UNIVERSITY OF CALIFORNIA PUBLICATIONS
ASTRONOMY

LICK OBSERVATORY BULLETIN

NUMBER 497

THE OCCURRENCE OF $\lambda 3727$ [OII] IN THE SPECTRA OF
EXTRAGALACTIC NEBULAE

BY

NICHOLAS U. MAYALL

Systematic observation of the near ultra-violet region in the spectra of the extragalactic nebulae was initiated at the Lick Observatory four years ago with the aid of a specially designed UV glass spectrograph.¹ An unexpected result was the appearance of the forbidden line of singly ionized oxygen at $\lambda 3727$ ² as an outstanding emission feature in the spectra of a remarkably high percentage of the nebulae observed. The bright line was recorded, in fact, in nearly one half of the first fifteen nebular spectra, and this high frequency of occurrence was noted in connection with the observations reporting on the performance of the spectrograph. Since that time, spectra of almost 70 additional nebulae have been obtained, and although the observations were made primarily for the determination of apparent radial velocity, it has seemed worthwhile to utilize them for a preliminary discussion of the occurrence of $\lambda 3727$. In this first discussion of the phenomenon, it will be convenient to examine the possibility of correlating the presence of the emission with certain other nebular characteristics, namely, the type of nebula, the accompanying spectrum, and the distribution with respect to the projected figures of the nebulae.

Before proceeding to the detailed description of the Lick material, which was obtained with the 36-inch Crossley reflector, it should be stated that M. L. Humason, of the Mount Wilson Observatory, also has found

$\lambda 3727$ in a number of nebulae. In his list³ of apparent radial velocities for 100 of these objects, he noted its presence in six of them. Since this low frequency of occurrence was due primarily to the relatively low efficiency of his spectrograph for ultra-violet light, he ventured the conclusion that $\lambda 3727$ probably occurred with a frequency considerably higher than that indicated by his observations. From what follows, it will be clear that this expectation has been realized.

$\lambda 3727$ and nebular type.—Table I summarizes those data which directly pertain to the question of a possible dependence of the occurrence of $\lambda 3727$ upon nebular type. For the sake of homogeneity, the material in the table has been restricted to the Lick observations. The types assigned to the nebulae in the table represent estimates by the writer from Crossley photographs, according to Hubble's system of classification.⁴ The estimates agree closely, in general, with the classifications previously given by Hubble;⁵ the few cases where the estimates differ appreciably—for example, Hubble lists NGC 2146 as Irr, 2300 as Sc,⁶ 2976 as Sc, 3055 as SBc, and 3607 as Ep—do not markedly affect the frequencies contained within the table. The presence of $\lambda 3727$ in the spectrum of a nebula is indicated by a plus sign (+) following the NGC number, its absence by a minus sign (−). In those spectra where the presence of $\lambda 3727$ is un-

³ *Ap. J.* **83**, 10, 1936; *Contr. Mt. W. Obs.* No. 426.

⁴ *Ap. J.* **64**, 321, 1926; *Contr. Mt. W. Obs.*, No. 324.

⁵ *Ap. J.* **84**, 158, 1936; **84**, 270, 1936; *Contr. Mt. W. Obs.* Nos. 548, 549.

⁶ Evidently NGC 2300 has been confused with 2276 in Hubble's Table II, *Contr.* No. 548. These two nebulae, with $\delta = +86^\circ$, are about 6' apart. The preceding one, 2276, is Sc, the following one, 2300, is E2.

¹ *Publ. A. S. P.* **48**, 14, 1936.

