On the Nature of Wolf-Rayet Emission. By C. S. Beals, M.A., D.I.C., Ph.D. (Plates 7 and 8.)

Introduction.

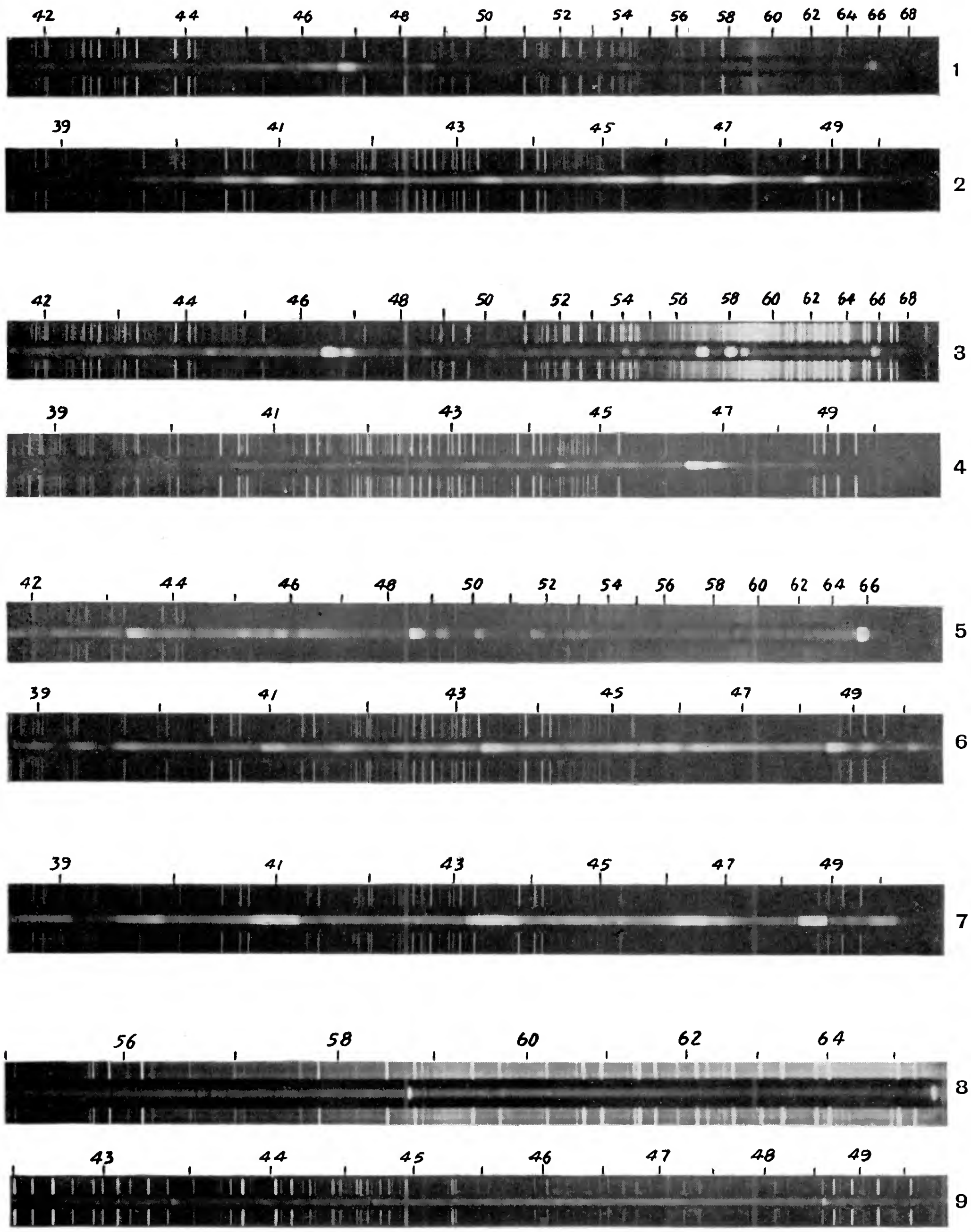
The first three examples of Wolf-Rayet stars were discovered visually by Wolf and Rayet * at the Paris Observatory in 1867. Respighi,† Pickering,‡ and Copeland § have recorded similar discoveries also by visual methods. The Harvard objective prism-plates revealed many more examples, and the majority of Wolf-Rayet stars now known were discovered by the Harvard observers.

