EMISSION-LINE PROFILES IN PLANETARY NEBULAE

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ABSTRACT

Measurements are presented of H I, He II, [O III], and [N II] emission-line profiles in several bright planetary nebulae. The lines are wider than the expected thermal Doppler widths, which indicates that there are significant mass motions within planetary nebulae. These observationally determined profiles may be used to test the predictions of physical models of expanding planetary nebulae. Only a few such models exist at present, all extremely simplified, but comparison with assumed sample models shows that the distribution of emission with radial velocity must have a fairly well-defined peak.

The internal velocity distributions in planetary nebulae were first observed by Campbell and Moore (1918) in the course of their radial velocity measurements of the [O III] lines λ4959, 5007. They noticed the double, bowed appearance of the emission lines in the spectra of some planetaries, particularly NGC 2392, 6210, 6720, and 7662, but were unable to interpret this observation. Later the very complete, higher-dispersion study by Wilson (1948, 1950) showed that doubling of the lines at the center of the planetary nebula is a common feature, and that these line shapes can be understood as resulting from the expansion of the nebular gas approximately radially outward (cf. Wilson 1958). Wilson measured ΔV, the separation between the two components of each emission line, and he showed that within a single nebula this quantity varies from ion to ion, but that in a general way the highest degrees of ionization, which are concentrated near the central star, have the smallest values of ΔV, while the lower stages of ionization, which are concentrated further out in the nebula, have larger values of ΔV. He interpreted this result as indicating an increase in the expansion velocity radially outward from the central star.

At the present time further study of the expansion of planetary nebulae is of considerable interest, because the available knowledge of the distances of these objects has been derived from a model based on their expansion (Shklovskii 1956; O'Dell 1963a; Harman and Seaton 1964). Also the expanding planetary-nebula shells are among the few known objects in which mass loss from stars to interstellar space is directly observed (O'Dell 1963a; Osterbrock 1966). Some beginning has been made on the gas-dynamic problem of the expansion of highly simplified model planetary nebulae (Turoff 1965; Mathews 1966), and it appears that further observational data on the internal velocities within planetary nebulae will aid in understanding of these objects.

All of our observations were made with the 100-inch telescope at Mount Wilson, using the motor-driven image rotator to hold the nebulae in a fixed orientation on the slit of the coudé spectrograph. The spectrograms used in the present paper were taken with the slit through the central star, and oriented either along the major diameter of the nebula or (for essentially circular planetaries) east-west. They were taken with the high-dispersion grating (No. 133-B), which has 900 lines/mm, giving a dispersion of about 4.1 Å/mm in the third-order blue-green spectral region, and about 6.5 Å/mm in the second-order red. The nebular lines He II λ 4686, Hβ λ 4861, and [O III] λλ 4959, 5007 were observed in the third order on baked HaO plates, while Hα λ 6563 and [N II] λ 6583 were observed in the second order on preflashed HaF plates, exposed in the same plate holder at the same time.

The photometric calibration was provided by exposures on the same plates taken through the regular calibration step slits on either side of the spectrograph slit. These

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calibration-strip exposures were taken through a filter transmitting radiation with $\lambda > 4500$ Å, using an incandescent bulb illuminating a ground glass as a light source, and were of approximately the same length of time as the nebular exposures (which ranged from 10 min to 8 hours, and averaged about 3 hours). The comparison spectrum for measuring the dispersion (and also for estimating the resolution) was provided by exposures with the hollow-cathode neon-iron source.

The individual photographic spectrograms were traced with the recording microphotometer at Yerkes Observatory to determine line profiles of the nebular emission lines. In some nebulae, for instance NGC 7662, the lines are tilted, indicating different radial velocities at the two ends of the major axis, probably resulting from an ellipsoidal expansion-velocity distribution (Wilson 1958). In tracing the spectrograms of these nebulae, the slits of the microphotometer were rotated so that they were parallel to the approximate axis of symmetry of the inclined emission lines, though the tracing was still made in the direction of the dispersion. This procedure, which would not be necessary if the length of the analyzing slit were infinitesimal, prevents the inclination of the line from artificially broadening the profile as recorded through a finite analyzing slit. The length of the analyzing slit was set so that it covered about 1.5 to 2″ of the image, and was always positioned at the center of the nebula. The comparison spectrum near each emission line was also traced in order to determine the dispersion on the resulting output, the Brown recorder chart. The dispersion on the tracings proved to be very stable, and an average value was therefore adopted for each line and used in the further reductions. The calibration-strip exposures were also traced at the wavelength of each line measured, so that an individual calibration-curve could be drawn for each line on each plate. The individual line profiles were then constructed, using the individual calibration-curves to give the relation between transmission on the spectrogram and relative intensity. The first eighteen line profiles were reduced in the standard way, using a hand computing machine and graph paper. A computer program was then written for the IBM 1620, and after it had been checked by reproducing some of the same profiles that had previously been reduced by hand, it was used in the further reduction of the rest of the profiles. The tracings were read directly onto cards, using a two-dimensional curve reader and punch, and all the further processing was done in the computer, leaving only the final profiles to be drawn by hand.