² This radiation is actually a double line, the two components having wave-lengths of 3726.16 Å and 3728.91 Å. However, it appears as a single line in all the spectra considered here, because the dispersion, 240 Å per mm., is insufficient for its resolution. Even if higher dispersion were used, it is very doubtful whether the line could be resolved in general, because, in a number of spectra, it is broadened by conditions within the nebulae.

certain but suspected, or its absence not definitely established, a colon (:) precedes the appropriate arithmetical sign. For approximately one-half of the irregular nebulae, a plus or minus sign ($\pm$) has been appended to indicate the fact that, when the observations were made, the slit of the spectrograph was placed on a suspected emission patch, and hence no information was obtained concerning the occurrence of $\lambda 3727$ in the object as a whole. It should be noted, however, that the condensa-

tion selected in each nebula shows an emission spectrum in which $\lambda 3727$ is one of the outstanding radiations.

The discussion of the material in Table I should be preceded by the frank statement that in a number of cases it was quite difficult to decide whether or not $\lambda 3727$ was present in a spectrum. In these borderline cases the symbol ultimately adopted to convey the decision merely represents the experienced observer's attempt to get the most out of long-exposed, but disappointingly weak

TABLE I
OCCURRENCE (+) AND NON-OCCURRENCE (-) OF $\lambda 3727$ IN EXTRAGALACTIC NEBULAE

Elliptical E	Barred Spirals				Normal Spirals					Irregular Irr
	SBab	SBb	SBbc	SBe	Sa	Sab	Sb	Sbc	Sc	
221 -	1398:-	718 -	613:+	3953 -	205 -	2551 -	224:+	210:-	278 +	428:-
1052 +		2523:-	2146 +	7479 +	2646:-	4151 +	1068 +	1961:+	598 +	520 -
1395 -		7723:+	2633 -		3607 -	4569 -	3031 +	2268 +	753:-	1569 $\pm$
1453:-			6951 -		3941 -		4565 -	2347:-	864 +	2366 $\pm$
1889:-			7318p-		4111 +		4736 +	3310 +	871 +	2537 $\pm$
2300 -			7318f-		4594 -		7331:-	4030:-	908:-	2976:-
2314:-					4762 -		7742 +	5055:+	1232:-	3034 -
4125:-					7727 -		7769:+	7716 -	IC342 +	3077 +
4406 -									IC391 +	4236 $\pm$
4494 -									2276 -	4395 $\pm$
4552 -									2336:-	4605 +
4889 -									2389:+	
7562 -									2748:+	
7671 -									3055 +	
									3887 -	
									5248 -	
									6217 +	
									6503 +	

spectra. There are 25 nebulae to which colons have been attached, and of this number 17 precede minus signs, while eight precede plus signs. The excess of minus over plus signs is due, as might be expected, to insufficient exposure of the plates in the region around $\lambda 3727$. Since there does not appear to be any adequate method to correct for this systematic effect, except to obtain stronger negatives, the present data may be examined with the reservation that the observed frequencies of occurrence of $\lambda 3727$, shown in Table II, probably represent minimum values.

Since the number of observations is rather small, especially for the barred spirals, the frequencies in Table I for the intermediate sub-classes SBab, SBbc, Sab, and Sbc have been equally apportioned between the adjacent early (a), intermediate (b), and late (c) types to give the frequencies shown in Table II. Thus, in this table the frequencies for Sb, 13.5 nebulae observed, 8.5, showing $\lambda 3727$, were obtained by forming the frequency totals from Table I in the sense $1/2 \text{ Sab} + \text{Sb} + 1/2 \text{ Sbc}$; i.e. $13.5 = 1/2 \cdot 3 + 8 + 1/2 \cdot 8$, and $8.5 = 1/2 \cdot 1 + 6 + 1/2 \cdot 4$.