The earliest wave-length measurements of emission bands were made by Campbell ‖ in 1892. Wright,¶ in 1918, showed that the nuclei of planetary nebulæ were frequently Wolf-Rayet stars, measured the wave-lengths of bands in a number of these objects, and identified many of them with laboratory wave-lengths. In 1924 J. S. Plaskett ** published the results of an investigation of all the northern Wolf-Rayet stars of magnitude 9·0 or brighter. His work included a detailed description of Wolf-Rayet spectra, measures of wave-length, identifications of bands, and suggestions as to the classification of these stars. Other workers in this field include Perrine †† and Miss Payne,‡‡ who have published data on a number of southern Wolf-Rayet stars.

The most characteristic feature of the spectra of Wolf-Rayet stars is the appearance of atomic emission in the form of broad bands superposed on a comparatively faint continuous background. The appearance of the bands and their contrast with the continuous spectrum is illustrated in Plate 7, where spectra of two typical stars of this type have been reproduced. That this broad band emission is of very different character from that met with in ordinary emission-line stars is evident from an examination of Wolf-Rayet spectra. The bands are from 10 to 100 angstroms in width, their strength, relative to the continuous spectrum, is enormously greater than that of the more usual type of stellar emission, and many of the wave-lengths appearing in Wolf-Rayet stars are not met with in other types of stellar emission spectra.

In attempting to frame a hypothesis to explain this type of emission, attention is naturally focussed on the great width of the bands, since this is the feature which differentiates Wolf-Rayet stars most sharply from other emission-line objects. The most promising explanation appears to be that the broadening is a Doppler effect, and that Wolf-Rayet emission is therefore associated with large velocities of the emitting gases in the line of sight. It is extremely unlikely that other known causes of broadening, such as the Stark effect, the Zeeman effect, or the effect of high pressure, could produce such large wave-

* *Comptes Rendus*, **65**, 292, 1867.
† *Ibid.*, **74**, 516, 1872.
‡ *Nature*, **23**, 604, 1881.
§ *Copernicus*, **3**, 206, 1884.
‖ *Astronomy and Astrophysics*, **13**, 448, 1894.
¶ *Lick Pub.*, **13**, Part 6, 1918.
** *Pub. D.A.O.*, **2**, No. 16, 1924.
†† *Ap. J.*, **52**, 39, 1920; *M.N.*, **81**, 142, 143, 1920.
‡‡ *H.B.*, Nos. 834, 836, 842, 843, 1926, 1927.



1 and 2, Wolf-Rayet Star B.D. 37° 3821; 3 and 4, Wolf-Rayet Star B.D. 35° 4013; 5 and 6, Nova Cygni (1920); 7 Nova Aquilæ (1918); 8 and 9, P. Cygni.

length displacements under the conditions believed to exist in stellar atmospheres. In the present paper some observational evidence in favour of a Doppler-effect explanation is put forward, and a mechanism for the production of the bands is suggested which is able to account for many of the observed peculiarities of Wolf-Rayet spectra. The paper is based on spectrograms taken by J. S. Plaskett and by the present writer.

Measurements of Band Width.

Quantitative evidence for the existence of Doppler effects may be derived from measures of band width. If, as has been suggested, the broadening is due to motions of the emitting gases in the line of sight, then the widths of bands due to the same atom in different regions of the spectrum should be proportional to wave-length. To test this point careful measures of the bands in a number of stars have been made, and the results of the measures are contained in Table I. In this table the band width has been denoted by $\Delta\lambda$, and a comparison has been made between the observed width and that calculated by means of a linear formula. The multiplying factor has been obtained by taking the average of the quantity, " $\Delta\lambda$ observed/λ" for the series of bands under consideration.

An inspection of the table shows that in every case there is an increase in band width with wave-length, though the rate of increase is somewhat greater than that predicted by a theory of Doppler broadening. In the first three stars in the table the Balmer and Pickering series have been measured. In these stars the discrepancy between observation and theory may well be due, at least in part, to diminishing contrast with the continuous spectrum in passing to higher series members. The two bands λ 4650 and λ 5695 have been measured in three of the stars. λ 4650 is known to be due to C^{++} and λ 5695 has been tentatively assigned to the same ion, though this identification is by no means certain. It is possible, therefore, that the discrepancies for these bands may be due to different atoms being involved. In any case, the bands show an increase in width with wave-length, and the evidence as a whole tends strongly to confirm the hypothesis that the broadening of the bands is due to Doppler effects. This hypothesis, then, serves as a starting-point in formulating a more complete theory of Wolf-Rayet emission.

Comparison with Novæ.

