APPARENT VELOCITY-SHIFTS IN THE SPECTRA OF FAINT NEBULAE[1]

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ABSTRACT

Apparent velocity-shifts of the spectral lines of 46 extra-galactic nebulae have been observed at Mount Wilson, 9 of them by F. G. Pease. Most of these objects are fainter and more distant than any heretofore observed; approximately half of them are cluster nebulae. With one exception these observations confirm Hubble's velocity-distance correlation and provide numerical data which may be used in discussions of the significance of the red-shift of spectral lines.

For all faint nebulae the displacements are large and toward the red, the maximum of the continuous spectrum shifting also.

The largest apparent velocity-shift observed, +19,700 km/sec., is that of the brightest nebula in W. H. Christie's cluster in Leo. Its photographic magnitude is 16.8.

With the exception of N.G.C. 205, classified as F5, the spectral types of all the nebulae having absorption lines fall within the narrow limits G1–G5.

In 1929 Hubble found a relation connecting the velocities and distances of the extra-galactic nebulae for which spectra were then available.[2] The spectra were, in general, those of the nearer and brighter nebulae, and the relation was thus established out to the nearest of the great clusters of nebulae—the Virgo cluster at a distance of the order of two million parsecs. A program of investigation was immediately planned with a view to testing the validity of the relation over as great a range in distance as could be covered with the 100-inch reflector. Spectra of 46 of the fainter nebulae have now been observed. With one exception, possibly the velocity of an isolated object seen in projection on a remote cluster, the new data fully confirm the velocity-distance relation[3] previously formulated and extend the observational range to a distance of about thirty-two million parsecs. This phase of the investigation will be presented in a joint paper by Hubble and myself. The present discussion deals primarily with the spectra themselves.

[1] *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 426.

[2] *Mt. Wilson Communications*, No. 105; *Proceedings of the National Academy of Sciences*, **15**, 168, 1929.

[3] It is not at all certain that the large red-shifts observed in the spectra are to be interpreted as a Doppler effect, but for convenience they are expressed in terms of velocity and referred to as apparent velocities.

THE SPECTROGRAPH

In general the spectra were photographed at the Cassegrain focus of the 100-inch reflector. Nebulae very rarely present uniform surfaces, and for the smaller condensations at least, the large aperture of the 100-inch is more efficient photographically than that of the 60-inch reflector. Moreover, by selecting the condensed elliptical nebulae with highly concentrated semistellar nuclei, it was possible to obtain with the 100-inch practically the full advantage which it offers in the case of stars.[1]

