensive generalized emission of other galaxies is spectrally different from the highly localized emissive areas of our own galaxy. Spectral evidence already in the literature is inconclusive. Seyfert[1] and Mayall[2] have remarked the general resemblance, but both have emphasized the conspicuousness of $\lambda3727$ of O II and, to some extent, of $\lambda6563$, Hα. Unfortunately, previous photography of extragalactic spectra has generally omitted the region of Hα. Therefore, commencing in the spring of 1958 I undertook the photography of the spectra of a number of typical galactic and extragalactic emission objects. These spectra included Hα. The emission radiation from both galactic and extragalactic sources was compared for similarity and intensity of lines.

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1. C. K. Seyfert, "Nuclear Emission in Spiral Nebulae", Berkeley Conference Notes, (1954), 221.

2. N. U. Mayall, "The Occurrence of $\lambda3727$ [O II] in the Spectra of Extragalactic Nebulae", Lick Observatory Bulletin, 497, (1939), 24.

II. Description of Equipment

All spectra were photographed with the Meinel Nebular Spectrograph at the Newtonian focus of the 36-inch Steward reflector. The latter has a mirror with an aluminum surface which has good reflectance throughout the entire visual and ultraviolet region. The design of the spectrograph was by Dr. A. B. Meinel, now director of the Kitt Peak National Observatory, and it introduced a greatly improved dispersing unit.

The dispersing unit consists of a right-angle-grooved transmittance grating mounted on the hypotenuse face of a right-angled prism. The dispersion is effected only by the grating, the prism serving solely to provide an exit face parallel to the entrance face of each groove and to provide a support for the grating. The height of each step in the grating is such that light, at the wave length of Hβ, incident on the step, is retarded by one wave length before encountering the base of the step, at which level the face of the next step is located. Thus the light of this wave length emerges from the grating into the prism in phase with light coming from the preceding step. Hence, most of the energy is in the first order dispersion rather than the zero order as in conventional grating design, the first order here being the undeviated beam of light. The prism is of borosilicate crown glass (BSC-2 in the Bausch and Lomb catalog) having good transmittance in the near ultraviolet.

The film, which is 15 mm. square, covers the region from the ultraviolet to $\lambda 6200$ in good definition when the film is centered in its specially curved holder. The dispersion is about 265 Å/mm with the high dispersion prism-grating and about 600 Å/mm with the low dispersion prism-grating. For this study only NGC 604 was obtained with the low dispersion unit. In order to include Hα on the film it is necessary to slide the film laterally beyond its holder by about two millimeters. This position of the film still permits the inclusion of $\lambda 3727$ at the other end. However, the film holder offers no support to the overhung portion of the film and hence Hα is not in good focus. For this reason Hα was not used in determining radial velocities, and the observed intensity of Hα is a bit less than it might otherwise have been.

The camera of the spectrograph is an F/0.8 Schmidt giving a 6.2:1 reduction of slit dimension on the film. Since the slit width was always 0.25 mm., the resolution on the film is 0.04 mm., or 10 Å, with the high dispersion unit. NGC 604 was photographed with a slit width half that for the high dispersion prism and since the dispersion is one half as great, the resulting wave length resolution on the film is just the same. A Ne + A glow lamp, built into the spectrograph, provides the comparison lines which were photographed along each side of the nebular spectrum.

Guiding was done from the reflection of the image off the polished slit jaws, as seen through an auxiliary eyepiece. The light efficiency of this instrument is high, a good exposure of the Orion Nebula taking about twenty minutes, and extragalactic objects of 11th magnitude registering in good intensity in about two and one-half hours. The film used throughout was 103aF which has uniformly good sensitivity in the spectral region photographed. All films were measured twice on a precision screw made by the Fred C. Henson Co., which could be read directly to 0.001 mm.

III. Results

The results of the investigation of the observed emission lines found in objects, both galactic and extragalactic, are summarized in Tables I and II on the following pages.

1. Description of Tables.

In Table I are listed the identifications and intensities of the observed lines, tabulated by celestial source. The intensities were estimated by eye, a designation of "1" being used for a line that is just visible, ranging up to a designation of "10" for a line of maximum intensity. In some cases the designation "tr" is used to indicate "trace", this latter being assigned to lines whose presence is in doubt but whose radial velocity measurement is consistent with that found from the other lines in the object. In addition, the designations 10+, 10++, and 10+++ are used to describe a line whose image has begun to spread on the photographic emulsion because of extreme brightness. When the emission line is superimposed on a dense continuum it becomes difficult to estimate its intensity and sometimes even its presence, and this fact is noted in the table. As pointed out in the previous section, Hα is in poor focus because of the overhung film, and hence the recorded intensity is perhaps lower than it might have been for an in-focus position. This feature also causes spreading of the Hα line and thus makes it difficult to tell whether the flanking lines of [N II] are present and, if they are, what their intensity is. Hence these two lines are assumed to be absent unless the amount of spreading and the density distribution are extraordinarily large. When two or more very close lines are blended into one image, the average intensity for all components is listed and remarked.

