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FAINT EMISSION LINES OF GASEOUS NEBULAE

J. B. KALER
University of Illinois Observatory

AND

L. H. ALLER
University of California, Los Angeles
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ABSTRACT

We have reexamined tracings of the long-exposure plates used in the studies of NGC 7009, NGC 6572, and IC 4997, and have identified and measured the intensities of many faint spectrum lines that lie just above the plate-noise limit. We have also measured the intensities of a number of lines which were previously identified visually but for which no intensity measurements were originally made, and we have corrected some errors in the earlier work.

I. INTRODUCTION

A great deal of effort has been expended in the last few years on the identification and the measurement of the intensities of spectrum lines of gaseous nebulae. We wish to report here on a reevaluation of the spectra of three bright nebulae, NGC 7009 (Aller and Kaler 1964*a*) and NGC 6572 and IC 4997 (Aller and Kaler 1964*b*); these papers are referred to as AK I and AK II, respectively. For each of these three nebulae, of the order of 300 spectrum lines have previously been identified between 3000 and 5000 Å.

Since these papers were published, we have greatly increased the number of data available on faint lines and have considerably improved the quality and completeness of line identifications by the observation of many more nebulae. In view of our increased experience and of the great difficulty of obtaining additional data, we feel that it is important to get as much out of the existing observations as possible. We have therefore studied the tracings of the long-exposure plates used in AK I and AK II in order to uncover faint lines which lie only a little above the plate noise. During the course of this study we found we were able to make a number of other additions and improvements to the original tables, which are also reported.

II. PROCEDURE AND RESULTS

The basic problem involved is one of signal to noise. We must detect a small signal in the noise produced by the grain of the plate. In practice we established an average noise level from the calibration wedges and from line-free portions of the plate. Any feature which rose above this level and which also satisfied a criterion for width (that the feature should have a shape and width similar to that of the stronger established lines) was called a line. The identifications were made from Moore's (1945) revised multiplet table (RMT) and Bowen's (1960) list of forbidden lines. We measured the intensities of the lines by the reduction procedures described in AK I and AK II. The results of this search are presented in Tables 1 (NGC 7009), 2 (NGC 6572), and 3 (IC 4997). Columns (1) and (2) give the measured wavelengths and the identifications, respectively; column (3) gives the RMT multiplet number (for permitted transitions only); column (4), the true wavelength (with the first two digits omitted) from the RMT and Bowen (1960); and the last column, the intensity on the scale $I(H\beta) = 100$. Notes regarding comments on individual lines are on the first page of Table 1.

Table 1

New Lines in NGC 7009
I(Hβ) = 100

λ	ID	Mult.	λ_R	I
4931	[O III]		31.0	0.45*
4882.5	[Fe III]		{81.1, 84.0}	0.09
4867.3	{N III, [Fe IV]}	9	67.2, {67.4, 66.5}	0.08
4784.5	[Cr V]†		85.0	0.10
4775.0	{C I, N II}	6, 20	75.9, 74.2	0.12 §
4689.2				0.05
4608.3	{K II?, [Fe III]}	3	08.5, 07.1	0.03
4518.1	N III	3	18.2	0.07
4466.2	O II	87	66.3	0.05
4452.4	O II	5	52.4	0.04
4396.0	O II	26	96.0	0.02
4365.9	Ne II	57	65.7	0.06
4353.7	{N III, O II}	10, 76	53.7, 53.6	0.02
4324.0	N III	10	23.9	0.02
4312.1	O II	79	12.1	0.02
4305.9	O II	55	05.5	0.02
4275.0‡	O II	67	75.5	0.05
4263.6	K II	2	63.4	0.05
4240.9				0.02
4179.7	N II	50	79.7	0.03
4166.3				0.02
4130.9?	[Fe III]†		30.8	0.03
4108.8	O II	48	08.8	0.03
4054.5	O II	98	{54.1, 54.6}	0.02
4005.0				0.03

Explanation for Tables 1, 2 and 3

* poor correction to outside the atmosphere.
† forbidden line previously unidentified in nebulae.
‡ blended with adjacent strong line.
§ enhanced toward outer, lower excitation portion of ring.