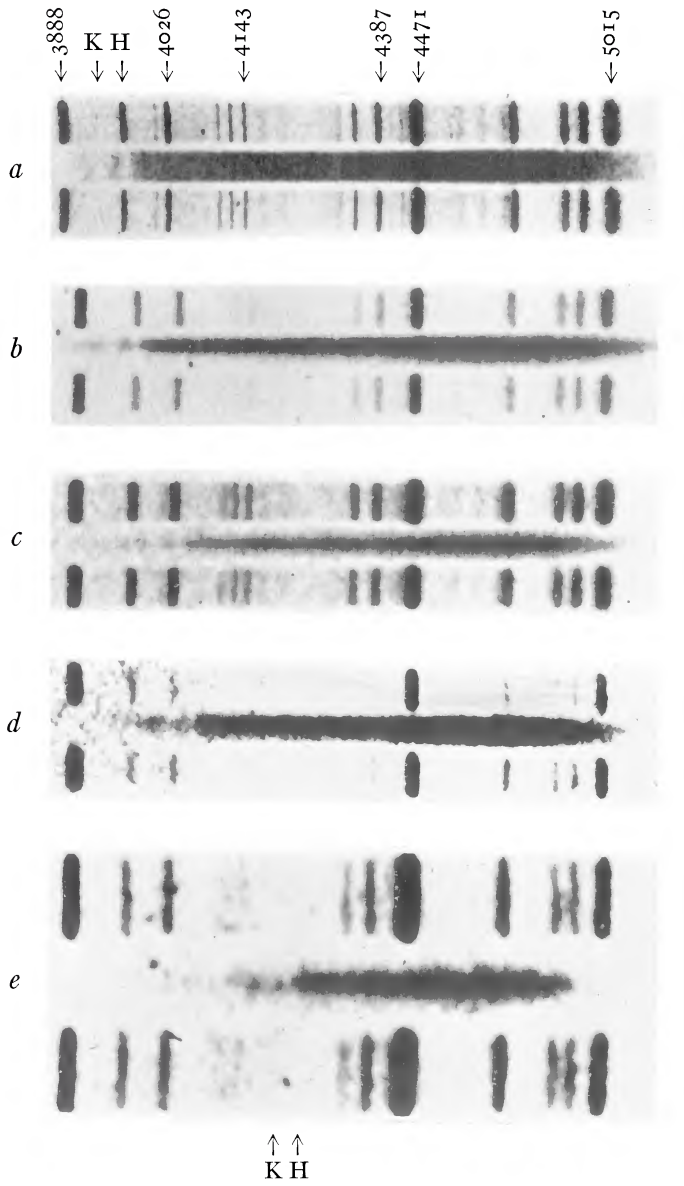
The first spectrograph used was provided with a 24-inch collimator, two prisms of light flint glass, and a 3-inch camera giving a dispersion of 170 A per millimeter at λ 4350. This combination proved too slow for efficient observation of faint nebulae. With prolonged exposures it was possible to record the region λλ 4200–5000; in general, however, the G band (λ 4303) was the only feature strong enough to be seen clearly, but, on account of the large displacements encountered, the identification was very uncertain.[2] For this reason one prism was removed, thus giving a dispersion of about 340 A per millimeter at λ 4350. The increased speed made it possible to register the spectra of faint nebulae to the violet of λ 4000 and hence to use the unmistakable H and K lines as a basis for identification of the other features.

The reduction in scale proved so effective that an even smaller dispersion seemed desirable. This was made possible by Dr. W. B. Rayton, of the Bausch and Lomb Optical Company, who designed a spectrograph objective having a ratio of F/0.6. The Rayton lens with two prisms gives a dispersion of about 418 A per millimeter at

[1] Hubble, *Mt. Wilson Contr.*, No. 398; *Astrophysical Journal*, **71**, 231, 1930. The steepness of the luminosity gradient in elliptical nebulae is illustrated by Fig. 1*a*, which gives transparency-curves for photographic images of N.G.C. 3379. The semistellar nucleus is indicated by the sharp maxima shown by the two shortest exposures.

[2] The case of N.G.C. 4884 is an example. The first spectrum obtained with the 60-inch reflector was very weak. The stronger of the two lines measured was assumed to be λ 4383 *Fe*, and gave the velocity +1500 km/sec. announced in *Summary of the Year's Work at Mount Wilson* for 1928. This seemed the most probable identification, since the highest velocity then known was V. M. Slipher's value, +1800 km/sec. for N.G.C. 584. A later spectrogram, showing the H and K lines of calcium, proved the true red-shift to be +6700 km/sec., and the strong line originally measured to be the G band.

PLATE III



Nebular spectra showing increase in red-shift with decreasing apparent brightness corresponding to increasing distance. Arrows indicate positions of H and K in (*a*) and (*e*). For (*a*) to (*d*) the enlargement is 28 times the scale of the original negatives; for (*e*), photographed with about one-half the dispersion used for the others, 47 times.

a) Sky; normal position of H and K; wave-lengths of several of the helium comparison lines are indicated.
b) N.G.C. 221 (M 32); apparent velocity, −185 km/sec.
c) N.G.C. 385; apparent velocity, +4900 km/sec.
d) N.G.C. 4884; apparent velocity, +6700 km/sec.
e) Brightest nebula in Leo cluster; apparent velocity, +19,700 km/sec.