It is well known that the emission spectra of novæ consist of broad bands, strongly resembling those found in the spectra of Wolf-Rayet stars. This similarity in appearance naturally suggests that similar causes may be at work in the production of the spectra. For purposes of comparison, a spectrogram of Nova Aquilæ (1918) taken by Dr. J. S. Plaskett and two spectrograms of Nova Cygni (1920) secured by Mr. W. E. Harper have been reproduced in Plate 7. These spectra are part of an

TABLE I.

Widths of Wolf-Rayet Bands.

B.D. 37° 3821.

Balmer Series.

$\Delta\lambda$ Calc. $=\lambda \times 0{\cdot}00833$.

λ.	Δλ Obs.	Δλ Calc.
6563	58·0	54·7
4861	41·2	40·5
4340	33·4	36·2

Pickering Series.

$\Delta\lambda$ Calc. $=\lambda \times 0{\cdot}00782$.

λ.	Δλ Obs.	Δλ Calc.
5411	41·6	42·3
4541	35·5	35·5
4200	33·4	32·8

B.D. 35° 4001.

Balmer Series.

$\Delta\lambda$ Calc. $=\lambda \times 0{\cdot}00883$.

λ.	Δλ Obs.	Δλ Calc.
6563	57·5	57·9
4861	43·9	42·9
4340	37·8	38·3

Pickering Series.

$\Delta\lambda$ Calc. $=\lambda \times 0{\cdot}00961$.

λ.	Δλ Obs.	Δλ Calc.
5411	53·0	52·0
4541	40·8	43·6
4200	42·2	40·4

B.D. −23° 4553.

Balmer Series.

$\Delta\lambda$ Calc. $=\lambda \times 0{\cdot}00961$.

λ.	Δλ Obs.	Δλ Calc.
6563	74·2	63·1
4861	44·8	46·7
4340	36·0	41·7

Pickering Series.

$\Delta\lambda$ Calc. $=\lambda \times 0{\cdot}00892$.

λ.	Δλ Obs.	Δλ Calc.
5411	50·8	48·3
4541	40·5	40·5
4200	35·5	37·5

B.D. 43° 3571.

$\Delta\lambda$ Calc. $=\lambda \times 0{\cdot}01707$.

λ.	Δλ Obs.	Δλ Calc.
5695	102·3	97·2
4650	75·2	79·4

B.D. 35° 4013.

$\Delta\lambda$ Calc. $=\lambda \times 0{\cdot}00711$.

λ.	Δλ Obs.	Δλ Calc.
5695	43·6	40·5
4650	30·5	33·6

B.D. 36° 3956.

$\Delta\lambda$ Calc. $=\lambda \times 0{\cdot}00863$.

λ.	Δλ Obs.	Δλ Calc.
5695	52·4	49·1
4650	37·5	40·1

excellent series of plates of Nova Aquilæ and Nova Cygni taken at this observatory, to which I have had access for the purpose of comparing the spectra of novæ and Wolf-Rayet stars. The result of this comparison has been to confirm the idea that the two types of spectra are fundamentally similar. This conclusion is based on the following points of resemblance.

The bands of both novæ and Wolf-Rayet stars are very strong relative to the continuous spectrum, and make a considerable contribution to the visual and photographic magnitude of these stars. This great concentration of energy in emission wave-lengths is found in no other type of purely stellar spectrum, and strongly suggests that the origin of the emission for the two types of objects is the same.

The wave-lengths of the centres of nova bands are approximately undisplaced from their normal positions. The same is true of Wolf-Rayet bands, as may be seen from the table of wave-lengths published by J. S. Plaskett * and from my own unpublished measures.

The widths of nova bands are of the same order as Wolf-Rayet bands, and the bands of both types of spectra show a progressive increase in width with wave-length. The measures of Wolf-Rayet bands have already been given in Table I. Measures of the bands of Nova Aquilæ and Nova Cygni in their later stages are shown in Table II. The bands of Nova Aquilæ are quite sharp, while those of Nova Cygni are exceedingly diffuse and difficult to measure. The measures for Nova Aquilæ are due to Lunt,† while Harper's ‡ measures have been given for Nova Cygni. Deviations from the values predicted from a theory of Doppler broadening are large for Nova Cygni and small for Nova Aquilæ. It is significant to note that deviations from the calculated values are of the same character for both novæ and Wolf-Rayet stars, and indicate a more rapid increase in width, in passing to the red region, than would be predicted by theory.

TABLE II.

Widths of Nova Bands.