Several different spectrograms were available for most of the planetary nebulae, and the individual profiles determined from them were combined to form average profiles for each observed ion in each nebula. For this averaging process wavelength shifts were converted to relative radial velocities, and all profiles were normalized to relative intensity 1.00 at peak intensity, so that it was possible to average together Ha and Hβ profiles, and also to average together [O III] $\lambda$ 4959 and $\lambda$ 5007 profiles. The individual profiles were averaged visually, using transparent graph paper on a light table. The number of individual profiles used in each average is listed in Table 1, and the resulting final profiles are shown in Figures 1–4 and Figure 6 (see below). The accuracy of the relative intensity at a particular velocity shift, as judged from the internal consistency of the individual determinations, is approximately ±4 per cent of the peak intensity. The exact form of the instrumental function could not be determined accurately from the tracings, but the full widths of the comparison lines at half-maximum range from 6 to 7 km/sec on the individual tracings, which is very much sharper than the nebular profiles.

Inspection of the profiles shows that the well-known double appearance of the planetary-nebula emission lines is easily apparent. Furthermore in each nebula the hydrogen lines are broadest and the [O III] or [N II] lines are sharpest, while the He α lines are intermediate in width. This progression in widths, which was noticed by Wilson (1958), indicates that the broadening of the nebular emission lines is at least partly due to thermal motions. However, our observations show that mass motions also play a role in the
broadening, because the line profiles observed cannot be fitted by double Gaussian profiles with a velocity separation ΔV, which would correspond to the difference between the velocity of approach of the front portion of the shell and the velocity of recession of the back portion of the shell. Furthermore, the widths of the profiles at one-half maximum intensity are much greater than the thermal Doppler widths corresponding to the temperatures of the planetaries, known from [O III] line-ratio measurements to be in the range from 10000° to 15000° K. To show this quantitatively, Table 2 lists the

<table>
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<tr>
<th>TABLE 1</th>
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<tr>
<td><strong>NUMBERS OF INDIVIDUAL PROFILES AVERAGED TOGETHER TO FIND OBSERVED PROFILE</strong></td>
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<tr>
<th></th>
<th>H I</th>
<th>H II</th>
<th>[O III]</th>
<th>[N II]</th>
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<td></td>
<td>Hα</td>
<td>Hβ</td>
<td>λ4686</td>
<td>λ4959</td>
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<td>3</td>
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<tr>
<td>NGC 7009</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NGC 6572</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>2</td>
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<tr>
<td>NGC 6826</td>
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<td>1</td>
<td>1</td>
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<tr>
<th>TABLE 2</th>
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<tr>
<td><strong>WIDTHS OF PLANETARY-NEBULA EMISSION-LINE COMPONENTS EXPRESSED AS TEMPERATURES</strong></td>
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<tr>
<th></th>
<th><strong>INDICATED TEMPERATURE FROM WIDTH (° K)</strong></th>
<th><strong>TEMPERATURE FROM [O III] LINE RATIO (° K)</strong></th>
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<tr>
<td></td>
<td>H I</td>
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<td>13600</td>
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<td>29700</td>
<td>35500</td>
</tr>
<tr>
<td>NGC 7009</td>
<td>14000</td>
<td>...</td>
</tr>
<tr>
<td>NGC 7662</td>
<td>17400</td>
<td>51700</td>
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temperatures that would be derived from the widths of the individual profiles at one-half maximum intensity for several ions in several nebulae, together with the known kinetic temperatures (in the [O III] emitting regions) in these nebulae, as derived from [O III] measurements by Liller and Aller (1954), and by using the formula of Seaton (1960) with the measurements (corrected for interstellar extinction) of O’Dell (1963b). The profiles thus give direct observational evidence of mass motions within planetary nebulae.

Any complete theoretical model of the expansion of a planetary nebula will include prediction of the flow velocity, density, and temperature at each point within the nebula, and therefore will furnish the information needed for calculating the expected emission-line profiles. We believe that the observationally determined profiles of the present paper will be most useful for comparison with such theoretically predicted profiles. However, since only one or two simplified models exist at the present time, we have tried to use
Fig. 1.—Observed line profiles in NGC 7009. Vertical scale, relative intensity, normalized to unity at peak intensity. Horizontal scale, radial velocity in km/sec, relative to a reference velocity midway between the two peaks.

