OBSERVATIONS MADE WITH THE NEBULAR SPECTROGRAPH OF THE McDONALD OBSERVATORY. II*

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ABSTRACT

A series of spectrograms in Monoceros and Canis Major reveal a number of new emission nebulosities, some of which seem to be unrelated to any individual stars while others form distinct groups which are related to O or B stars. A spectrophotometric study of $H\alpha$ and $H\beta$ in the outer loop of Orion near BD+1°1126 gives $n_4 = 4$ cm^{-2} and $n_3 = 3$ cm^{-2}. It is estimated that the faintest recorded emission nebulosities have three times fewer atoms in the fourth and the third energy-levels of H, per square centimeter. This agrees satisfactorily with former estimates.

The present series of observations is a continuation of those published in former issues of this *Journal*.[1] The instrument and the technique were the same as those used before, but the Agfa Superpan Press film was hypersensitized with ammonia, in accordance with the method of Bowen and Wyse.[2] A marked increase in speed was obtained. The numbering of the regions follows chronologically that of our previous series.

The emission features of the spectrum of the night sky were relatively faint throughout the present series of observations. This was especially valuable in distinguishing the nebular emission line [*O* II] 3727, which was of even greater use in this series than $H\alpha$. We are not prepared to state that there is a real systematic difference in the ratio [*O* II]/$H\alpha$ between the summer Milky Way (Cygnus, Cepheus) and the winter Milky Way (Monoceros, Canis Major). But there can be no doubt that the large diffuse nebula around S Monoceratis is especially strong in [*O* II]. This, incidentally, explains our former observation that this nebula is relatively weak when photographed in red light.[3]

The preponderance of emission spectra in Table 1 is partly due to the fact that we have included in our program a number of known

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[1] *Ap. J.*, **89**, 119, 1939.

[2] *Pub. A.S.P.*, **50**, 305, 1938.

[3] Struve, *Ap. J.*, **86**, 98, n. 13, 1937.

diffuse nebulosities for which hitherto no spectra were available. The great majority of these extended films of nebulosity in and near the Milky Way have emission spectra. However, several regions show no trace of nebulosity on the direct photographs, although the spectrograph reveals conclusive evidence of emission by interstellar gaseous matter. Only one of the regions listed in the table was located far from the Milky Way. It showed no emission. In addition, the evidence of the comparison spectra is instructive: they were usually taken 30°–40° north of the Milky Way region. This would place them about 10° north of the eastern edge of the Milky Way. Not one of these exposures reveals a trace of emission.

The principal purpose of the observations was to obtain a determination of the number of hydrogen atoms per square centimeter of a standard nebula. The value used in our former work ($n_3 = 10$ atoms/cm^2)[4] depended upon a comparison with the Orion nebula for which Ambarzumian[5] had determined the numbers of hydrogen atoms in the fourth, fifth, and sixth energy-levels. An independent determination is greatly needed because of the astrophysical significance of these quantities.[6]

We have chosen for this purpose the outer loop of Orion, near the star BD+1°1126. The nebula is relatively strong at this point and is fairly uniform over the length of our slit. We estimate that the faintest emission nebulae recorded by us are about three times fainter than the region selected as standard. The spectral type of the standard star is G5, and the photographic magnitude is 6.95, according to the *Henry Draper Catalogue*. Dr. C. K. Seyfert has very kindly determined the magnitude with the 6-inch UV refractor. His results are

$$\text{BD} + 1°1126 \begin{cases} \text{photographic magnitude } 6.67 \\ \text{photovisual magnitude } 5.92 \end{cases}$$

Dr. W. W. Morgan has redetermined the spectral type at the Yerkes Observatory and has found it to be G5 on his system. The lumi-

[4] *Ibid.*, **88**, 367, 1938.

[5] *Zs. f. Ap.*, **6**, 112, 1933.

[6] See Struve, *Proc. Nat. Acad. Sci.*, **25**, 36, 1939; Struve, Wurm, and Henyey, *ibid.*, p. 67; Struve, *Zs. f. Ap.*, **17**, 316, 1939.

nosity classification by Morgan makes it a subgiant or a dwarf, and the color index on the international system should therefore be +0.7 mag—in close agreement with the determination by Seyfert.