λ 4500, and with one prism, about 875 A per millimeter for the same region. This is much the fastest combination in actual use at Mount Wilson.[1] The definition is excellent, and four lines are generally recognizable in nebular spectra. These lines are H and K, *Hδ* (λ 4101), and the G band (λ 4303.14). Occasionally *Hγ* (λ 4340), λ 4383 *Fe*, and *Hβ* (λ 4861) can also be identified.

OBSERVING PROGRAM

The nebulae selected for observation are about equally divided between clusters and isolated objects. Clusters of nebulae offer the great advantage that fairly reliable distances can be derived from the mean luminosities of the many individual members, while the observations can be restricted to the several brightest members of each cluster. Thus the greatest possible distance for a given apparent luminosity is assured. Further, since there appears to be no correlation of red-shift with absolute luminosity among nebulae whose distances are known, the several brightest members of a cluster may safely be assumed to represent the cluster as a whole in respect to line displacement.

The isolated nebulae were included in order to test the possibility of a systematic difference between them and the cluster nebulae, and later to afford data for special problems involving the distances. Since apparent luminosity furnishes only a statistical criterion of distance, it was necessary to observe enough isolated objects to form several groups. Mean velocities could then be compared with the mean distances of the groups.

Table I lists the nebulae observed, together with the measured apparent velocities, spectral types, and estimated uncertainties. The uncertainties are possibly three times the probable errors as formally derived from the few lines measured and are believed to be a fair indication of the reliability. They depend on the scale, the exposure, and the number of lines that could be measured.

Spectra of 9 of the 46 nebulae were photographed by F. G. Pease, who has kindly placed the spectrograms at my disposal for

[1] For a further description of the extraordinarily efficient Rayton lens, together with some account of its performance, see Rayton, *Astrophysical Journal*, **72**, 59, 1930, and Humason, *Mt. Wilson Contr.*, No. 400; *Astrophysical Journal*, **71**, 351, 1930.

TABLE I

APPARENT VELOCITY-SHIFT AND SPECTRAL TYPE

N.G.C.	Apparent Velocity-Shift	Estimated Uncertainty	Spectral Type	Remarks
	km/sec.	km/sec.		
380.....	+ 4400	75	G5	Group in Pisces; not one of the large clusters but a group of about 25 nebulae
383.....	+ 4500	100	G3	
384.....	+ 4500	100	G5	
385.....	+ 4900	100	G5	
1270.....	+ 4800	100	G4	Cluster in Perseus
1273.....	+ 5800	75	G5	
1275.....	+ 5200	25	G+P (pec.)	
1277.....	+ 5200	75	G3	
2562.....	+ 5100	100	G4	Cluster in Cancer
2563.....	+ 4800	100	G4	
*.....	+ 19700	300†	G5	Christie's cluster in Leo
‡.....	+ 11700§	200	G5	Baade's cluster in Ursa Major
4192||....	+ 1150§	100	G2	Cluster in Virgo
4374||....	+ 1050	100	G4	
4853||....	+ 7600§	100	G1	Cluster in Coma Berenices; N.G.C. 4865 may not be a member; velocity of N.G.C. 4884 previously announced as +1500 km/sec.
4860||....	+ 7900§	75	G3	
4865.....	+ 5000§	75	G3	
4872.....	+ 6900	200†	G3	
4874.....	+ 7000	200†	G4	
4881.....	+ 6900	200†	G3	
4884.....	+ 6700§	75	G3	
4895.....	+ 8500	200†	G4	
I.C. 4045.....	+ 6600	200†	G1	
7611.....	+ 3400	75	G2	Cluster in Pegasus
7617.....	+ 3900	100	G1	
7619.....	+ 3800§	75	G3	
7623.....	+ 3800	125	G2	
7626||....	+ 3700	100	G3	
205.....	− 300§	50	F5	Distant companion of Andromeda
2859.....	+ 1500	100	G3	
2950.....	+ 1500	75	G4	
3193.....	+ 1300	100	G3	
3227.....	+ 1150§	30	G+Pd	
3610.....	+ 1850	75	G2	
4051.....	+ 650§	40	G+Pb	
5457.....	+ 300¶	25	G+Pd	

* The nebula observed is the brightest one in the cluster.