Despite the scarcity of material for the barred, and early-type normal spirals, the data in Table II strongly

TABLE II
FREQUENCY OF $\lambda 3727$ ACCORDING TO NEBULAR TYPE

Nebular type	No. of Neb. obs.	No. of Neb. showing $\lambda 3727$	Percent of Neb. showing $\lambda 3727$
All E	14	1	7%
SBa	0.5	0	0
SBb	6.5	2	31
SBc	5	2	40
All SB	12	4	33
Sa	9.5	1.5	16
Sb	13.5	8.5	63
Sc	22	13	59
All S	45	23	51
All S+SB	57	27	47
All Irr	6*	2	33
All Neb.	77	30	39

* Irr nebulae marked $\pm$ in Table I are omitted.

indicate the following conclusions concerning the occurrence of $\lambda 3727$ as a function of nebular type:

In the elliptical nebulae, this emission probably is quite rare. It has been found only in two such objects up to the present time: in NGC 1052 (at Lick) and in NGC 3377 (at Mount Wilson), although nearly 50 of the brightest of these nebulae have been observed spectroscopically. Even if allowance is made for the fact that many of the spectra were photographed with instruments not especially designed to cover the spectral region in the vicinity of $\lambda 3727$, it seems very doubtful whether the [OII] doublet would be present in considerable intensity in more than a few percent of the elliptical nebulae so far observed. In them, the concentration of light toward the nuclear region is so pronounced that they are very inviting objects for spectroscopic investigation. Hence, it may reasonably be assumed that their spectra were strongly enough recorded to show $\lambda 3727$ if it were a prominent feature of the spectrum.

2. For the normal spirals, there is fairly good evidence that $\lambda 3727$ occurs much more often among the intermediate and late types than it does in the early types, the relative frequency being somewhat less than 4 times as great for the former as for the latter. In type Sa, $\lambda 3727$ was found in about 1 in 6 nebulae, while in types Sb and Sc it appeared in 6 in 10. Undoubtedly, more data would be desirable to determine whether the variation in frequency takes place uniformly according to type and subtype, but the present material appears adequate to establish the existence and direction of the trend.

3. The barred spirals, unfortunately, are too poorly represented in the present observations to give significant results, insofar as the occurrence of $\lambda 3727$ in the series of nebular types is concerned. About all that can safely be said for these objects is that the bright line was found with a frequency of 1 in 3 for the entire group of 12 nebulae. If this uncertain result be compared with the corresponding figure for all the normal spirals, 1 in 2, there is a hint that perhaps $\lambda 3727$ is not quite so common in the barred as in the normal spirals. Additional weight for this inference comes from the circumstance, discussed in detail below, that, in this material, the spectra of the barred spirals seem to be intermediate between those of the elliptical nebulae and those of the normal spirals. Consequently, a frequency of occurrence for $\lambda 3727$ which falls between those for types E and S might reasonably be anticipated for type SB.

4. The irregular nebulae likewise are very incompletely observed. According to Table II, there are but six spectra capable of yielding any information about the occurrence of $\lambda 3727$ in these peculiar and interesting objects; of the six, two show the emission in question, giving an observed frequency of 1 in 3. It is not easy to estimate how much this value departs from the true one, principally because of the extreme difficulty of obtaining spectra of

the low surface-brightness systems of NGC 2366, 4236, 4395, and others. Nevertheless, irregular nebulae of this type almost invariably contain one or more condensations known to have emission spectra, and, as already mentioned, $\lambda 3727$ is always present as a prominent line. On this basis, therefore, it might be asserted that a frequency of occurrence of $\lambda 3727$ of 1 in 3 is to be regarded as a minimum value for the irregular nebulae.

$\lambda 3727$ and the accompanying spectrum.—Table III and Plate I have been prepared with the idea of giving a very rough, qualitative description of the general nature of those nebular spectra in which the [OII] doublet is present or suspected. Too much emphasis cannot be laid on the fact that the tabulated estimates of intensity given for the bright lines, the terms employed to describe the width, visibility, and spectral type of the absorption lines, and the words used to designate the strength of the near ultra-violet continuous spectrum ($\lambda\lambda 3700-3900$) relative to the spectrum of the ordinary photographic region ($\lambda\lambda 3900-5000$), are all undoubtedly seriously influenced by the quality of the original negatives, the variable atmospheric transparency during long exposures, photographic effects, and, above all, by the writer's personal equation. The value of such data, therefore, is clearly limited, and the estimates are to be regarded as but crude indicators of possible correlations between the variables considered.