Table II lists the measured mean radial velocity for each of the observed extragalactic objects. The earth's annual velocity is considered negligible with respect to these motions, which may be taken as referred to the sun as the standard of rest. Also listed, for comparison, are the mean radial velocities for such of these galaxies as have been reported by the Palomar-Mt. Wilson Observatories and the Lick Observatory[3]. Their values are corrected for the earth's motion, however, which amounts to $\pm$ 29 Km./sec at maximum. Hα was not used in the mean values for the radial velocities because of its out-of-focus image. In a few spectra the H and K stellar absorption lines of calcium were quite prevalent, and when present were used in the mean value. In each case they yielded smaller radial velocity values than the emission lines in the same galaxy, a fact which will be commented on later, and this resulted in a lower value for the mean radial velocity than would have been found from emission lines only. These few instances are noted in the table of notes following Table II. Each observed object was in high galactic latitude, the lowest latitude being 31°.

3. M. L. Humason, N. U. Mayall, A. R. Sandage, "Red Shifts and Magnitudes of Extra-Galactic Nebulae", Astronomical Journal, Vol. 61, No. 3, April, 1956.

Therefore the galactic interstellar H and K lines do not contaminate the observed wave length measurements of the galaxian H and K lines.

All pertinent information concerning the extragalactic spectra is listed in the table of notes.

2. Table I

Observed Lines and Intensities, Tabulated by Object

Legend:		
	x?	intensity in doubt
	?x	line in doubt
	c	dense continuum
	b	line(s) broadened

GALACTIC EMISSION OBJECTS

λ (Å)		Diffuse Nebulae						Planetary Nebulae																
		NGC 1976	NGC 2261	NGC 6514	NGC 6523	NGC 6618	NGC 6960	NGC 2022	NGC 2371-2	NGC 2392	NGC 2440	NGC 3242	NGC 3587	NGC 6058	NGC 6210	NGC 6543	NGC 6572	NGC 6720	NGC 6826	NGC 6853	IC 4997	NGC 6905	NGC 7009	NGC 7662
3428.0	O III									3	6	3	1										6	3
3444.1	O II																							5
3726.16, 3728.91	[O II]	10+		9	10	9	6		3	10	8	8	8		9	10+	10	10	10	10	9	2	10	7
3750	H I H_κ	5			4	2	1				3	}5			4	9	7	2	7	1	7		7	5
3759	O III										3												?5	
3771	H I H_ι	6			4	2	1				3				4	9	7	2	7	2	7		7	4
3798	H I H_θ	6		1	5	3	1			2	3	7			5	10	8	3	7	3	7	5	8	5
3820	He I	2			1	1						2				9	5		6		3		4	
3835.5	H I H_η	6		1	6	4	1		1	2	4	7			7	10	9	4	8	3	8	5	9	6
3868.74	[Ne III]	9		4	7	7	2	5	6	9	9	10	6	7	10	10+	10	10	10	10	10	8	10+	10
3888.96	He I, H I H_ζ	9		3	8	7		2	1	7	7	9	3		9	10	10	7	10	6	9	5	10	9
3924	He II																							1
3967.51, 3970.08	[Ne III], H_ϵ H I	9		4	9	8	1	4	4	9	7	10	5	4	10	10+	10	9	10	10	10	7	10+	10
4009	He I																4							
4026.2	He I, He II	4			3	2					3	4			6	9	8	3	6	2	6		8	4
4068.62	[S II]	}4			}3	}3					3	}3			}4	8	}8	}4		}3	}7		}7	}2
4076.22	[S II]										3					8								
4104.74	H I H_δ	10		6	10	9		4	5	8	7	10	4	4	10	10	10	8	10	9	10	5	10	10
4200	He II																							2
4340.6	H I H_γ	10	?4		10	10		4	5	8	9	10+	5	5	10	10+	10	9	10	9	10	7	10	10
4363.21	[O III]			7							7	8?			7?	?8?	9	7	7		10		9	8
4378	N III									3?						8								
4388.0	He I																5				3			
4471.54	He I	8			6	6					5	6			7	9	10	4	8	3	8		8	5
4541.4	He II										3	3				6	4	1				2		4
4634.1	Ne III																							
4640.9	N III										}3	}5			}5	}9	}5	}1					}8	}5
4649.2	C III, O II	3																						
4659	C IV																				2		?3	
4685.76	He II				1		2	7	7	10	7	10	2	5	6		4	8		9		9	10	10
4711.4	[A IV]							1	1	4	5	8			6	8	7	2		2	2	2	8	7
4712.6	He I																							
4740.2	[A IV]							1	1	2	5	8			4	5	7	2		1		1	8	7
4861.32	H I H_β	10++	6	8	10	10	1	6	6	10	9	10+	5	5	10	10+	10+	9	10	9	10	8	10+	10
4922.2	He I	4	1		3											7	5		2		2		4	
4958.91	[O III]	10++		4	10	10	2	8	8	10	10	10++	8	9	10++	10++	10++	10	10+	10	10+	10	10++	10+
5006.84	[O III]	10++	1	7	10+	10+	5	10	10	10+	10+	10+++	10	10	10+++	10++	10+++	10+	10+	10+	10++	10	10+++	10+++
5198.5	[N I]										4						3							
5411.3	He II									2	3	3											3	6
5517.8	[Cl III]																3						1	
5537.5	[Cl III]																3						2	
5754.8	[N II]										6					3	7							
5800	[C IV]	10															5							
5875.7	He I			?2	8	8				4	5	8			9	10	10	4	9	3	8		10	8
6548.1	[N II]				10	10				10	10+				10++	10+	10+	10	10+	10	10+		10+	
6562.79	H I H_α	}10+	8	9	10	10	1?	8	7	10	10+	10+++	6	5	10++	10+	10+	10	10+	10	10+	9	10	10+
6583.6	[N II]			5	10	?9					10+				8	10+	10+				9			4
					7													3						