† The large uncertainty is due to the dispersion, 875 A per millimeter.

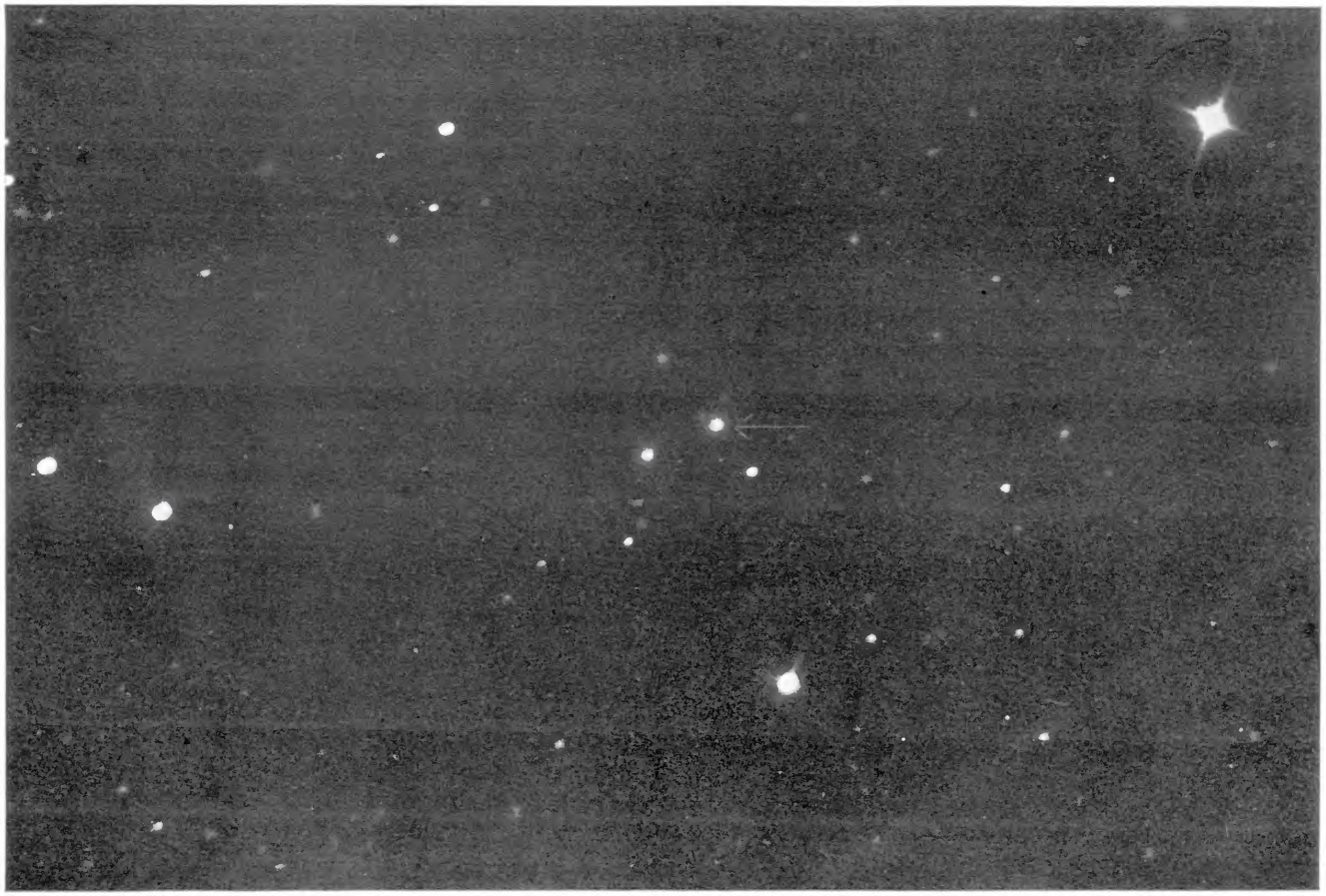
‡ The velocity is from the brightest nebula, Baade No. 24.