In the first place, there appears to be a loose relation between the strength of $\lambda 3727$ and the presence of other bright lines. It is in the expected sense that when $\lambda 3727$ 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. Very faint bright lines, could, of course, occur in the spectra and still not be recognized as such because of the low dispersion used, but this possibility has to be passed over in a preliminary discussion.

Second, there is no conspicuous connection between the intensity of $\lambda 3727$ and the width of the absorption lines. Nearly all possible combinations of different line-widths and intensities are found in the spectra of the nebulae observed. Although the table contains no estimates of the width of $\lambda 3727$, it should be mentioned that, when it is wide, all the other lines, both dark and bright, are correspondingly broadened.

Third, there is some indication that the presence of $\lambda 3727$ is connected with the visibility of the absorption lines. For distinctly seen dark lines, the average intensity of $\lambda 3727$ is 2.6, for indistinct lines, 4.0, and for those barely seen, 5.1. Approximate as the relation is, it is of very real importance for radial velocity measurements, for it frequently happens, especially among Sc spectra, that $\lambda 3727$ is about the only feature of the spectrum that gives a reliable measure of the red-shift. Once it is seen, a

TABLE III
CHARACTER OF SPECTRUM ACCOMPANYING $\lambda 3727$

NGC	Type	$\lambda 3727$ (Intensity)	Other Emission Lines (Intensities)	Character of Absorption Lines*			Rel. Strength UV Cont. Sp.
				Width	Visibility	Sp. Type	
1052	E3	(5)	none observed	wide	distinct	G5	normal
7723	SBb	(1)	none observed	wide	indistinct	G5	weak
613	SBbc	(1)	none observed	normal	distinct	G5	weak
2146	SBbc	(4)	none observed	v. wide	barely seen	G5:	strong
7479	SBc	(2)	none observed	narrow	distinct	G4	normal
4111	Sa	(2)	none observed	normal	distinct	G2	normal
4151	Sab	(10)	cf. A. S. P. 46, 134, 1934	v. wide	barely seen	(G—)	strong
224	Sb	(1)	none observed	wide	distinct	G5	normal
1068	Sb	(8)	3869 (9), 3968 (0), H δ (1), H γ (3), 4686 (4), H β (2), N $_2$ (4), N $_1$ (6)	wide	indistinct	G5	normal
3031	Sb	(3)	none observed	normal	distinct	G5	normal
4736	Sb	(6)	H γ (1), H β (2)	wide	indistinct	G2	strong
7742	Sb	(2)	none observed	narrow	indistinct	G4	normal
7769	Sb	(1)	none observed	normal	indistinct	G2	strong
1961	Sbc	(1)	none observed	v. wide	barely seen	G5:	weak
2268	Sbc	(2)	none observed	wide	indistinct	G5	normal
3310	Sbc	(10)	3968 (1), H δ (2), H β (3), N $_1$ and N $_2$ (1) not res.	narrow	barely seen	G0	strong
5055	Sbc	(1)	none observed	wide	distinct	G2	normal
278	Sc	(5)	none observed	wide	indistinct	(A6)	strong
598	Sc	(6)	none observed	normal	distinct	G0	normal
864	Sc	(2)	none observed	normal	indistinct	G4:	weak
871	Sc	(6)	none observed	wide	barely seen	G5:	strong
IC342	Sc	(2)	H β (2)	wide	indistinct	G2	normal
IC391	Sc	(5)	none observed	wide	barely seen	G0:	strong
2389	Sc	(1)	none observed	wide	barely seen	G2:	weak
2748	Sc	(1)	none observed	v. wide	barely seen	G2:	weak
3055	Sc	(3)	H γ (1), H β (2)	v. wide	barely seen	G0:	normal
6217	Sc	(3)	H γ (1), H β (2)	wide	indistinct	G0	normal
6503	Sc	(2)	none observed	normal	distinct	G0	strong
3077	Irr	(10)	H γ (2), 4363 (1), H β (4), N $_1$ (1), N $_2$ (2)	wide	indistinct	G2	strong
4605	Irr	(6)	none observed	wide	indistinct	G0	strong

* The absorption lines are: K, H+H ϵ , H δ , G-band, H γ , and, occasionally, Fe 4383.

few dark lines also can be identified and measured to confirm the general order of the red-shift, but because of their poor visibility, the settings normally are given low weight.