Nova Aquilæ (1918) (*Lunt*).			*Nova Cygni* (1920) (*Harper*).		
$\Delta\lambda$ Calc. $=\lambda\times 0{\cdot}01104$.			$\Delta\lambda$ Calc. $=\lambda\times 0{\cdot}00532$.		
λ.	Δλ Obs.	Δλ Calc.	λ.	Δλ Obs.	Δλ Calc.
5006·9	55·9	55·3	6563	39·9	34·9
4959·1	56·1	54·7	5169	30·9	27·5
4861·5	53·8	53·7	5018	25·0	26·7
4641·1	51·5	51·2	4924	27·0	26·2
4363·4	48·8	48·2	4861	28·0	25·9
4340·6	46·5	47·9	4341	22·6	23·1
4102·0	44·2	45·3	4102	18·8	21·8
			3933	17·8	20·9

One of the most significant points of resemblance between novæ and Wolf-Rayet stars is the appearance of absorption on the violet edges of emission bands. Such displaced absorption, which assumes somewhat different forms for different stars, is a conspicuous feature

* *Pub. D.A.O.*, **2**, No. 16, 1924.
† *M.N.*, **80**, 523, 1920.
‡ *Pub. D.A.O.*, **1**, 270, 1921.

of the spectra of novæ. Absorption on the violet edges of Wolf-Rayet bands has been observed by Wright,* Plaskett,† Perrine,‡ Miss Payne,§ and by the present writer. Perrine has observed absorption lines to the violet of the bands of γ Argus which vary both in intensity and position. He concluded that they are due to motion of the absorbing gases, and that they suggest an analogy with the novæ. The phenomenon is less conspicuous in Wolf-Rayet stars than in novæ, but of its existence there can be little doubt. The strength of the absorption appears to be different for different bands, and is strongest for the bands of *He* I and *C* III. In Plate 8 are reproduced microphotometer tracings of a number of Wolf-Rayet spectra secured at this observatory. The tracings clearly show absorption on the violet edges of the wave-lengths 4650 *C* III, 4471 *He* I, and 3889 *He* I.

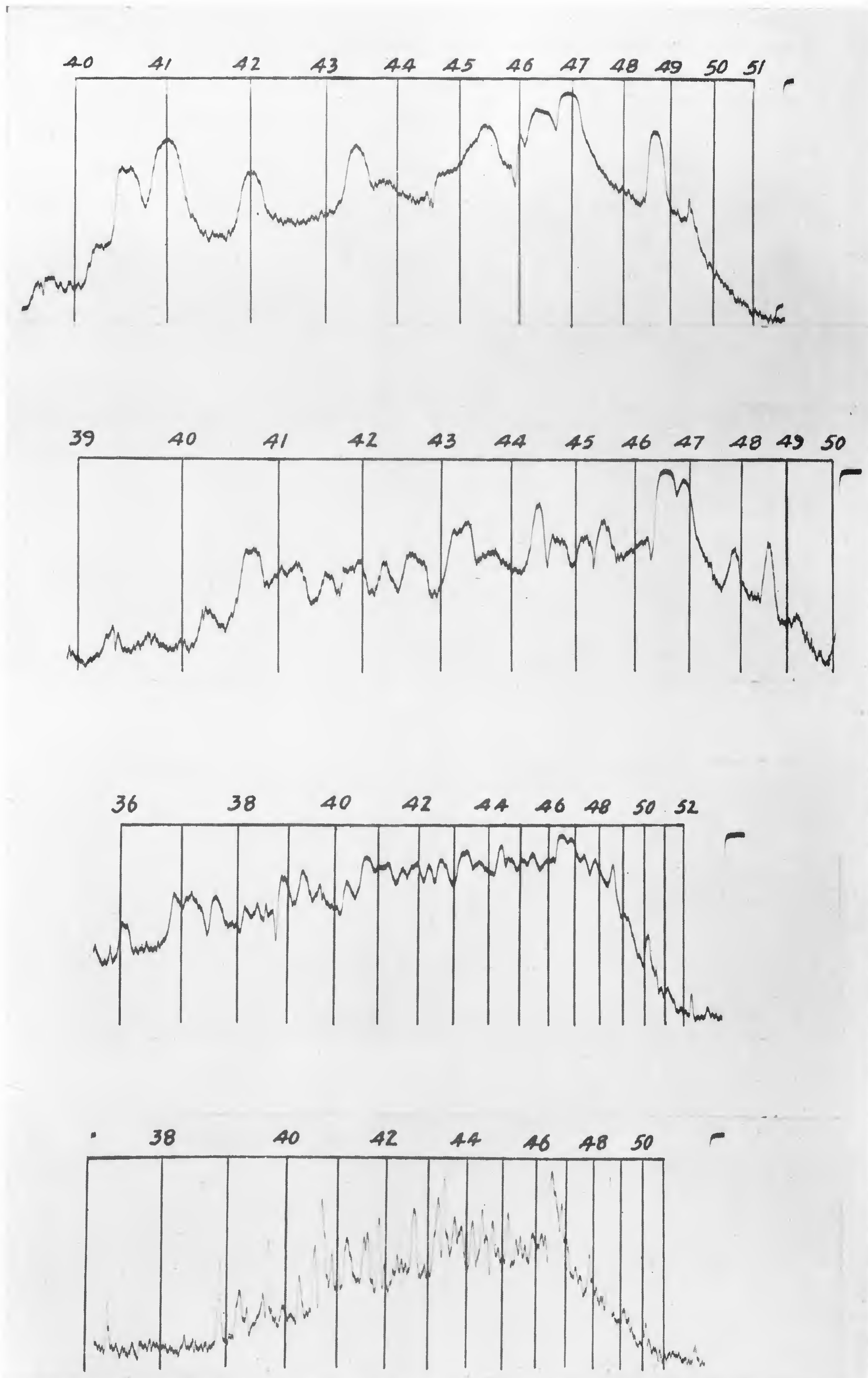
Proposed Theory of Wolf-Rayet Emission.