EXTRAGALACTIC EMISSION OBJECTS

λ (Å)	Irr.		E (E0)	E (E1)	E (S0)	Sa		Sb					Sb (SBb)	Sc			Double Galaxies (E1+Sb)	Double Galaxies (Sc+Sc)	Double Galaxies (E+Sb)	Double Galaxies (Epec+Sc)	Misc.
	NGC 3077	NGC 4449	NGC 4486	NGC 1453	NGC 4111	NGC 4151	NGC 7469	NGC 1068	NGC 2841	NGC 4051	NGC 4258	NGC 4736	NGC 7479	NGC 598	NGC 2903-5	NGC 4321	NGC 3226-7	NGC 3395-6	NGC 4435-8	NGC 4485-90	NGC 604
3726.16, 3728.91	7	8	4	1	2	10	1	8b	tr,b	2	6	3b		1	2c	4	1/4b	6/7	-/tr	tr/7	9
3750								tr													
3759		2	1	1	1	3		tr		1											
3771			1																		
3820																					tr
3835.5																					1
3868.74		2			3b	9c		7b		1	2b		2						-/2		
3888.96						5bc												-/1	-/tr		2
3924						3c													-/1		
3967.51, 3970.08			3bc			8c															3
4104.74						8?bc															6
4340.6		4					3														7
4685.76						3															
4861.32	2	6				8b	3	2b		3								1/1		-/1	9
4958.91		5				9b	tr	9b										1/1		-/tr	7
5006.84	1	7				10b	3	10b		3							5b/1	tr/1		-/2	10
5875.7										2	2										
6562.79	4	6b			tr	}9b	5b	}8b		}4b					3	3b	-/4b	2b/2b		-/3	}10++b

3. Table II

Mean Value of Radial Velocities of Extragalactic Objects

(unadjusted for Sun's motion)

NGC	Chriss* (Km/sec)	Palomar-Wilson (Km/sec)	Lick (Km/sec)
598	+ 378 n	- 189	
604	- 295	- 226	- 244
1068	+1279	+1020	+1121
1453	+ 938	+3919	+4035
2841	+ 521 n	+ 584	+ 740
2903-5	+ 845	+ 642	+ 645
3077	+ 115 n		- 158
{3226	+ 954	+1338	
{3227	+ 954	+1111	
{3395	+1334		+1751
{3396	+1371		+1643
4051	+ 500	+ 627	
4111	+ 652 n	+ 784	+ 870
4151	+ 806	+ 960	+ 934
4258	+ 332 n	+ 420	
4321	+2052	+1617	
{4435			
{4438	+2457		
4449	+ 116	+ 206	
{4485	+ 491		
{4490	+ 428	+ 625	
4486	+1913 n		+1196
4736	+ 237 n	+ 282	+ 313
7469	+4864	+4780	+4692
7479	+2959	+2492	+2425

* - uncorrected for Earth's annual motion also, = 28.8 Km/sec max. value

n - refer to notes.

4. Notes to Tables I and II.

NGC 598 — Sc film 492B Oct 17, 1958 PA 090°S Exp. 2^h HA* 2:15W slit on nucleus. λ3727 position uncertain.

NGC 604 — Em patch on 598 film 383B Dec 24,1957 PA090°S Exp 1^h low dispersion prism, spectrum photographed by E.F.Carpenter

NGC 1068 — Sb film 493B Oct 17,1958 PA 090°S Exp 1^h HA 2:15W slit on nucleus. all lines are extremely broad.

NGC 1453 — El film 505B Dec 11,1958 PA 090°S Exp 2^h45^m HA 1:10W very small image, star-like

NGC 2841 — Sb film 522B Jan 7,1959 PA 090°S Exp 1^h50^m HA 0:45E slit on prominent nucleus. very weak λ3727. H and K lines very broad and show rad. vel. of +320 Km/sec. thick haze for 40^m of exp.

NGC 2903-5 — Sc film 506B Jan 2,1959 PA 020°S exp 2^h HA 0:10E slit goes through nucleus and prominent patch in arm; no emission observed in patch.

NGC 3077 — Irr film 527B Jan 31,1959 PA 087°S Exp 3^h HA 1:00W extended, no nucleus. large scatter in rad. vel. value of individual lines.

NGC 3226-7 — El,Sb film 523B Jan 14,1959 PA 347°S Exp 3^h HA 0:48W interaction evident on direct photographs and visually.

NGC 3395-6 — Sc,Sc film 525B Jan 15,1959 PA 070°S Exp 3^h15^m HA 0:45W possible interaction. λ3727 emission in space between galaxies.

NGC 4051 — Sb film 470B Apr 18,1958 PA 022°N Exp 2^h45^m HA 2:55W irregular, brighter middle?

NGC 4111 — S0 film 511B Jan 4,1959 PA 148°S Exp 1^h30^m HA 2:45E slit along arms and including nucleus. H and K lines very broad and show a rad. vel. of +663 Km/sec and +416 Km/sec respectively.

NGC 4151 — Sa film 471B Apr 21,1958 PA 090°N Exp 2^h45^m HA 1:40W starlike image with brighter nucleus. dense continuum, inclined emission lines.

* - Hour Angle at end of exposure.