Fourth, the spectral type of the absorption spectrum shows very little correlation with the intensity of $\lambda 3727$. The average intensity for seven G0, eight G2, three G4, and ten G5 nebulae is 5, 3, 2, and 3.2, respectively. It may be significant that the earliest spectral class shows the highest average intensity for $\lambda 3727$, but the data clearly are too meager to establish a definite run with spectral type. It is interesting to note at this time that there is an apparent progression in Table III of spectral type with respect to nebular type for those objects showing $\lambda 3727$. It is in the sense that E, SB, S, and Irr nebulae have average spectral types of G5, G4.8, G2.4, and G1 respectively, but because of the small number of objects involved (one E, four SB, twenty-one S, and two Irr), the reality of the correlation may be ques-

tioned. The types for the few E and SB objects showing $\lambda 3727$, nevertheless, seem to be fairly representative, since the average spectral types for all 14 elliptical nebulae, and for all 12 barred spirals listed in Table I, are G5.0 and G3.7, respectively. Possibly additional observations of SBc nebulae, which are poorly represented in this material, would yield an average spectral type more like that for the normal spirals, but until they are available, a value for the barred spirals intermediate between those for elliptical and normal spirals is suggested by the present data.

Finally, the intensity of $\lambda 3727$ evidently is closely related to the relative strength of the near ultra-violet continuous spectrum. For weak, normal, and strong continua the average intensities of $\lambda 3727$ are 1.2, 3.1, and 5.9, respectively.

Distribution of $\lambda 3727$ in the projected nebular figures.—Not all of the present material is adapted to the investigation of the distribution of $\lambda 3727$ in the projected nebu-

NGC 7769
Int. $\lambda 3727=1$

NGC 7742
Int. $\lambda 3727=2$

NGC 6217
Int. $\lambda 3727=3$

NGC 3055
Int. $\lambda 3727=3$

NGC 2146
Int. $\lambda 3727=4$

NGC 1052
Int. $\lambda 3727=5$

NGC 278
Int. $\lambda 3727=5$

NGC 1068
Int. $\lambda 3727=8$

Typical spectra of extragalactic nebulae with $\lambda 3727$ [OII] showing different intensities.

NGC 3031

Type Sb Int. $\lambda 3727 = 3$

NGC 4005

Type Irr Int. $\lambda 3727 = 6$

NGC 4736

Type Sb Int. $\lambda 3727 = 6$

NGC 5055

Type Sbc Int. $\lambda 3727 = 1$

NGC 6503

Type Sc Int. $\lambda 3727 = 2$

NGC 3077

Type Irr Int. $\lambda 3727 = 10$

NGC 3310

Type Sbc Int. $\lambda 3727 = 10$

Spectra of extragalactic nebulae showing the distribution of $\lambda 3727$ [OII] within the nebulae.