The similarities with the spectra of novæ, outlined above, have suggested that the emission spectra of Wolf-Rayet stars may be due to a cause similar to that which is generally considered to be responsible for the band spectra of novæ—namely, the continuous ejection of gaseous material from the star. Practically all the characteristic features of Wolf-Rayet spectra may be explained on the assumption that gaseous material is continuously being ejected in a radial direction and with high velocity into space. On this theory the star is surrounded by an expanding envelope of nebulous gases, whose extension in space is large, relative to the diameter of the star itself. As in novæ,|| the gases on the side of the star nearer to the observer will, owing to their velocity, be transparent to radiation from other parts of the nebulous envelope, all parts of which will contribute to the observed intensity of the emission bands.

Both the width of the bands and the absorption on their violet edges have a logical explanation on this hypothesis. The width of the bands will depend on the maximum positive and negative velocities in the line of sight. The filling in of the band between the two extremes may be attributed to the spread in velocities and to the fact that the velocities of the radiating gases make angles with the line of sight having all values from 0° to 180°. The dark borders on the violet edges of bands may be explained as due to absorption of the continuous spectrum of the star by that part of the nebulous envelope between the star and the observer. Since the gases in this part have the largest negative velocity in the line of sight, the position of the absorption would be expected to coincide with the violet edge of an emission band.

The great intensity of emission wave-lengths relative to the continuous spectrum in the stellar region of observation may be explained on the assumption that the light of the star is relatively rich in light of very short wave-lengths. This light is absorbed by the nebulous

* *Lick Pub.*, **13**, 224, 1918.
† *Pub. D.A.O.*, **2**, No. 16, 1924.
‡ *Ap. J.*, **52**, 39, 1920.
§ *H.B.*, No. 844, 1927.
|| See Dingle, *Modern Astrophysics*, p. 272, 1924.



B.D. 37° 3821

B.D. 35° 4013

B.D. 35° 4013

B.D. 30° 3639

Tracings of Wolf-Rayet Spectra.

envelope and re-emitted in the longer wave-length regions. Such a mechanism has obvious similarities to that suggested by Hubble * and Zanstra † to explain the spectra of planetary nebulæ, and by Rosseland ‡ to account for ordinary stellar emission. In this connection it is of interest to note that Wolf-Rayet spectra show a remarkable similarity to the spectra of planetary nebulæ in the comparative distribution of energy between the continuous spectrum (due to the star) and the emission wave-lengths (due to the nebulosity) in the stellar region of observation.

Old Novæ as Wolf-Rayet Stars.

The fact that old novæ have, in some cases, been shown to be Wolf-Rayet stars, lends a certain amount of support to the theory of the origin of Wolf-Rayet emission that has just been outlined. Adams and Pease § have shown that Nova Aurigæ (1891) and Nova Persei (1901), twenty-three years and fourteen years respectively after the initial outbursts, were typical Wolf-Rayet stars in so far as the observations, made with small dispersion apparatus, could determine. Since there seems no reason for supposing that the agency responsible for the broad band emission in the final state of a nova is different from that causing the bands in its earlier stages, these observations appear to indicate that the cause of nova and Wolf-Rayet emission is the same.

Ejection of Atoms by Selective Radiation Pressure.