NGC 4258 Sb film 526B Jan 15,1959 PA 070°S Exp 1^h40^m HA 1:22W
slit through nucleus. λ3727 inclined corresponding to 128.8 Km/sec line of sight velocity with respect to nucleus. H and K lines have rad. vel. of +107 Km/sec and +423 Km/sec respectively.

NGC 4321 Sc film 474B Apr 25,1958 PA 090°S Exp 2^h20^m HA 4:15W
indistinct, no evidence of arms. direct photography shows H II regions in arms.

NGC 4435-38 E,Sb film 529B Feb 6,1959 PA 345°S Exp 2^h HA 0:45W
possible interaction. comparison spectrum on one side only. slit through center.

NGC 4449 I film 468B Apr 17,1958 PA 022°N Exp 2^h30^m HA 2:25W
slit along major axis and what appears to be nucleus.

NGC 4485-90 I,Sc film 528B Jan 31,1959 PA 350°S Exp 2^h HA 0:45E
Possible interaction. B.A.Vorontsov-Velyaminov lists this as an Epec-I in strong interaction. comparison spectrum on one side only. slit through nucleus.

NGC 4486 (M 87) Eop film 507B Jan 2,1959 PA 020°S Exp 2^h HA 0:35E
slit through nucleus. λ3970 difficult to measure because of dense continuum and not included in mean rad. vel. value. radio galaxy.

NGC 4736 (M94) Sb film 524B Jan 14,1959 PA 347°S Exp 1^h35^m HA 0:15E
slit through nucleus. all lines very broad. H and K lines have rad. vel. of +68 Km/sec.

NGC 7469 Sa film 485B Jun 9,1958 PA 090°S Exp 1^h50^m HA 2:06E
slit through center.

NGC 7479 SBc film 490B Oct 9,1958 PA 090°S Exp 2^h30^m HA 1:06W
faint, not sure if on slit for entire length of exposure.

IV. Interpretation of Results and General Discussion

1. Summary of observational results for objects studied in this paper.

The most persistent (but not universal) difference in the emission spectra of galactic and extragalactic objects is the inversion of the brightness ratio of $\lambda 3727$ [O II] and Hα.

The objects studied in the Milky Way were of two general types: (1) diffuse gaseous nebulae (e.g. Orion Nebula, Lagoon Nebula), and (2) planetary nebulae (e.g. NGC 2440, Ring Nebula). For almost every such object included in this study, the intensity ratio of the two aforementioned lines is:

$$\lambda 3727/\mathrm{H}\alpha \leqslant 1$$

Often this intensity ratio was very close to unity (NGC 3242, NGC 6210), and in some cases the intensities of these two lines were equal (NGC 1976, NGC 6523). But hardly ever was $\lambda 3727 >$ Hα in intensity, i.e., the ratio written above was almost never more than unity for emission objects in our own galaxy. The two lone exceptions in my list are the Owl Nebula (NGC 3587) and the Loop Nebula (NGC 6960). These exceptions will be discussed in a later section when the excitation mechanisms existing in these objects will be discussed.

On the other hand, in the twenty-one galaxies photographed in this study, the intensity ratio frequently is:

$$\lambda 3727/\mathrm{H}\alpha > 1$$

This condition is not as consistent as the converse condition for galactic emission objects. In fact, only fifteen out of twenty-one extragalactic objects showed stronger λ3727 emission than Hα emission. The other six objects showed either equal intensity for these lines (one object) or exhibited Hα stronger than λ3727 (four objects). In one galaxy (NGC 7479) neither line showed. In almost all of the fifteen galaxies which showed stronger λ3727, the ratio of λ3727 to Hα is much greater than unity as compared to the galactic objects where the ratio is not quite unity. In many examples of the extragalactic objects, Hα does not appear at all.

Recognition of the presence of other emission lines in the two types of objects should be noted. In the galactic emission sources the Balmer series from Hα to H_{κ} is usually present in conspicuous intensity ranging from an intensity of 10+++ for Hα down to 3 for H_{κ}. Conversely, while O III λ3759 appears fairly consistently in other galaxies, its appearance is limited to only two objects in our own galaxy, and in one of these objects the line is in doubt. Mayall found similar circumstances when he made the following summary[4]:

> There appears to be a loose relation between the strength of λ3727 and the presence of other bright lines. It is in the expected sense that when λ3727 is quite faint (intensities 1-2) no other emissions are found; when it is of intermediate strength (intensities 3-6), others may or may not be present; and, lastly, when it is quite strong (intensities 8-10), a number of them can be identified.

It should be noted that Mayall's spectra did not include Hα.

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4. Mayall, op. cit., 35.

After $\lambda 3727$, the most frequently observed emission lines are: $H\alpha$, $H\beta$, and the nebular lines N_1 and N_2 [O III] ($\lambda 5007$, 4959).

Finally, some mention must be made of the location of the areas in other galaxies from which emission radiation arises. All of the objects studied in this paper, save two, are sufficiently small in angular dimension so that the entire image could be included on the slit. The spectrograph slit was always oriented to include the nuclei and major axes of galaxies. The two exceptions are NGC 598, a member of the local group, and NGC 604 which is a patch of bright gas in an arm of NGC 598. For the other objects, it was found that emission is usually present along the entire lengths of the images of the galaxies, but is particularly prevalent in the nuclear regions. In NGC 598, of which the slit included only the nucleus, only a trace of $\lambda 3727$ was found. The emission patch NGC 604 showed strong $\lambda 3727$ as well as many of the Balmer lines of hydrogen.