§ Velocity previously announced. || Spectrum obtained by F. G. Pease.

¶ The velocity previously published was +200 km/sec. Recently the nucleus and two emission patches have been observed, making the mean +300 km/sec.

PLATE IV

N



W

Small region in the Leo cluster; R.A. $10^{h}24^{m}1$, Dec. $+10°47'$ (1930). The nebula observed, the brightest in the cluster, photographic magnitude about 16.8, is indicated by the arrow. The bright star in the upper right-hand corner is B.D. $+11°2230$. Scale, 1 mm = 7″.

TABLE I—*Continued*

N.G.C.	Apparent Velocity-Shift	Estimated Uncertainty	Spectral Type	Remarks
	km/sec.	km/sec.		
6359.....	+ 3000§	75	G3	
6658.....	+ 4100	75	G3	
6661.....	+ 3900	100	G5	
6702||....	+ 2250	75	G4	
6703||....	+ 2000	75	G3	
6710.....	+ 5100	100	G3	
6822.....	− 150§	25	Pd	Emission patch in N.G.C. 6822
6824.....	+ 3200	75	G4	
7217||....	+ 1050	100	G4	
7242||....	+ 5000	200	G3	The large uncertainty is on account of a weak plate

measurement and discussion. Velocities of 13 of the nebulae have previously been published, 4 of them by Pease and myself jointly. The table thus includes all recent measures made at Mount Wilson. The velocities previously available, for the most part those made by V. M. Slipher at the Lowell Observatory, but including 7 measures from Mount Wilson and 3 from Lick Observatory, have been collected by G. Strömberg.[1] The two lists together include all velocities published to date.[2]

The present list gives velocities of 24 nebulae in 7 clusters, 4 in a group in Pisces, and 18 isolated objects. The nebulae range from irregular objects (N.G.C. 6822) and late-type spirals (M 101) to the early elliptical nebulae which predominate in the clusters. The largest displacement found is that for the brightest nebula in Christie's cluster in Leo,[3] which has a photographic magnitude of about 16.8. The observation was made with the smallest dispersion used, but the measured displacement of +19,700 km/sec. is believed correct within a few hundred kilometers. The single spectrogram available was exposed 13 hours and is one of the best so far obtained.

Where several velocities have been measured in a single cluster, the range is small compared with the mean in all except the Coma

[1] *Mt. Wilson Contr.*, No. 292, p. 2; *Astrophysical Journal*, 61, 354, 1925.

[2] Slipher reports spectra for three additional nebulae in the Virgo cluster, but has published no velocities as yet.

[3] This cluster was found by W. H. Christie, on plates taken at Mount Wilson with the 60-inch reflector. The 1930 position is: R.A. 10^h24^m1, Dec. $+10°47'$.

cluster. There, around a mean of +7300 km/sec., 8 nebulae show a range of 1900 km/sec., which is the maximum among all the clusters. A ninth object (N.G.C. 4865) gives +5000 km/sec. On direct photographs this object is in no way distinguishable from the other bright cluster nebulae, but the velocity derived from two spectrograms is the one conspicuously discordant result in the table.

MEASUREMENTS

On the average, the velocities depend on measures of about three lines. These are generally H and K and the G band (λ 4303), with occasionally one or more of the lines $H\delta$ (λ 4101), $H\gamma$ (λ 4340), λ 4384 *Fe*, and $H\beta$ (λ 4861), according to the density of the spectrograms in the region of the lines. As an example of the results obtained from spectra having a dispersion of 875 A per millimeter, the individual measurements are listed for the brightest nebula in

	E.M.	M.H
3933 (K)	+19,890 km/sec.	+19,925 km/sec.
3968 (H)	19,571	19,708
4101 ($H\delta$)	19,609	19,615
4303 (G)	19,778	19,276
4340 ($H\gamma$)	+19,815	+19,579
Mean	+19,733	+19,621

Christie's cluster. In Table I the probable uncertainty is given as 300 km/sec., and the apparent velocity entered to the nearest 100 km/sec.