The conclusion that Wolf-Rayet emission is caused by continuous ejection of gaseous material from a star is a deduction from the observations which is not necessarily dependent on any specific assumption as to the forces responsible for such ejection. It is obvious, however, that the validity of the theory depends on the existence of some agency which is at once capable of producing the observed effects and likely to be operative under stellar conditions. Such an agency may be found in the force exerted on atoms by selective radiation-pressure in the manner discussed by Milne and others in connection with theories of the solar chromosphere. In one of his earlier papers on the theory of the solar chromosphere, Milne ‖ suggests the possibility of the continuous ejection of high-speed atoms from stars by radiation-pressure. In a later paper ¶ the mechanism responsible for the ejection of atoms is developed in sufficient detail to permit of a calculation of the limiting velocities likely to be acquired. These turn out to be of the order of several hundred km. per sec., a figure which approximates to the order of the hypothetical velocity effects observed in novæ and Wolf-Rayet stars, which vary from 300 km. for stars with narrow bands to 2400 km. for B.D. 43° 3571. A similar mechanism is considered by Milne to be responsible for the emission bands and displaced absorption lines of novæ.

* *Ap. J.*, **56**, 162, 1922.
† *Ibid.*, **65**, 50, 1927.
‡ *Ibid.*, **63**, 226, 1926.
§ *Ibid.*, **40**, 294, 1914.
‖ *M.N.*, **84**, 354, 1924.
¶ *Ibid.*, **86**, 459, 1926.

M. C. Johnson,* investigating the same subject, has put forward a suggestion which may be of considerable value for the interpretation of certain anomalous line intensities in Wolf-Rayet spectra. His work appears to show that the value of R/G, the ratio of radiation-pressure to gravity at the surface of a star, may have widely different values for different atoms and for atoms in different stages of ionization. Thus, for a giant star at a temperature of 30,000° the values of R/G for *H*, *He*, and He^+ have been calculated as follows :—

Atom.	R/G.
H	$40/3\times 10^3$
He	$190/3\times 10^3$
He^+	$2{\cdot}5\times 10^5/3\times 10^3$

Other ions likely to have high values of R/G are C^{++}, Si^{+++}, and probably O^{++} and N^{++}.

From this it appears that the intensity of a given emission band may depend partly on a selective effect due to radiation-pressure, since it seems reasonable to suppose that atoms for which R/G is largest would be given off most abundantly. An effect such as this is undoubtedly present in the sun, causing the appearance of Ca^+, almost alone, in the highest levels of the chromosphere. In Wolf-Rayet stars hydrogen appears to be abnormally weak (the bands in the approximate positions of the Balmer lines are probably mainly due to He^+), while *He* II and *C* III appear with much greater intensity than would be expected from their behaviour in absorption O-type spectra. The probability that these anomalous intensities are due to the selective effect of radiation-pressure removes a serious difficulty, and points to the necessity for revising some previously held ideas concerning the classification of these stars.

Loss of Mass due to Ejection of Stellar Material.

In connection with the theory that Wolf-Rayet emission is a result of the ejection of stellar material, it is of some importance to calculate the loss of mass which a star may sustain due to such ejection. In order for the observed frequency of occurrence of Wolf-Rayet stars to be accounted for, the duration of the Wolf-Rayet stage must be considerable even on the assumption that every star in the sky becomes a Wolf-Rayet star at some time in its history. The loss of mass has been calculated, first for a star of mass and radius equal to those of the sun, and secondly for a star of 30 times the sun's mass and radius equal to 100,000,000 km. The velocity of ejection has been taken as equal to 2000 km. per second, greater than necessary to account for the width of most Wolf-Rayet bands. The density is that given by Milne † for the solar chromosphere, 3×10^{-17} gm. per c.c. This value is probably rather high, even for the solar chromosphere, but it provides

* *M.N.*, **86**, 300, 1926.
† *Ibid.*, **85**, 141, 1924.

an upper limit for the rate of diminution of the star's mass. The result of the calculation is as follows :—

Star with mass and radius of sun:
Fraction of mass lost per year $= 6 \times 10^{-12}$.

Star with mass $30 \times \odot$ and radius 100,000,000 km.:
Fraction of mass lost per year $= 4 \times 10^{-9}$.

Since these are upper limits, it would appear from the above calculation that the rate of diminution of mass is not sufficiently large to offer a serious obstacle to the theory.

P Cygni, η Carinæ, and Stars of Similar Type.