Before attempting to correlate the results of this study, it will be fruitful to summarize the findings of earlier investigators who have examined a great many more extragalactic objects, though usually not in the red, than are considered in this study. This will be done in the following section.

2. The occurrence of emission in other galaxies.

λ3727 and galactic type

Systematic observation of the near ultraviolet region in the spectra of other galaxies was begun in 1936 at the Lick Observatory with the aid of a specially designed ultraviolet glass spectrograph[5]. It was an unexpected result to find the doublet of [O II], λ3726.16 and λ3728.91, which appears as a broad line at λ3727, in the spectra of a high percentage of the observed galaxies. This result led to various investigations at the Mount Wilson and the Lick Observatories, in an effort to search for some correlation between the existence of this emission line, as well as various other lines which frequently appeared with λ3727, and other observable features of the objects. As observing lists became longer, certain flexible but unmistakable relationships were realized between the distribution of ionized gas (which exhibits λ3727 in emission) and galaxian structure, i.e., the classification of the galaxy in Hubble's scheme. It was noticed by Seyfert[6] that out of ten spirals which he examined for, and in which he found, emission, all were of Sa or Sb type and all had nuclei of high luminosity which could scarcely be distinguished from stellar images on direct photographs, the luminosity and appearance having been previously noted by Humason. It is a matter of fact that this observation was also valid for most of the galaxies studied in this paper. There also seems to be

5. Ibid, 33.

6. C. K. Seyfert, "Nuclear Emission in Spiral Nebulae", Astrophysical Journal, Vol. 97 (1943), 28.

a dependence of the existence of the $\lambda 3727$ line and the form of the galaxy. Humason and Mayall found that about 20% of the elliptical galaxies they studied exhibited the [O II] line and this percentage of occurrence increased as they considered later classifications of galaxies, with 80% of the Sc types showing [O II] emission in their spectra. The findings of Humason and Sandage are summarized in the following table[7] which was based upon the observation of nearly 300 galaxies and which clearly shows the dependence of $\lambda 3727$ occurrence on galaxian form or type:

Galactic Type	No. in Sample	% occurrence of $\lambda 3727$
E0 - 7	82	18
S0 + SBo	52	48
Sa + SBa	37	62
Sb + SBb	66	80
Sc + SBc	41	85
All	278	54

The intensity of $\lambda 3727$ also follows a similar dependence. This relationship immediately suggests that the occurrence of $\lambda 3727$ depends upon the amount of gas in the system, since it is recognized that the later galaxian types have greater amounts of gas in their equatorial planes, and perhaps even outside the equatorial planes. This should be remembered when the possible mechanisms of [O II] emission are considered

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7. Humason, Mayall, Sandage, op. cit., 113.

in a later section of this thesis.

The dependence discussed above is emphasized by the double galaxies included in Table I. In the two cases where ellipticals and spirals were in interaction, $\lambda 3727$ was either very weak in the ellipticals or it was not present at all, while it was fairly bright in the spirals.

This relationship is, however, not as consistent for double galaxies. Mayall finds that in NGC 1888-9 (Sb + E0) and NGC 4647-9 (Sc + E2) $\lambda 3727$ is decidedly more intense in the elliptical members while it is only barely visible in the spirals. He remarks that this is not to be taken as an indication that the dependence is not valid for double galaxies, but only that the rule is complex for both doubles and singles and more complex for double galaxies[8].

Location of general emission

It has already been stated that Seyfert found [O II] emission in the nuclei of the handful of galaxies which he studied. Again, Mayall's and Humason's extensive observations give an indication that the location of the emission sources in other galaxies is dependent on galactic type. Mayall points out that it is hard to make generalizations as to the precise location of the emitting sources solely with the use of a spectrograph since the orientation of the slit yields a picture in

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8. N. U. Mayall, "Spectroscopic Evidence Bearing on the Distribution of Gas in Extragalactic Systems", Contributions from the Lick Observatory, Series II, No. 81, 28-29.

only one plane of the galaxy and it is difficult to evaluate the effect of this arbitrary selection. This obstacle could be resolved by use of narrow band photography which would include the whole system. But nevertheless, there again appears a certain flexible yet unmistakable correlation between the location of the emission sources within the galaxy and galactic type. There is a tendency for λ3727 to be more pronounced in the nuclear regions of elliptical galaxies than it is in the next later class, i.e., the SO types. As later classes are considered it is found that λ3727 radiation becomes less concentrated toward the nucleus although it continues to appear strongly in the nucleus. Barred spirals, although structurally different from normal spirals, appear to have identical spectral characteristics, i.e., the same emission and absorption lines occur with the same diversity in intensity and with the same complex relationship to galactic structure. In some examples, for instance NGC 1640 and NGC 7479, both of which are SBb spirals, λ3727 appears faintly, but mainly, in the nucleus and not at all in the arms or along the bar. On the other hand, in the SBc spirals NGC 672 and NGC 7640, λ3727 is not confined to the nucleus at all but can be found all along the bars[9]. Mayall summed up the few general relationships that could be deduced from twenty-two years of observation ending in 1958 in the following four points[10]:

> a. In the progression of nebular types from ellipticals to spirals, the ionized gas (as detected by the presence

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9. Ibid., 28.