Table 1--Continued

λ	ID	Mult.	λ_R	I
3974.2				0.03
3959.9				0.03
3955.9	N II	6	55.9	0.03
3912.0	O II	17	{12.0, 12.1}	0.03
3875.3	O II	13	75.8	0.03
3864.6	O II	12	{64.5, 64.7}	0.04
3860.6	S III	5	60.6	0.04
3848.0	O II	12	47.9	0.03
3843.0	O II	12	42.8	0.02
3795.2	[Fe V]		95.2	0.05
3792.7:	N III	11	92.9	0.03
3783.8	[Fe V]		83.6	0.03
3781.8	He II	5	81.7	0.07
3780.5				0.03
3779.5	N III	11	79.2	0.03
3755.9	He I	66	56.1	0.04
3748.5	He II			0.04
3717.8	S III	6	17.8	0.04
3710.5	S III	1	10.4	0.04
3698.9	O III	21	98.7	0.04
3648.9	O III	35	49.2	0.03
3601.2				0.05
3599.7	He I	30	99.4	0.04
3566.0?				0.03
3561.0	Ne II	31	61.2	0.03
3558.3	Ne II	6	57.8	0.03
3545.2				0.04
3542.5	Ne II	50	42.3	0.03
3495.3	O II	70	95.4	0.04
3463.1				0.04
3461.0	He I			0.03
3456.8	He I			0.03
3453.2	He I			0.03
3427.5				0.05
3423.7				0.06
3354.0	N III	5	{53.8, 54.3}	0.05
3331.0	N II	22	31.3	0.09
3329.2	Ne II	12	29.2	0.08
3323.9	Ne II	7	23.8	0.08
3218.3	{Ne II, O II}	13, 107	18.2, 18.1	0.05

Table 2

New Lines in NGC 6572
I(Hβ) = 100

(See Table 1 for explanation of footnotes.)

λ	ID	Mult.	λ_R	I
4903.5				*
4702.0	[Fe III] O II	 58	01.6 01.8	0.06
4653.7	O I?	18	54.2 54.6	0.05
4513.0				0.05
4452.9	O II	5	52.4	0.05
4448.9	O II	35	48.2	0.05
4446.9	N II	15	47.0	0.05
4320.2	O II	61	19.9	0.09
4315.8	O II	78	15.8	0.06
4313.6	O II C II	78 28	13.4 13.5	0.04
4295.3	O II C II	54 42	94.8 96.1	0.06
4283.7	O II	67	83.8	0.06
4257.2				0.06
4192.9	O II	42	92.5	0.04
4093.2	O II	10	92.9	0.06
4087.2	O II N II	48 37	87.2 87.4	0.06
4056.4	C III	24	56.1	0.05
4041.6	O II N II	50 39	41.3 41.3	0.06
3988.4				0.06
3963.0	O II	43	63.1	0.06
3958.6				0.06
3951.3				0.04
3947.9	C II	31	47.6 47.9	0.04
3946.0	C II	31,32	46.4	0.04
3935.9	He I	57	35.9	0.04
3914.9				0.05
3912.5	O II	17	12.0 12.1	0.05
3911.4				0.05
3909.9				0.07
3896.3	O II	11	96.3	0.05

Table 2--Continued

λ	ID	Mult.	λ_R	I
3892.5				0.05
3884.2	C III	15	83.8	0.05
3817.8				0.06
3811.2	O III	2	11.0	0.07
3808.7				0.06
3783.1	K II?	2	83.2	0.05
3780.2				0.05
3764.7				0.03
3737.5				0.04
3717.2				0.06
3640.5				0.06
3628.3	Ne II	41	28.1	0.08
3615.6	N II Mg II?	26 2	15.9 15.9	0.10
3599.8	He I	30	99.4	0.08
3563.0	He I	33	63.0	0.08
3543.1	Ne II	34	42.9	0.07
3503.5	Ne II	28	03.6	0.06
3480.6	Ne II	49	80.8	0.12
3470.5	O II	27	70.8 70.4	0.08
3387.0?	S III	2	87.1	0.15
3385.8	Ne II O III	12 27	86.2 85.0	0.10
3356.0	O III	28	55.9	0.15
3299.4	O III?	3	99.4	0.09
3262.6	C III	6	62.2	0.08
3260.7	O III	8	70.0	0.17
3234.8				0.16
3201.2	O III	31	01.1	0.15
3109.0	[A III]		09.2	0.25

Table 3

New Lines in IC 4997
I(Hβ) = 100

(See Table 1 for explanation of footnotes.)