The spectrum of P Cygni consists of strong, moderately narrow, emission lines, bordered on their violet edges by strong absorption. The displaced absorption lines correspond to a velocity of 82 km./sec. The small displacement of the centres of emission lines from their normal positions is believed to be due to the radial velocity of the star. Measures of the widths of emission lines by Frost * and by the present writer indicate that for lines due to a given atom the width increases with increasing wave-length. Means of my own measures of the lines of hydrogen and helium are given in Table III. The increase in width of these lines is more rapid than a simple linear formula connected with wave-length would indicate, as may be seen from an inspection of the table. In this the behaviour of the lines is similar to that of the lines of Nova Cygni (1920), measures of which have already been given. The bands of Nova Geminorum (1912) also, immediately after maximum, have been shown by Wright † to vary as the square of the corresponding wave-length and not directly as the wave-length. Since the width of the nova bands is generally attributed to motions of the emitting gases, it would appear that the Doppler effect is not necessarily ruled out as a cause for the widths of P Cygni lines. Rapidly decreasing intensities in passing to higher series members, combined with errors of measurement caused by the varying dispersion of the spectrograph, may account for the observed differences.

The star η Carinæ also has an emission spectrum, and the emission lines have been observed by Lunt, ‡ Miss Cannon, § and Perrine to be bordered on their violet edges by absorption. There appears to be no information available as to the variation of the width of emission lines with wave-length. Both P Cygni and η Carinæ have been numbered among the novæ by Stratton, ‖ though the course of their variation has differed somewhat from that followed by most novæ. This similarity with novæ, considered in connection with the absorption on the violet edges of emission lines and the variation in width of P Cygni lines with wave-length, suggests that the peculiarities in the spectra of these

* *Ap. J.*, **35**, 286, 1912.
† *Lick Pub.*, **14**, 36, 1926.
‡ *M.N.*, **79**, 621, 1919.
§ *H.A.*, **28**, 175, 1901.
‖ *Handbuch der Astrophysik*, Band 6, p. 286, 1928.

stars is due to the ejection of gaseous material in a manner similar to that suggested for Wolf-Rayet stars.

TABLE III.

Widths of P Cygni Emission Lines.

He I $\Delta\lambda$ Calc. $=\lambda\times 0{\cdot}000803$.			*H* $\Delta\lambda$ Calc. $=\lambda\times 0{\cdot}001040$.		
λ.	Δλ Obs.	Δλ Calc.	λ.	Δλ Obs.	Δλ Calc.
5875·6	5·5	4·7	6562·8	8·7	6·8
4471·5	3·0	3·6	4861·3	4·8	5·1
			4340·5	4·0	4·5
			4101·7	3·8	4·3

Of somewhat similar character are the two stars H.D. 45910 and B.D. 11° 4673, whose spectra have been described by J. S. Plaskett * and by Merrill † respectively. Both of these stars have emission lines with dark borders on their more refrangible edges. They have shown, in addition, certain peculiar variations in their absorption spectra which serve to indicate a relationship with the novæ. These stars are individual members of a considerable class of stars which show the P Cygni characteristic of emission lines with dark borders on their violet edges. These stars may be assumed to have certain physical characteristics in common, though the precise explanation of their peculiarities is still a matter for speculation. There seems some reason to suppose that the puzzle presented by their peculiar emission may be solved, in part at least, by the application of the present theory of emission to their spectra.

Summary and Discussion.

As a result of the observation and measurement of Wolf-Rayet spectra a theory of stellar emission has been put forward which postulates the continuous ejection of high-speed atoms from a star by selective radiation-pressure. The observational data have been shown to be in agreement with this theory, and it has been found possible to provide a logical explanation of the width of Wolf-Rayet bands, their variation in width with wave-length, the appearance of absorption on their violet edges, and the great intensity of the bands relative to the continuous spectrum. A calculation of the rate of loss of mass of a star by this mechanism appears to indicate that it is not sufficiently rapid to cause doubts as to the validity of the theory. Finally, there appears good reason to believe that the spectral peculiarities of P Cygni, η Carinæ, and other stars which show the P Cygni characteristic may be explained, in part at least, on the basis of the same theory.

The relationship which appears to exist between Wolf-Rayet stars

* *Pub. D.A.O.*, **4**, No. 1, 1927. † *Ap. J.*, **69**, 330, 1929.

and stars of P Cygni type naturally raises the question as to the physical causes operating in the two cases to produce spectra which in some respects are widely different and in others appear to be fundamentally similar. In view of the uncertainty which exists concerning the nature of these bodies it is desirable to proceed with caution in attempting any explanation. There are, however, certain elementary theoretical considerations which suggest themselves and which may lead to a clearer understanding of the problem.