The procedure was quite similar to that adopted by Ambarzumian. The star served as guiding star for the nebula. Hence, there are no corrections for extinction. The exposure was obtained on January 18/19 (see Region No. 41), and the star was trailed uniformly over a distance of 11′ along the slit. Sensitometer exposures were used to construct the characteristic curves separately for each wave length. The width of the slit corresponded to 2′.4.

The only important difference between our work and that of Ambarzumian consisted in the fact that in our instrument the slit acts as a diaphragm which reduces the intensity of the star but leaves the nebula unaffected. For the equivalent slit width of 50 mm the correction resulting from this effect corresponds to somewhat less than a factor of 2. We shall adopt a factor of 2 in order to compensate for small losses of starlight at the ends of the trailed image and because of optical imperfections in the plane mirrors.

Although the spectral type is not exactly that of the sun, the resulting error is insignificant if we use the photographic magnitudes of star and sun for $H\beta$, etc., and the photovisual magnitudes for $H\alpha$.

We apply Ambarzumian's expression, corrected for the diaphragming effect of the slit:

$$\log \frac{E_{n\lambda}}{E_{\odot\lambda}} = \log P_\lambda - 0.4(m_* - m_\odot) + \log S - \log 2 ,$$

where $E_{n\lambda}$ is the energy radiated by 1 cm^2 of the nebula per second in unit solid angle, in the monochromatic line λ, $E_{\odot\lambda}$ the energy radiated by 1 cm^2 of the sun's surface per second per angstrom unit in unit solid angle, near wave length λ, P_λ the ratio of intensity in the monochromatic nebular image, per square minute of arc, to intensity in the star spectrum at neighboring wave lengths, per angstrom unit, over the full width of the spectrum, expressed in minutes of arc, and S the surface of the sun in square minutes of arc. Since the linear dispersion on our plates is approximately 1000

A/mm at $H\alpha$ and 440 A/mm at $H\beta$, we can easily derive P_λ for both lines and then compute log $E_{n\lambda}/E_{\odot\lambda}$. The results are:

$$H\beta\colon \log \frac{E_{n\lambda}}{E_{\odot\lambda}} = -10.26 ,$$

$$H\alpha\colon \log \frac{E_{n\lambda}}{E_{\odot\lambda}} = -9.56 .$$

For $H\beta$ in the Orion nebula, Ambarzumian found log $E_{n\lambda}/E_{\odot\lambda} = -7.95$. Hence, our nebula is about 2000 times fainter. Remembering that we have estimated our faintest nebulae to be about three times fainter than the standard in the outer loop of Orion, we conclude that our former ratio of 1000 was too small by a factor of 6. Hence, the number of atoms in the fourth energy-level of H for the outer loop of Orion is

$$n_4 = 4 \text{ cm}^{-2} ,$$

and for the faintest recorded nebulae

$$n_4 = 1 \text{ cm}^{-2} .$$

For $H\alpha$, which was not observed by Ambarzumian, we first compute the value of $E_{n\lambda}$ and then derive the number of atoms in the third energy-level:

$$n_3 = \frac{4\pi E_{n\lambda}}{h\nu A_{31}} ,$$

where $A_{31} = 0.43 \times 10^8 \text{ sec}^{-1}$. The result is, for the outer loop of Orion,

$$n_3 = 3 \text{ cm}^{-2} ,$$

and for the faintest recorded nebulae,

$$n_3 = 1 \text{ cm}^{-2} .$$

This result agrees reasonably with the one used in our previous computations ($n_3 = 10 \text{ cm}^{-2}$), but the precision of the measurement is, of course, very low. It is, therefore, not disturbing that n_3 is slightly smaller than n_4. Both results may easily be in error by a factor of as much as 10.