10. Ibid., 30.

of $\lambda 3727$) tends to become less centrally concentrated and to occur more frequently by a factor of 5 or 6.

b. While H II regions are related to structural features like nuclei, arms, bars, the relationship is not close and there appears little difference between normal and barred spirals in this relationship.

c. For close doubles, there is indication of increased ionization when the components are either of very late type or are irregular, or when peculiar structure suggests strong interaction.

d. In two cases of wider pairs having bright connecting filaments, there is no evidence for an ionized gaseous constituent in the filaments, i.e., the filaments appear to be constituted of stars.

It must be stated for emphasis that these rules of correlation are only generally adhered to and many flagrant violations exist. In many cases of late spirals, emission shows in the nucleus and wherever the spectrograph slit crosses the arms. But again, there are many examples where emission appears only in the nucleus (NGC 2903-5) and again there are cases where emission appears only weakly in the nucleus but strongly in the arms (NGC 2835).

<u>Emission patches</u>

The foregoing rules apply only to general emission in extragalactic objects. There exist also definite bright patches in other galaxies which are the sources of strong emission. These emission patches are particularly noticeable in the nearer galaxies where the detailed structure can be easily seen. NGC 604 is such an object appearing on direct photographs as a diffuse amorphous area of light in one of the arms of NGC 598. The barred spiral NGC 3510 which shows $\lambda 3727$ only weakly in its nucleus, has a condensation at the end of one of its bars which exhibits strong $\lambda 3727$ radiation. Mayall reports that in many instances the Crossley spectrograph slit was oriented to include faint areas of condensation in other galaxies and $\lambda 3727$ was found to be present[11]. Mayall and Aller[12] found twelve emission patches in the Andromeda Galaxy, all of which resemble NGC 604 in appearance and spectrum. Even an irregular object like the Large Magellanic Cloud has a multitude of emission patches. Two hundred seventy eight such areas were counted by R. E. Wilson. Spectrally, these patches resemble very closely the characteristics of emission objects in our own galaxy. Indeed, to an observer in a galaxy which contains these sources of emission, they probably resemble very much the local emission objects in the Milky Way.

Line broadening

Before leaving this section on the results of extragalactic emission investigations by other observers, one more important and distinguishing feature must be mentioned. This is the abnormal broadening of galaxian emission lines which has been found, almost without exception, by previous observers. In general, all observed emission lines are extremely broad when compared with the same emission lines observed in objects in the Milky Way. This would seem to imply that

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11. Ibid., 28.

12. N. U. Mayall and L. H. Aller, "Emission Nebulosities in the Spiral Nebula Messier 33", Publications of the Astronomical Society of the Pacific, Vol. 51, (1939), 112.

the gas from which these emissions arise is in a state of high velocity. However, there is a striking exception to this generally observed fact in that emission patches in close galaxies show no evidence of this broadening. Evidently, the emission arising from such patches represents a process different from that which causes the general emission observed along the entire lengths and in the nuclei of other galaxies. Furthermore, the amount of broadening appears to increase with the ratio of the brightness of the nucleus to the brightness of the rest of the galaxy[13]. This important observation will later be referred to in the section dealing with possible mechanisms of extragalactic emission.

3. The occurrence of emission in the Milky Way.

The previous section summarized the present state of knowledge concerning emission observed in extragalactic objects. This section will deal briefly with the regions in our own galaxy from which emission spectra are obtained. Emission occurs primarily in two classes of objects in our galaxy: (1) planetary nebulae, (2) diffuse nebulae. These objects were the subject of spectrographic investigation in this thesis, the results being included in Table I.

Planetary nebulae

Planetary nebulae present rather striking appearances at the eyepiece of a large telescope or on direct photographs. Most assume

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13. Seyfert, Ap. J., Vol. 97, 39.

the form of an annulus of hazy light rather like a smoke ring. The actual form is a hollow sphere, at the center of which is a high-temperature star, which usually appears faintly, if at all, in visual observation because most of its light is in the ultraviolet where the eye is not very sensitive. The origin of these objects is unknown but it is thought that this may represent a very short phase in the life of a star. Shklovsky speculates that they may have developed from red giant stars which have used all available hydrogen. As the star collapses because of decreased radiation pressure, the core heats up and perhaps triggers an expansion of the gaseous debris left behind by the collapsing star[14]. There is sufficient evidence to rule out ordinary novae as the cause of the planetaries, namely that novae do not emit a sufficient amount of material to make up shells of the size and density of those observed. Using the observed density distribution in the neighborhood of the sun, Shklovsky also estimates that there are approximately 60,000 planetaries in the entire galaxy, and that, on the average, three are born every year[15]. The distribution of the planetaries is spherically symmetrical with respect to the galactic center and is characterized by a marked concentration toward the galactic center. Hence, the planetaries appear to occupy the substratum and are therefore Population II objects. They range in size from 20,000

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14. O. Struve, "The Origin of Planetary Nebulae", Sky and Telescope, XVI, (Aug., 1957), 469.

15. Loc. cit.

astronomical units to 200,000 astronomical units. Any larger dimension probably represents instability and the spherical shell begins to disintegrate. Spectrally, the Balmer lines of hydrogen are quite dominant although the forbidden O II line (λ3727) often rivals Hα in intensity. The degree of ionization is high, lines of O III, A IV, and Ne III showing quite brightly. The existence of many forbidden lines indicates that electron densities are very low in these objects.