λ	ID	Mult.	λ_R	I
4931	[O III]			*
4921	He I	49	21.9	1.4
4783.1	Ne II	71	82.0	0.06
4774.4	N II	20	74.2	0.04
4695.8	N II	68	95.9	0.04
4568.8	Ne II	69	69.0	0.03
4489.0	O II	86	89.5	0.02
4475.0	Ne II	65	75.2	0.02
4439.5	{Ne II S III	65 7	39.3 39.9}	0.015
4264.5				0.02
4142.3	O II	106	42.2	0.05
4116.2	Si IV	1	16.1	0.015
4103.8	N III	1	03.4	0.06
3945.9	C II	31,32	46.3	0.03
3929.4				0.03
3881.5	O II	12	82.2	0.02
3852.6				0.02
3849.1				0.02
3813.7				0.03
3564.3				0.04
3562.5	He I	33	63.0	0.04
3456.8	He I			0.03
3399.0				0.03
3346.9				0.03
3306.1	O II	23	06.6	0.04
3278.7	{K III Si III	1 12	78.8 79.3}	0.04
3260.7?	O III	8	61.0	0.02
3239.1	{[Fe III]† O III	 9	39.7 38.6}	0.05
3236.9				0.05
3232.9	S III	3	33.2	0.03
3216.8	O II	107	16.8	0.05
3209.4	Ne II	16	09.4	0.05

It is quite possible, of course, that any given weak line can be a noise bump instead of a line. In order to aid in the interpretation of the tables (and for that matter those of AK I and AK II), we present in Figure 1 the half peak-to-peak noise levels for these long-exposure plates in intensity units corrected to outside the atmosphere. The stronger the observed line, the greater the probability that it exists. For example, if the intensity of the line is more than twice as great as the average noise level at the appropriate wavelength, the line is almost certainly real. The lines which should be most suspect are the weak ones with no identifications. Of course, an identification is no absolute criterion for proving the reality of a given line, as the wavelength density of lines is high enough to produce occasional coincidental identifications of noise bumps. Of the observations, those of NGC 7009 have the highest weight, and IC 4997 the lowest.

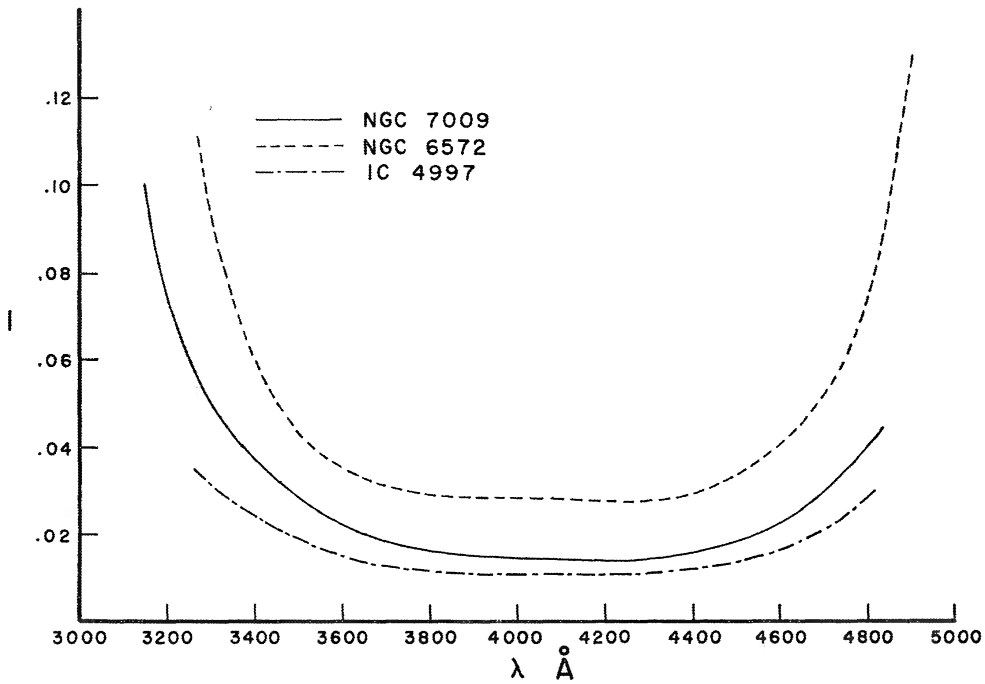

FIG. 1.—Half peak-to-peak noise levels in intensity units corrected to outside the atmosphere

In all three nebulae the wavelengths were measured from the tracings, where the stronger well-known lines were used as wavelength standards. The wavelengths of the lines thus measured are accurate to about 0.2 Å for NGC 7009 and NGC 6572, and to 0.2–0.5 Å for IC 4997. The wavelength accuracy decreases with intensity, because of the effect of the noise.

The intensities of the faintest lines are subject to large error, possibly up to a factor of 2. The identifications of the lines from the tracing of NGC 7009 were checked against the original plate, and the agreement was found to be very good.