No. 36.—Guiding star 15 S Mon. 1939, Jan. 14/15. Exp. 3^h45^m. Comparison mirror $\Delta\delta = +30°$. Slit eq. 40 mm. [*O* II] 3727 is very conspicuous; $H\alpha$ is strong; $H\beta$, $H\gamma$, $H\delta$, and N_1 are present. The emission is slightly stronger west of the star than at the eastern end of the slit. This nebula has already been observed by Greenstein and Henyey.[7] The most conspicuous feature is the great strength of [*O* II] 3727 and the relative weakness of $H\alpha$. The spectral type of the guiding star is O7s.

No. 37.—Guiding star BD+9° 1376. 1939, Jan. 14/15. Exp. 4^h. Comparison mirror $\Delta\delta = +30°$. Slit eq. 40 mm. This region is about 1° east of No. 36, and the spectrum is closely similar. [*O* II] 3727 is very strong; $H\alpha$ is relatively weak; N_1 is very weak; $H\beta$ and $H\gamma$ are faint. The Balmer decrement seems to be low.[7] The emission weakens toward the east but is still fairly conspicuous at the eastern end of the slit (45′ west of the guiding star). This agrees with the extent of the large nebulosity photographed by Ross.[8]

No. 38.—Guiding star BD+10°1335. 1939, Jan. 15/16. Exp. 4^h4^m. Comparison mirror $\Delta\delta = +30°$. Slit eq. 40 mm. This region is about 4° east of No. 36. There is no definite emission, but we suspect an exceedingly faint trace of [*O* II] 3727. This may, however, be the night-sky line of the same wave length.

No. 39.—Guiding star BD+10°1335. 1939, Jan. 15/16. Exp. 4^h7^m. Comparison mirror $\Delta\delta = +30°$. Slit eq. 40 mm. This region is about 1° west of No. 36. The small bright nebulosity, NGC 2245, which surrounds the guiding star shows no trace of emission, and its spectrum must be purely continuous. This agrees with the observation by Hubble.[9] There is, however, superposed a weak emission spectrum, strong at the eastern end of the slit and weak at the western end, which evidently represents an extension of the large nebula around S Mon. [*O* II] 3727 is fairly strong, while $H\alpha$ is very weak. The spectral type of the guiding star is B8, according to the *Henry Draper Catalogue*.

[7] *Ap. J.*, **87**, 80, 1938.

[8] *Ibid.*, **67**, Pl. VI, 1928.

[9] *Ibid.*, **44**, 196, 1916; **56**, 173, 405, 1922.

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TABLE 1

OBSERVATIONS MADE WITH THE NEBULAR SPECTROGRAPH

No.	Object	Guiding Star	Date	Identification*	Result
36....	Nebula NGC 2264	15 S Mon	1939, Jan. 14/15	Ross 35; 168 mm from right; 162 mm from bottom	Strong emission
37....	Nebula	BD+ 9°1376	Jan. 14/15	Ross 35; 148 mm from left; 160 mm from bottom	Strong emission
38....	Milky Way	BD+10°1335	Jan. 15/16	Ross 35; 107 mm from left; 165 mm from bottom	Probably no emission
39....	NGC 2245	BD+10°1159	Jan. 15/16	Ross 35; 126 mm from right; 162 mm from bottom	Emission
40....	IC 448	BD+ 7°1337	Jan. 16/17	Ross 35; 139 mm from right; 122 mm from bottom	Emission
41....	Outer loop of Orion	BD+ 1°1126	Jan. 17/18	Ross 34; 114 mm from left; 128 mm from top	Emission
42....	Milky Way	BD+ 8°1438	Jan. 17/18	Ross 35; 167 mm from right; 135 mm from bottom	Strong emission
43....	Milky Way	BD+15°1075	Jan. 19/20	Ross 35; 44 mm from right; 79 mm from top	Strong emission
44....	Milky Way	30 τ CMa	Jan. 19/20	Ross 38; 112 mm from left; 146 mm from bottom	Emission
45....	Nebula IC 2177	BD−10°1862	Jan. 20/21	Ross 37; 82 mm from right; 164 mm from top	Strong emission
46....	Milky Way	BD−10°1892	Jan. 22/23	Ross 37; 95 mm from right; 159 mm from top	Emission
47....	....	ρ Leonis	Jan. 22/23	....	No emission
48....	Milky Way	BD− 8°1862	Jan. 23/24	Ross 37; 139 mm from right; 134 mm from top	Emission

* The co-ordinates are only approximate. Differences of the order of 1 mm in each co-ordinate are possible on different prints of the same photograph of Ross's *Atlas of the Milky Way*.