TABLE IV
DISTRIBUTION OF $\lambda 3727$ IN THE PROJECTED FIGURES OF NEBULAE

NGC	Type	Slit		Orientation on nebula	Exp. time	Description of Regions which show $\lambda 3727$
		Length	P.A.			
224 (M31)	Sb	6'2	37°	Major axis	7 ^h 20 ^m *	Susp. near nucleus. Cf. Babcock, <i>Publ. A. S. P.</i> 50, 175, 1938.
598 (M33)	Sc	6.2	110	Minor axis	15 45	Out to 1' each side of nucleus. Cf. <i>Publ. A. S. P.</i> 51, 113, 1939
871	Sc	0.75	0	Major axis	4 30	Entire nebula. Intensity varies like that in direct image
2748	Sc	2.4	40	Major axis	8 30	Susp. across entire nebula in faint, irregular intensity.
3031 (M81)	Sb	6.2	155	Major axis	17 00*	Probably only in the nucleus
3031 (M81)	Sb	6.2	65	Minor axis	6 30*	Probably only in the nucleus
3055	Sc	3.2	72	Major axis	5 00	Central part about 0'3 long (i.e. in short central bar)
3077	Irr	1.0	90	East-west	5 00	About 0'4 of nuclear region
3310	Sbc	1.0	90	East-west	2 30	In the spiral arms, each side of center, where they crossed the slit
4111	Sa	6.2	150	Major axis	4 30	Probably only in the nucleus
4151	Sab	6.2	125	Major axis	16 00	Nucleus, and possibly in very faint outer spiral structure
4605	Irr	6.2	118	Major axis	5 00	Entire nebula, with intensity varying like that in direct image
4736 (M94)	Sb	6.2	123	Major axis	14 25*	In the inner spiral structure, where it crossed the slit
5055 (M63)	Sbc	6.2	100	Major axis	7 00*	Susp. out to 1' each side of nucleus
6503	Sc	1.6	124	Major axis	6 00	Across all of the nebula which fell on the slit
7479	Sbc	0.75	6	Along bar	5 30	Nucleus. (Slit too short to cover all of the bar)
7742	Sb	0.5	90	East-west	6 00	Nucleus, and probably where ring crossed the slit

* Plates taken by H. W. Babcock. That for 224 will be reproduced in a forthcoming Lick Observatory Bulletin entitled "The Rotation of the Andromeda Nebula."

lar figures. For the case of small nebulae, or for semi-stellar nuclei of large, faint spirals, the object on the slit was allowed to drift in order to give a spectrum sufficiently wide for reliable measurements of apparent radial velocity. Furthermore, during the first two years when these spectra were being photographed, it was not possible to use a long slit. However, when it became clear that the general prevalence of $\lambda 3727$ among the spirals was a phenomenon deserving of careful attention, the construction of the slit mounting was modified so as to permit the use of slit lengths up to a maximum of 6.2 minutes of arc. The observations were thereafter made, whenever practicable, by keeping the slit stationary with respect to the nebula, choosing its length to suit the object, and orienting it, in general, along the major or minor axis. Of the nebulae listed in Table III, only about one-half were observed in this manner.

Table IV contains brief descriptions of the relation of $\lambda 3727$ to the general appearance of the nebula, and Plate II shows some of the spectra, together with the corresponding nebulae as they appear on direct photographs.

The data in Table IV do not permit any very clear-cut generalizations. There may be a slight tendency for

$\lambda 3727$ to be confined principally toward the nuclear regions in the earlier type spirals, and for it to be distributed more or less uniformly throughout the entire nebula in the later types. Three of the Sc objects, NGC 871, 2748, 6503, in which $\lambda 3727$ was found across the entire nebula, are oriented with their principal planes nearly in the line of sight, and hence the chance of detecting $\lambda 3727$ throughout each system was thereby very considerably increased. On the other hand, when an Sc nebula is placed with its plane nearly at right angles to the line of sight, the difficulty of obtaining a spectrum of the faint, outer structure is so great as to discourage the making of observations, and the usual practice has been to photograph only the spectrum of the nucleus, in which $\lambda 3727$ has been found with a frequency of about 6 in 10, as has been mentioned. There is also some suggestion that the occurrence of the [OII] doublet is related to the spiral structure. In three cases, NGC 3310, 4736, and 7742, where the spiral is characterized by prominent, bright spiral arms, or by a ring containing spiral structure, $\lambda 3727$ has been found in those regions in considerable intensity. A similar nebula, well worth study from this point of view, is NGC 5194-5 (M51), the famous Whirlpool Nebula.