III. IMPROVEMENTS TO ORIGINAL TABLES

During the search for faint lines we were able to make a number of improvements and corrections to the original tables in AK I and AK II. These results are presented in Tables 4, 5, and 6. Column (1) gives the wavelength as taken from AK I and AK II; column (2), the currently adopted identification; column (3), the RMT multiplet number for permitted lines; column (4), the currently measured intensity; and column (5), the type of change that has been made to the line. The explanation to these tables and

Table 4

Corrections and Additions to Lines Already Identified in NGC 7009

λ	ID	Mult.	I	Remarks
4921.96	He I	48	1.1	1
4805.06				2 λ3203
4782.39				2 λ3187
4705.36	O II	25	0.05	1
4702				3
4698.27				2 λ3132
4683.40				2 λ3121
4667.28	N II	11	0.06	1
4658.4	C IV	8	0.07	1
4631.10	N II	5	0.10	1, 4
4621.07	O II	92	0.03	1, 4
4613.30	O II	93	0.03	1
4557.72				3
4552.4	N II	58	0.07	1
4531.96				3
4530.32	N II	59	0.07	1
4529.7	O III	32	0.05	1
4527.82				3
4521.07				3
4517.32	C III	9	0.04	1
4453.29				3
4442.47				3
4434.87			0.03	1
4432.76	N II	55	0.07	1
4428.5	Ne II	61,57	0.07	1

Explanation for Tables 4, 5 and 6

1 addition of or correction to intensity.
2 third order line of wavelength given.
3 no line.
4 change in identification.
5 correction to wavelength as given in last column.
6 night sky Hg.
7 one line only, at mean wavelength.
* no intensity, line blended.
† no correction to outside the atmosphere.
‡ line originates in central star, not in nebula.

Table 4--Continued

λ	ID	Mult.	I	Remarks
4425.4				3
4327.63				3
4325.83	O II	2	0.07	1
4309.21	K II	7	0.02	1
4307.33	O II	53	0.05	1
4267.11	C II	6	1.04	1
4241.24	Ne II	52	0.10	4, 5 λ4242.24
4225.07	K II	4	0.03	4
4176.75	N II	42	0.03	5 λ4176.0
4109.82				3
4083.86	O II	49	0.14	1
4060.22	O II	97	0.04	4, 5 λ4060.8
3914.90				3
3866.68			*	
3839.8	[Fe V]		0.04	3
3778.65				3
3746.37				3
3736.6	O IV	6	0.02	1
3494.55				3
3480.80	Ne II	49	0.04	1
3468.44				3
3466.04	He I		0.05	1
3464.21			0.02	1
3425.57	[Ne V] O IV	1 3	0.05	1
3397.9				3
3306.60	O II	23	0.06	1

Table 5

Corrections and Additions to Lines Already Identified in NGC 6572

(See Table 4 for explanation of footnotes.)

λ	ID	Mult.	I	Remarks
4931.19	[O III]		†	
4921.19	He I		†	
4781.58				2 λ3187
4698.85				2 λ3132
4686.59 ‡	He II			3
4620.87	{N II / O II	5 / 96}	0.07	4, 5 λ4621.6
4609.87	O II	92,93	0.07	1
4604.6	[Fe II]		0.05	1
4373.2			0.04	1
4317.1	{O II / O II	53 / 2}	0.10	4, 5 λ4317.5
4314.94				3
4301.73				3
4258.3				3
4171.31				3
4150.39				3
4148.71				3
4084.01	O II	10	0.05	4, 5 λ4085.0
3984.51				3
3860.43				3
3849	O II	12	0.09	4, 5 λ3848.1
3778 9				3
3654.80				6
3650.04				6
3476.30				3
3469.89				3
3441.78				3
3411.42	Ne II	45	0.15	4
3403.51				3
3396.81				3
3370.12				3
3326.03				3
3324.89				3
3323.91				3
3322.04				3
3305.14				3
3303.71				3
3076.93				3

Table 6

Corrections and Additions to Lines Already Identified in IC 4997

(See Table 4 for explanation of footnotes.)