The possibility of the ejection of atoms from a star by radiation-pressure depends on two factors: (*a*) the temperature of the photosphere, and (*b*) the value of gravity at the stellar surface. The work of Johnson * has shown that the probability of atoms of a given sort being ejected is by no means a simple function of these two variables, even when certain perhaps unjustifiable assumptions are made concerning the depth of the absorption lines. Nevertheless it would appear, in general, that such ejection would be rendered more probable or increased in amount by increases in temperature or by decreases in the value of surface gravity. Although there are not at present any published measures of the distribution of intensity in the continuous spectra of Wolf-Rayet stars, the high degree of ionization in their atmospheres, the great intensity of Wolf-Rayet bands relative to the continuous spectrum, and the occurrence of Wolf-Rayet stars as the nuclei of planetary nebulæ, all point to very high temperatures in the photospheres of these stars. P Cygni stars, on the other hand, are generally assumed to be of lower temperature. From what has been said concerning the effect of high temperature and low surface gravity, combined with the knowledge we have of other early type stars, it seems logical to suppose that Wolf-Rayet stars are very massive, diffuse, and highly luminous objects, differing from ordinary absorption O-type stars mainly in their lower density and lower values of surface gravity, though perhaps possessing higher photospheric temperatures as well. The same may probably be said of stars of P Cygni type as compared with absorption-line stars of the same spectral class.

As regards a comparison between the two types of objects, the process of reasoning outlined above would suggest that, since the Wolf-Rayet stars have the higher photospheric temperatures, the P Cygni stars are characterized by lower density and lower values of surface gravity. If, then, we are correct in designating the Wolf-Rayet stars as giants, we should, perhaps, think of the P Cygni stars as super-giants.

The ideas presented in this paper were developed during an extended investigation of Wolf-Rayet stars which included all the northern objects of this type down to magnitude 11·0. A complete account of this investigation, including wave-length data as well as a discussion of the classification of these stars, will appear in the publications of this observatory. The work was undertaken at the suggestion of the director, Dr. J. S. Plaskett, whose helpful advice and kind interest throughout the investigation are very gratefully acknowledged. It is a

* *M.N.*, **86**, 300, 1926.

pleasure also to acknowledge assistance received from other members of the staff. In particular, I am indebted to Mr. W. E. Harper for a discussion of the data on novæ, to Mr. R. O. Redman for criticism and suggestions on the theoretical aspects of the investigation, and to Mr. J. A. Pearce for the loan of plates of P Cygni. I wish at the same time to thank Professor A. Pannekoek for the use of a three-prism plate of P Cygni, and Dr. A. V. Douglas, who prepared the microphotometer tracings which have been reproduced.

Dominion Astrophysical Observatory,
Victoria, B.C., Canada :
1929 *September* 23.

The Distribution of the Double Stars along the Giant Series.

By Dr. E. A. Kreiken.

In several earlier papers * various reasons were discussed why the double stars should statistically be considered to be dwarfs. There can, however, be no doubt that giant visual doubles and spectroscopic ones do occur, though I should expect their relative frequency to be far less among giants than among dwarfs. Moreover, both with the visual and with the spectroscopic doubles a selected material was used, and therefore a direct physical interpretation of our results might lead to erroneous conclusions. With the visual doubles our results were based on the pairs with $d \leqslant 15''$ and $\Delta m \leqslant 2{\cdot}5$, which are contained in the Southern Double Star Catalogue. As a rule we may expect the apparent angular distance d to be larger with the dwarfs than with the giants. Therefore it is not probable that many giant doubles have been excluded. On the other hand, the numbers of double stars with $d < 1''$ may statistically be incomplete. So with the giants of fainter apparent magnitude a number of double stars might have escaped observation. If this were the case the numbers of faint double stars would increase. Now our conclusions were partly based on the fact that the increase of the double star numbers with the fainter magnitudes is much larger than the corresponding increase of the stars in general. If therefore the numbers of double stars were influenced by an effect of selection, this would only strengthen our conclusions.

With the spectroscopic doubles we used those systems for which the spectra of both the main star and its fainter companion have been observed. Evidently the spectrum of the companion will be most easily observed if the mass-ratio between the two components is small. According to Vogt,† this mainly occurs with the stars of the main sequence. So here we may expect selection to have influenced our results. G. Shajn has treated the eclipsing variables and has found that they are mainly dwarfs. Evidently the variability of such a system will be most easily discovered if the luminosities of the two

* *B.A.N.*, **173**, 1929 ; *M.N.R.A.S.*, April 1929 ; *M.N.R.A.S.*, May 1929.

† *Zeitschrift für Physik*, **26**, 139, 1924.