General discussion and interpretation of the observations.—In a preliminary attempt to interpret the phenomenon, two questions come naturally to mind: (1) Why should $\lambda 3727$ in particular be found more often than other forbidden lines? (2) What do the circumstances of its occurrence signify? In the present state of our knowledge, the first question can be answered more satisfactorily than the second, since relatively much more is known about atomic structure than nebular structure.

Bowen⁷ has shown that the intensity I of an emission line may be written as

$$I = N \cdot \frac{A_1}{B+C+A_1+A_2+A_3+\dots} \cdot h\nu.$$

In this formula N is the number of atoms arriving in the upper or initial state of the transition which gives the line in question. The expression

$$\frac{A_1}{B+C+A_1+A_2+A_3+\dots},$$

is the fraction of these atoms that drop to the lower state with the emission of the line considered. Here the numerator, A_1 , is the transition probability between the upper and lower states that give the line, and the denominator is the sum of the probabilities of all possible means of removal from the upper state. These other possibilities for removal from the upper state, in addition to that represented by the emission of the line considered, are: (1) removal by collision, the probability for which is B ; (2) removal by absorption of radiation, having a probability C ; and (3) removal by transitions to other states lower than that for the line considered, the separate probabilities for which are A_2 , A_3 , etc. The term $h\nu$ is the energy of the quantum, which is equal to Planck's constant, h , times the frequency, ν , of the line emitted.

The application of the above formula to the particular case of $\lambda 3727$ requires a knowledge of the character of its upper and lower states, its transition probability, and some information concerning the physical conditions in the sources where it is observed. In the first place, the upper level, 2D , is metastable, and no permitted lines from it are possible. Secondly, the upper level is the penultimate state, and the lower, 4S , is the ground state. Hence no other forbidden lines are possible. For these two reasons, $A_2 + A_3 + \dots = 0$. In a sense, therefore, the emission in question is an ultimate or resonance line in the entire spectrum of OII, and its excitation requires less energy than any of the other lines. However, this circumstance probably is not the most important one in the production of the line in the extragalactic nebulae. A much more likely explanation is suggested by the following consideration. Although the transition

⁷ *Rev. of Mod. Phys.*, **8**, 55, 1936.

probability A_1 is extremely small, or, the mean life ($1/A_1$) in the 2D level extremely long (of the order of 2–3 hours⁸) compared to most of the known metastable states, the mean density of matter and radiation in these nebulae is so low that B and C may become small in comparison with A_1 . Consequently, despite the very low transition probability for this line the fraction

$$\frac{A_1}{B+C+A_1+A_2+A_3+\dots} \text{ for } \lambda 3727 \text{ may approach unity}$$

under these rather special physical conditions. The result is that the number of transitions from the 2D to the 4S level may become nearly equal to the number of atoms arriving in the 2D level, which is the condition, according to Bowen,⁹ for the appearance of a forbidden line in full strength. Hence the observed fact that $\lambda 3727$ is found more frequently than other forbidden lines in the spectra of the extragalactic nebulae is quite consistent with the known properties of the [OII] atom, taken in connection with the probable state of matter in the nebulae.