λ	ID	Mult.	I	Remarks
4880.68	[Fe III]		0.52	4
4813.66	Si III	9	0.11	1, 4
4685.76 ‡				3
4616.78			0.03	1
4601.87	O II	93	0.03	1
4465.04	O II	94	0.04	1
4445.88	Ne II	56	0.03	1
4434.08	Mg II	9	0.02	1
4432.40				3
4403.87			0.02	1
4400.23			0.03	1, 4
4389.88			0.02	1
4382.11			0.015	1
4378.34	O II	102	0.015	1
4317.11	O II	2	0.07	1
4303.10	O II	54,100	0.015	1
4292.63				3
4278.85			0.02	1, 4
4242.24	Ne	52	0.04	1
4240.49				3
4231.59	Ne II	52	0.02	1
4230.27 } 4230.18 }			0.02	7, 4
4186.83	C III	18	0.04	1
4183.92			0.04	1
4174.58			0.03	1, 4
4166.82	Mg I	15	0.03	1
4147.83			0.02	1, 4
4136.35				3
4129.77				3

Table 6--Continued

λ	ID	Mult.	I	Remarks
4094.42	O II	10	0.03	1
4056.51	C III	24	0.03	1
4050.86			0.02	1
4048.80			0.02	1
4043.99			0.015	1
4040.97				3
4029.59			0.02	1
4023.81	He I	54	0.04	1
4019.60			0.03	1
4008.50	[Fe III]		0.07	4
4004.38				3
4000.49			0.08	1
3992.94				3
3985.48	O II	22	0.05	1
3983.25	O II	6	0.04	1
3943.72			0.02	1
3935.73	He I	57	0.03	1
3926.56	He I	58	0.11	1
3920.56	C II	4	0.05	1
3878.37	C II	33	0.02	1
3876.80				3
3874.74	O II	11	0.05	1
3858.20			0.02	1
3853.88	Si II	1	0.02	1
3842.95	O II	12	0.02	1
3831.82	S III Mg I C II	15 3 13	0.02	1
3829.76	Ne II N II Mg I	34 30 3	0.02	1
3812.92				3
3810.59	O III	2	0.03	1
3784.90	O II He I	95 64	0.05	1

Table 6--Continued

λ	ID	Mult.	I	Remarks
3783.60				3
3781.95			0.03	1
3780.09			0.03	1
3777.24	Ne II	1	0.03	1
3773.97	O III	2	0.03	1
3766.58	Ne II	1	0.03	1
3757.64	N III	11	0.04	1
3755.99	He I	66	0.05	1
3754.55	N III	4	0.04	1
3747.83				3
3745.89	{He I N III	4}	0.03	1
3743.21				3
3739.55	O II	31	0.02	1
3730.64	He I		0.04	1, 4
3699.03	{S III O II	21	0.03	1
3695.34	O III	21	0.02	1
3561.19	Ne II	31	0.04	1
3517.54	He I	37	0.02	1
3481.35	{Ne II K III	49 3}	0.03	1
3471.8	He I	44	0.03	1
3453.00	He I		0.03	1
3451.09	He I		0.02	1
3387.19	S III	2	0.04	1
3301.47	O II	23	0.04	1

to the numbers in column (5) are on the first page of Table 4. The most common type of change is the addition of or correction to the intensity of a line. A number of lines in Tables 4, 5, and 6 are purposely mentioned as being excluded by the present criteria as being plate-grain effects. Only those lines which had previously measured intensities are included in this manner in these tables. If a line in the tables of AK I and AK II has no measured intensity, it is most likely a noise bump. These "lines" were seen visually, but either they cannot be found on the tracing or they can be identified with what appear to be noise effects on the plate.

IV. REMARKS

The identification of O III in IC 4997 is quite uncertain. The lines which one would expect to be strongest are missing. This nebula is one of the few, however, which might have O III in the spectrum, but for which the Bowen fluorescent mechanism (Bowen 1935) is totally absent. There is absolutely no evidence of He II λ4686 in this nebula (as is also true for NGC 6572). The only λ4686 emission present in these spectra is very broad and certainly arises in the central star. There is little evidence in either of these two nebulae for ions with an ionization potential greater than 50–55 eV.

One important new identification is that of permitted lines of K II in NGC 7009 at λλ4263 and 4309 (the latter was previously identified as Ar II). The λ3618 line was previously identified in NGC 6572, but is now considered spurious. Another possible line is part of a blend at λ4608. The λ3783 line may occur in NGC 6572. More observations are needed for confirmation.

In general, for any of these tables, or those in AK I and AK II, any weak line which has no identification should be considered suspect. (This is not to say that there are not some true lines without identifications.) The only true proof of the existence of any of these faint lines is the occurrence of the line on more than one plate of the same object.

It is not going to be possible to verify these lines until we can get an improved signal-to-noise ratio in the observations, which will be a difficult matter. Ce 14769 of NGC 7009 already represents an exposure time of 16 hours with a fast spectrograph at moderately high dispersions (20 Å mm^{-1}). In the spectrum of NGC 7009, there are so many lines that blending is a serious problem. In some spectral regions increased exposure time would be a great help, but we are beginning to reach an intrinsic limit of line detection where the lines are truly blended irrespective of instrumental profile.

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