The wave-length of the blend which forms the G band (λ 4303.14) was derived from spectra of standard velocity stars having as nearly as possible the same type as the nebulae. Before this wave-length was obtained, the value λ 4307.91 was used in reducing measures of N.G.C. 4853, 4860, and 4865, but their velocities have since been corrected by an average of +233 km/sec.

Each spectrogram has been measured twice, once by Miss Elizabeth MacCormack and once by the writer. These duplicate measures are in good agreement. Velocities less than 2000 km/sec. are given to the nearest 50 km/sec., those larger to the nearest 100 km/sec.

Valuable confirmation that the velocity displacements, $\delta\lambda/\lambda$, do

not vary appreciably with the wave-length is afforded by the emission spectra from the nucleus of N.G.C. 1275 in the Perseus cluster of nebulae. The measured lines range from λ 3727 to λ 4861, with no systematic difference in the velocities.

DETERMINATION OF SPECTRAL TYPES

Except for the bright-line nebulae, classifications have been based on a comparison with spectra of N.G.C. 221 (M 32). This nebula was chosen as the standard type because plates of high dispersion were available, from which the spectrum was classified as dG_3 by Adams, Joy, and the writer. Additional spectrograms were obtained with the different dispersions in order that comparisons might always be made between spectra having the same scale.

The criteria used in assigning types to the bright-line nebulae are those adopted by the International Astronomical Union and given in the *International Critical Tables*.

Nebulae having absorption lines show only a small dispersion in type, all of them, except N.G.C. 205, falling within the narrow limits G1–G5. N.G.C. 205 has been classified as F5.

Bright-line spectra are of two different types, according as the continuous spectrum is strong or weak in comparison with the emission. The relative intensity of the continuous spectrum in the first type appears the same as in spectra having absorption lines. Examples are N.G.C. 3227, 4051, and 1275—all nebulae having bright stellar nuclei. The emission lines in the spectrum of N.G.C. 1275 are shifted to the red by the same amount as the absorption lines in the spectra of other members of the cluster to which it belongs, namely, +5200 km/sec.

Examples of the second type, in which the bright lines predominate, are obtained from emission patches in the outer regions of large nebulae, for instance, N.G.C. 5457 (M 101) and N.G.C. 6822.

Wide, shallow absorption lines have been observed in high-dispersion spectra of M 31 and M 32, and have been found approximately twice as wide in M 32 and almost four times as wide in M 31 as the lines in the spectrum of skylight. A widening of the lines seems noticeable in spectra of the fainter nebulae, but no definite

statement in regard to this can be made, on account of the small scale.

The maximum of the continuous spectrum is shifted by an amount equal to the displacement due to the velocity. This suggests a color excess, which has actually been found from extra-focal photographic and photovisual magnitudes and which in some cases exceeds the amount expected. Nebulae in the Perseus cluster have an excess color-index of half a magnitude. Indications are that color-index appears to depend upon galactic latitude rather than distance.

FUTURE INVESTIGATIONS

An attempt will be made to extend the observed range in distance by measures of fainter clusters of nebulae. Some extension seems quite possible, but the limit with the 100-inch reflector will be reached at about photographic magnitude 17.5. Exposures necessary for the fainter nebulae are not so long as the magnitudes would indicate because the red-shift is so large that the H and K lines are brought into the region to which the photographic plate is highly sensitive. Further, lower dispersion can be used, for, since the red-shift is larger, a larger probable error can be tolerated. The main difficulty arises from the fact that at photographic magnitude $17.5\pm$ the nebulae become so faint visually at the Cassegrain focus of the 100-inch reflector that they cannot be seen on the slit of the spectrograph.

In order to test thoroughly the agreement of the velocities for individual members of a cluster, a larger number of velocities will be observed in the Virgo cluster.

High-dispersion spectra of some of the brightest nebulae will be obtained in order to investigate further the widening of the absorption lines which appears in such objects as M 31 and M 32.

I wish to express my thanks to Mr. T. A. Nelson, night assistant at the 100-inch telescope, and to Mr. Glenn Moore, relief night assistant, for their aid in obtaining the spectrograms.

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