No. 40.—Guiding star BD+7°1337. 1939, Jan. 16/17. Exp. 5^h. Comparison mirror $\Delta\delta = +30°$. Slit eq. 40 mm. This region is about 3° southwest of No. 36. [*O* II] 3727 is a very strong emission line, but *Hα* is rather weak. The oxygen line is of uniform brightness along the entire slit and must belong to the large nebula around S Mon. Since there is no strengthening of the emission lines near the guiding star, we believe that the faint nebula, IC 448, surrounding it has a continuous spectrum. The spectrum of the guiding star is Aop and the lines are described in the *Henry Draper Catalogue* as very narrow and sharply defined, resembling in intensity those of η Leonis.

No. 41.—Guiding star BD+1°1126. 1939, Jan. 17/18. Exp. 4^h5^m. Comparison mirror $\Delta\delta = +40°$. Slit eq. 40 mm. 1939, Jan. 18/19. Exp. 4^h. Slit eq. 50 mm. *Hα* is very strong; [*O* II] 3727 is somewhat fainter, confirming the reality of the unusual strength of the oxygen line (or weakness of *Hα*) in the large nebula around S Mon. *Hβ* and *Hγ* are faint; N_1 is not visible on our plate. This observation confirms in every detail that by Greenstein and Henyey[10] which was made slightly farther south.

No. 42.—Guiding star BD+8°1438. 1939, Jan. 17/18. Exp. 4^h5^m. Comparison mirror $\Delta\delta = +30°$. Slit eq. 40 mm. [*O* II] 3727 is exceptionally strong; *Hα* is fairly strong; *Hβ* and *Hγ* are weak. The lines are fairly uniform along the slit. This is an extension of the nebula around S Mon.

No. 43.—Guiding star BD+15°1075. 1939, Jan. 19/20. Exp. 3^h30^m. Comparison mirror $\Delta\delta = +30°$. Slit eq. 40 mm. This region was chosen because of the strong emission nebulosity revealed in red light, by H. A. Lower.[11] This fairly large, round nebula seems not to have been recognized previously, but a careful inspection of Ross's plates No. 35 and 33 shows an exceedingly faint trace of it. Barnard's photograph[12] does not show it. The nebula must be very faint in blue and violet light. This is substantiated by our spectrum: *Hα* is very strong in emission; [*O* II] 3727 is relatively weak; *Hβ* and *Hγ* are very faint; there is no trace of N_1. The emission lines are strongly concentrated toward the middle of the slit, suggesting that

[10] *Ibid.*, **87**, 79, 1938.

[11] *Ibid.*, **89**, Pl. XIV, 1939.

[12] *Pub. Lick Obs.*, **11**, Pl. 25, 1913.

the brightest part of the nebula has a diameter of 15′–20′. However, $H\alpha$ extends to both ends of the slit. The nebula is considerably larger than should be expected from Hubble's relation. The spectrum of the guiding star is not known. The nebula may be associated with the slightly brighter star, BD+15°1079 = HD 41997, the spectrum of which is given as B in the *Henry Draper Catalogue*. The absorption lines are described as showing slight contrast to other portions of the spectrum. The photographic magnitude is 8.3. This interesting nebula deserves further study.