Diffuse nebulae

Diffuse nebulae appear as tenuous forms of luminous gas usually found in the neighborhood of hot stars, the latter serving as the cause of excitation. The spectra of diffuse nebulae are almost identical with those of the planetaries except that certain lines in the planetary spectra may be stronger, a feature which is evident in the tabulation of the λ3869 line of N III (Table I). The spectra of diffuse nebulae, like those of planetaries, are characterized by exceptionally strong lines of hydrogen, particularly Hα.

The Crab Nebula

Another but infrequent galactic type of object exhibiting strong emission spectra consists of remnants of supernova explosions. The most striking of these examples is the Crab Nebula (M 1) of which the Chinese recorded the explosion in 1054 A.D. In form it appears as an unsymmetrical volume of gas which is expanding outward from an internal point, as shown by radial velocity measurements. Its spectrum also resembles those of diffuse and planetary nebulae, Hα being the most intense line. There is however a strong magnetic field in the nebula, as shown by the definite polarization of its continuous emission. The cause of excitation is probably non-thermal[16] and may result from the motions of large numbers of free electrons. This prompted Shklovsky to suggest that the emission of radiation is perhaps due to synchrotron action, the free electrons being accelerated along lines of magnetic force. This will give rise to polarization in all emitted wave lengths[17]. The origin of the required magnetic field is however unexplained.

In addition to its optical emission, the Crab Nebula is also the source of very strong radio noise which appears to be polarized in the same direction as the optical emission[18]. There seems to be a tendency for radio emission to accompany continuous optical emission when the cause of excitation is mechanical rather than thermal, although many radio sources are known in which there is little, if any, optical emission.

One other example of possible supernova origin is the extended Loop Nebula (NGC 6960, et al.) in Cygnus. This is also a radio source

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16. O. Struve, "The Crab Nebula as a Supernova Remnant", Sky and Telescope, XVII, (Feb., 1958), 177.

17. Ibid., 174.

18. Ibid., 175.

although not as intense as the Crab Nebula. Radial velocity measurements show that the rate of expansion is far less than for the Crab Nebula. Since the linear diameter of the Loop Nebula is greater than that of the Crab Nebula, the supernova causing the former nebula may have occurred considerably earlier. Interaction of the Loop Nebula with the existing interstellar medium has also been acting to slow down the expansion and this may be the reason for its reduced expansion velocity. If there is truly a dependence of radio emission upon the intensity of atomic collisions, this would also tend to explain the reduced radio activity of the Loop Nebula.

General emission

In the previous section on the occurrence of emission in other galaxies, considerable mention was made of the fact that most of the emission appears to be generally distributed along the entire galaxy rather than being confined to specific areas in the galaxy. The last few pages discussed specific sources in our galaxy which are the counterparts of many small emission spots which are observed in close galaxies, such as M 31 and M 33. It becomes important to inquire if there is also, perhaps, very faint emission all along the galactic plane. For if this turns out to be the case, it is entirely possible that when viewed from a distance the Milky Way would also exhibit emission along its entire length.

Struve and Elvey, in 1938, photographed the spectra of extensive areas of luminosity in the Milky Way with a novel spectrograph.

Their results were most enlightening[19]. Emission lines of Hα and λ3727 were dominant, although as a rule Hα was more intense than any other line. The nebular lines of O III were observed, as well as the [N II] companions of Hα. They found unexpectedly that the emission areas, although generally in the area of hot stars, were not particularly concentrated toward these stars. This is quite the opposite of what is observed for diffuse clouds of gas, like the Orion Nebula. Struve comments that the existence of emission as far as 7° from λ Orionis is indeed surprising, but as there is no other high temperature star in the region he concludes that the cause of excitation is actually λ Orionis. Even dark nebulae, like the Horsehead Nebula, seem to be the source of λ3727 and Hα[20]. Another unexpected result was the intensity ratio of the lines λ3727 and Hα. In the summer Milky Way, i.e. in Cygnus and Cepheus, Hα was found to be brighter than λ3727, a feature existing in nearly all diffuse and planetary objects. In fact Hα was usually about twice the intensity of λ3727 in these regions. On the other hand, the most conspicuous spectral feature of the winter Milky Way (in Monoceros, Canis Major) was the relative faintness of Hα as compared with λ3727, i.e. the ratio λ3727/Hα suffered a complete reversal in the Cygnus-Cepheus region as compared with the Monoceros-Canis Major region. In the S Monoceros

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19. O. Struve and others, "The 150 ft. Spectrograph of the MacDonald Observatory", Astrophysical Journal, Vol. 87, (1938), 559.

20. Ibid., 563.

region the ratio was in fact much greater than unity[21]. While Struve and Elvey[22] "are not prepared to state that there is a real systematic difference in the ratio of [O II] /Hα between the summer Milky Way and the winter Milky Way", Aller does interpret this reversal of intensity ratio as indicating that different physical conditions do exist in different parts of the Milky Way[23].

It is usually accepted that the cause of this general emission in the galaxy is in part integrated ultraviolet radiation from all the O and B stars in the galactic plane. However, some of this excitation may also be the result of the gaseous collisions of the interstellar medium, for generalized radio emission has been well established in the Milky Way, and, as already mentioned, radio noise is related to large scale collisions of atoms.