With respect to the second question, the significance of the circumstances of occurrence of $\lambda 3727$, there appear to be two alternative interpretations. One is that the line originates in more or less localized or patchy, diffuse gaseous nebulae, which probably derive their energy from involved stars of fairly high luminosity. The relation established by Hubble¹⁰ for the galactic diffuse emission nebulae and stars hotter than B1 is an example of this mechanism. The second interpretation is that the line is primarily of interstellar origin, deriving its excitation energy from the general radiation field of many stars in a given system. From this viewpoint, the emission in question may be regarded as the bright-line counterpart of the dark absorption lines of Ca^+ , Na , and Ti^+ due to interstellar material in the Galaxy. It was natural to suspect, therefore, that $\lambda 3727$ may exist also as a faint diffuse emission in the Milky Way, the more especially so because our own stellar system gives many signs that it is a late type, presumably spiral, nebula similar to those in which $\lambda 3727$ most frequently occurs. This expectation has been realized within the past year when Struve and Elvey¹¹ discovered that this emission exists in the Galaxy as faintly luminous, very extensive nebulosities in Cygnus and Cepheus. They also consider it probable that many other portions of the Milky Way would reveal the presence of the same bright line, and remarked that to an external observer, the general galactic spectrum would consist of "a fairly strong emission spectrum superimposed over the integrated spectrum of all the stars." The spectroscopic observations of the extragalactic nebulae reported herein are altogether consistent with this conclusion.

⁸ Pasternack, *Publ. A. S. P.*, **51**, 161, 1939. ⁹ *Loc. Cit.* p. 64.

¹⁰ *A. J.* **56**, 162, 400, 1922; *Contr. Mt. W. Obs.*, Nos. 241, 250.

¹¹ *Science*, **88**, supp. p. 8, 1938.

Which of these two possible interpretations of $\lambda 3727$ is the more probable, apparently cannot be decided from the available data. It may be that the phenomenon actually represents a combination of both sources of excitation, the relative importance of the two varying according to the type of system considered. In this respect, the frequency of occurrence of $\lambda 3727$ according to nebular type is a relation sufficiently important to warrant careful attention in future discussions of other nebular characteristics which show progressions in Hubble's scheme of classification. If the line is not predominately interstellar, studies of its distribution in nebulae of different types may give useful information concerning the distribution of the higher luminosity stars in these systems. On the other hand, if the line is primarily of interstellar origin, investigations of its distribution offer a means for obtaining information concerning the rôle played by interstellar material in the sequence of nebular forms. In either case, however, the present data yield new evidence in support of the adopted system of classification of nebulae.

It may be appropriate to consider briefly at this time the occurrence in nebular spectra of other bright lines, although they are not, in general, so characteristic as is $\lambda 3727$. According to Table III, when the [O II] doublet is strong, the other emissions usually are the hydrogen lines $H\delta$, $H\gamma$, and $H\beta$, the chief nebular lines N_1 , N_2 , and $\lambda 4363$ of [O III], and, occasionally, $\lambda 3869$ and $\lambda 3968$ of [Ne III]. The presence of the latter pair of lines in several nebulae is especially noteworthy, since a fairly high de-

gree of excitation is required for their production. In this connection, it is important to draw attention to the spiral nebula NGC 4151, which has a truly remarkable spectrum. In this object, a number of lines of extremely high excitation have been found. Among these are the principal forbidden radiations of Ne V, A IV, and Fe VII. The spectrum is so interesting, in fact, that it deserves special treatment, and it is hoped to present the detailed observations in the near future in a separate paper.

One other emission of particular interest from the standpoint of a possible interstellar origin is the [N I] close doublet at $\lambda 5200$, which corresponds to the $^4S-^2D$ transition that gives $\lambda 3727$ of [O II]. Bowen has pointed out to the writer that this [N I] line has an extremely long mean life (of the order of 9-13 hours¹²) in its upper state. For the same reasons that have been advanced to explain the general prevalence of $\lambda 3727$, this [N I] emission may be expected to exist in the spectra of a number of extragalactic nebulae. At the present time it has been found only in NGC 4151, but whether or not this is a significant observation clearly cannot be decided on the basis of this one instance, especially since the spectrum accompanying it is so anomalous.

In conclusion, the writer wishes to express his indebtedness to Dr. H. W. Babcock for obtaining the long exposures identified in Table IV, and to Professor I. S. Bowen for valuable discussions of his published and unpublished material on forbidden lines.

¹² Pasternack, *Loc. Cit.*

LICK OBSERVATORY,
MAY, 1939
ISSUED SEPTEMBER 25, 1939.