No. 44.—Guiding star 30 τ Can. Maj. 1939, Jan. 19/20. Exp. 3^h52^m. Comparison mirror $\Delta\delta = +50°$. Slit eq. 40 mm. This region contains no known nebulosity, but a slight milkiness on Ross's photograph suggests the possible existence of a very large diffuse nebulosity which merges into a large obscured region on the east. $H\alpha$ is strong in emission and so is [*O* II] 3727; $H\beta$ and $H\gamma$ are faint; N_1 is not definitely seen but may be present. The lines are slightly stronger near the eastern end of the slit than in the immediate vicinity of the guiding star. The spectral type of τ Can. Maj. is O9, and that of the neighboring star, 29 Can. Maj., is O7e.

No. 45.—Guiding star BD−10°1862. 1939, Jan. 20/21. Exp. 3^h54^m. Comparison mirror $\Delta\delta = +40°$. Slit eq. 40 mm. $H\alpha$ and [*O* II] 3727 are very strong and decrease slightly from the guiding star toward the eastern end of the slit; $H\beta$, $H\gamma$, and $H\delta$ show the same structure; N_1 is clearly visible, but its structure differs from that of the other lines; it is absent west of the guiding star, is faint immediately east of it, and increases slightly in intensity toward the eastern end of the slit, 45′ from the star. The spectrum of the guiding star is B3. The strengthening of N_1 toward the east suggests that the excitation may come from the O7s star[13] BD−10°1892 = HD 54662.

No. 46.—Guiding star BD−10°1892. 1939, Jan. 22/23. Exp. 2^h30^m. Comparison mirror $\Delta\delta = +40°$. Slit eq. 40 mm. The Ross *Atlas* shows no trace of nebulosity in this region, although it lies only about 1° east of the diffuse nebula IC 2177 (Region 45). $H\alpha$ and [*O* II] 3727 are strong over the entire length of the slit, weakening slightly toward the east; N_1 is equal to $H\beta$, thus confirming the

[13] C. H. Payne, *The Stars of High Luminosity*, p. 64, 1930.

result obtained for Region 45. The spectrum of the guiding star is O7s.

No. 47.—Guiding star ρ Leonis. 1939, Jan. 22/23. Exp. 2^h40^m. Comparison mirror $\Delta\delta = +30°$. Slit eq. 40 mm. This Bop star has a galactic latitude of $+54°$. There is no emission.

No. 48.—Guiding star BD $-8°1862$. 1939, Jan. 23/24. Exp. 3^h5^m. Comparison mirror $\Delta\delta = +40°$. Slit eq. 40 mm. This region is about 4° northeast of No. 46 and is located in a dense region of the Milky Way, without any indication of nebulosity on the direct photograph by Ross. [*O* II] 3727 is present as a faint but well-defined emission line which decreases slightly in strength near the eastern edge. There is only a suspicion of bright $H\alpha$, but this plate is slightly out of focus in the red part of the spectrum. The presence of emission in this normal region of the Milky Way is perhaps even more startling than the presence of emission in the star clouds of Cygnus and Cepheus.[14]

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[14] Dr. W. H. Wright has called our attention to the fact that the strong $H\alpha$ line coincides on spectrograms of small dispersion with the forbidden doublet of *N* II, λ 6548 and λ 6584, and there is good reason to suspect that the red images of certain nebulae are due principally to this doublet (*Pub. Lick Obs.*, **13**, 217, 1918). Since the other Balmer lines, $H\beta$, $H\gamma$, etc., are also often present on our spectrograms, $H\alpha$ is doubtless a fairly strong emission line; but it is entirely possible that a large fraction of the light comes from the nitrogen doublet. If this conclusion is correct, the number of atoms which we have derived for the third quantum level of hydrogen must be somewhat reduced. However, it will not be altered sufficiently to require a revision of the computations because we are here concerned only with a precision corresponding to a factor of 3 or 4. Dr. Wright's suggestion probably accounts for the remarkable changes in the relative intensities of $H\alpha$ and of other Balmer lines which we had heretofore interpreted as changes in Balmer decrement. Stoy (*Lick Obs. Bull.*, **17**, 181, 1935) assigns slightly weaker intensities to the [*N* II] lines than to $H\alpha$, in the nebulae observed by him, but it is quite possible that the combined intensity of the two [*N* II] lines in our tenuous nebulae is of the same order as that of $H\alpha$.