In summing up his preliminary findings Struve writes[24] that the great majority of extended films of nebulosity in and near the Milky Way have emission spectra. Several regions show no nebulosity on direct photographs but the spectrograph reveals emission by inter-

21. L. H. Aller, Astrophysics II, (New York, 1954), 251.

22. O. Struve and C. T. Elvey, "Observations made with the Nebular Spectrograph of the MacDonald Observatory. II", Astrophysical Journal, Vol. 89, (1939), 517.

23. Aller, op. cit., 251.

24. Struve and Elvey, Ap. J., Vol. 89, 518.

stellar gas. It is significant to note that the only region in which he did not find emission was an area of faint nebulosity in high galactic latitude.

4. Atomic Mechanisms Producing Excitation.

First Mechanism: This comprises (1) photo-excitation and (2) photo-ionization and recombination. Process (1) occurs when a photon of exactly the proper energy impinges on an atom and raises it to a given quantum state. Process (2) takes place when a photon of any energy sufficient to ionize an atom impinges on the atom; the emission occurs when the electron is recaptured and falls to lower energy levels. The latter process is the more important in diffuse and planetary nebulae since they are associated with stars whose black body radiation is most intense in the ultraviolet. The photons thus emitted by the stars are of greater than ionizing energy for most of the atoms contained in the nebulae, and emission occurs when recombination takes place. Since the density is very low in these objects an electron reaching a metastable state frequently goes directly to the ground state, because the collision rate is low, and emits a forbidden line in doing so. This accounts for the forbidden radiations being so intense in these objects.

Second Mechanism: This is the mechanism whereby an atom is excited by collision with a free electron which imparts all or part of its kinetic energy to the bound electron and thus raises it to an excited state. This mechanism is not very effective for producing permitted lines since even the first state above the ground level requires more energy than is usually found in the free electrons. But the metastable level from which forbidden radiation results requires only a fraction of the energy that the first permitted level requires, and hence the collision mechanism is very important in accounting for the forbidden lines. λ3727 has a 3.31 volt potential above the ground state of O II which corresponds to an electron velocity of about 1000 Km/sec for the required kinetic energy. Electron velocities of this order have been observed in other emission galaxies.

Third Mechanism: This last process is fluorescence, which results from the chance coincidence of an atomic excitation level with the energy content of very intense but unobservable emission radiation which arises from a basically abundant element, for example the Lyman - α line of hydrogen. No such coincidences have been demonstrated for the lines under discussion.

In considering the ionization potentials of H I and O I, 13.53 volts and 13.55 volts respectively, it is seen that any mechanism which will ionize oxygen will also ionize hydrogen. It is entirely possible that λ3727 of O II may arise from photo-ionization plus 3.31 electron-volts of collision energy which would raise a neutral oxygen atom to the singly ionized metastable state producing λ3727 in emission. But, as pointed out above, this mechanism would also ionize any hydrogen which is present and thus would seem to demand that $H\alpha$ not be less intense than $\lambda 3727$.

V. Summary

The gaseous emission radiation in the Milky Way and other galaxies can be divided into two general categories:

Category I	Category II
1. Emission originates in definite patches along arms of galaxy.	1. Emission originates all along arms of galaxy and in nucleus.
2. $H\alpha \gg \lambda 3727$ in intensity (usually).	2. $\lambda 3727 \gg H\alpha$ in intensity (usually).
3. Emission lines not broadened (Seyfert, Mayall).	3. Emission lines very broad (Seyfert).
4. Occasional association with radio emission.	4. Frequent association with radio emission.
5. Intensity not dependent on galactic type (Mayall, Aller).	5. Intensity of general emission increases as later types are considered (Humason, et al.).
	6. Intensity of nuclear emission increases with later types (Humason).
	7. Amount of broadening increases as nuclear brightness increases (Seyfert).

It appears that the emission of Category II, i.e., the general emission observed along and in the nucleus of galaxies, is not primarily due to the existence of the counterparts of hydrogen "spheres" and diffuse nebulae which are the sources of the brightest emission in the Milky Way and which show $H\alpha$ brighter than $\lambda 3727$ almost without exception. However it is highly probable that the extragalactic emission which fits into category I may be due to the existence of these objects in other galaxies. NGC 604 is close enough to us so we are able to interpret it as a diffuse nebula in one of the arms of NGC 598 and it is no surprise to find that its spectrum has the characteristics found in the spectra of diffuse nebulae in our own galaxy. If NGC 598 were farther away, the nature of NGC 604 would not be apparent by direct photography but would be revealed spectroscopically. This may be what is observed in NGC 4151 (see Table I) where many of the lines have intensities resembling those of NGC 604. However $\lambda 3727$ appears more intense than Hα and it may be that the emission consists of both local and general types.

The general emission found in most extragalactic objects falls into category II. While the excitation mechanism for category I is probably the close association of the emission patches with high temperature stars, the excitation mechanism in category II may be a combination of photo-excitation from the integrated light of O and B stars in the plane of the galaxy, and from collisions of atoms. The existence of radio emission does indeed lend weight to the suggestion of turbulence and high-energy collisions in these objects. The dependence of line widths on nuclear brightnesses also gives support to the theory of the existence of this excitation mechanism. In the Milky Way this general emission has been observed optically by Struve and Elvey, and the nuclear emission has been observed with radio techniques by Bok and others. However, just as Struve's work on general emission in our own galaxy showed that $\lambda 3727$ was not always stronger than Hα, it is entirely possible that galaxies which exhibit Hα the more strongly may also be radiating emission of category II. At this time the circumstances favoring the dominance of Hα over $\lambda 3727$ are not understood.

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