Fig. 2.—Observed line profiles in NGC 6210. Scales as in Fig. 1.
Fig. 4.—Observed line profiles in NGC 7662. Scales as in Fig. 1.
the observed profiles to get some approximate information about the internal velocity distribution.

The function which determines the form of a line profile is $E(V)$, the distribution function of the emission coefficient in that line per unit radial velocity range. In a nebula of constant temperature and ionization, $E(V)$ would simply be proportional to $N^2(V)l$, the square of the density, integrated along the line of sight, of the material with velocity in unit velocity range about radial velocity $V$, and in more complicated models $E(V)$ can be calculated from the density of the ion that emits the line, the electron density, the path length, and the temperature. If there were no thermal Doppler motions, the true profile $P(V)$ would simply be

$$P(V) = E(V).$$

However, because of the thermal Doppler broadening, the true emitted profile becomes

$$P(V) = \text{const.} \int_{-\infty}^{\infty} E(U) e^{-m(U-V)^2/2kT} dU,$$

(for an ion of mass $m$ in an isothermal nebula of temperature $T$). We have therefore assumed various simple forms for $E(U)$, carried out numerically the integration of equation (2), and compared the resulting “predicted” models with the observed profiles.

As stated above, the first set of assumed models represented expanding shells with no internal velocity dispersion, namely,

$$E(U) = a\delta(U - \frac{1}{2}\Delta V) + b\delta(U + \frac{1}{2}\Delta V).$$

In this form of the emission distribution function, $a$ and $b$ may have different values, reflecting the observation that the two sides of the profile often do not have equal intensity, an indication that the shell is not perfectly symmetric. As we have seen above, profiles derived from distribution functions of the type specified in equation (3) do not fit the observations at all well.

The next set of assumed distribution functions were square waves of width $W$ of the type

$$E(U) = a \quad \text{for} \quad -\frac{W}{2} < U < \frac{1}{2}\Delta V < \frac{W}{2},$$

$$= b \quad \text{for} \quad -\frac{W}{2} < U + \frac{1}{2}\Delta V < \frac{W}{2},$$

$$= 0 \quad \text{for} \quad \text{all other} \quad U.$$

Profiles derived from this type of distribution function also do not fit the observational data well, their defect being that, if the profile is sufficiently wide to fit the lower-intensity part of the observed profile well, it is too flat-topped to fit the higher-intensity part of the observed profile, while conversely, if the calculated profile fits the high-intensity part of the observed profile, it is narrower than the low-intensity part of the observed profile.

Next we assumed triangular-shaped velocity-distribution functions having a maximum of the emission coefficient at a definite expansion radial velocity and dropping off linearly on either side of this peak velocity. This type of distribution function turned out to fit the observed profiles well, and as a sample the results are shown for NGC 7662 in Figure 5. In this figure the predicted profiles are drawn with a solid line, and in addition for $H\alpha$ and $[O\,\text{III}]$ the effects of the finite instrumental resolution on these profiles...
Fig. 5.—Calculated line profiles at $T = 12500^\circ$ K to match NGC 7662. Triangular-shaped velocity-distribution functions shown in upper right corners. Dashed lines show effects of instrumental broadening by assumed Gaussian profiles with full width at half-maximum of 6 km/sec for H I profile and 7 km/sec for [O III] profile, as explained in text.
is indicated by the dashed lines. For this calculation the predicted profile $P(V)$ was further broadened by an assumed Gaussian instrumental profile according to the equation

$$O(V) = \text{const.} \int_{-\infty}^{\infty} P(v) e^{-\beta(v-V)^2} dv,$$

where $O(V)$ is the profile expected to be observed, and where $\beta$ is chosen to give the widths of the comparison lines on the tracing (6 km/sec for $\text{H}\ I$ and 7 km/sec for $\text{[O III]}$, both at half-maximum). In Figure 5 the assumed form of the emission distribution function $E(U)$ is shown in the upper right-hand corner of the drawing. Note that only one side of the distribution function, $E(U)$ for $U > 0$ is shown, and that for $U < 0$ the same form of the function but with a smaller amplitude was assumed, in order to match the relative intensities of the two sides of the observed profile. Note furthermore that in the models for NGC 7662 the assumed form of the distribution function is nearly

**Fig. 6.**—Observed line profiles in NGC 6826. Scales as in Fig. 1

**Fig. 7.**—Calculated line profiles at $T = 11500^\circ$K to match NGC 6826. Triangular-shaped velocity-distribution functions shown in upper right corners.
identical for the three ions $\text{H} \, \lambda$, $\text{He} \, \lambda$ and $[\text{O} \, \text{III}]$. In general, if the flow velocity varies with position in the nebula, some differences should be expected in the distribution functions for different ions because of the variation of ionization through the nebula. The observed profiles of the other nebulae shown in Figures 1–3 and Figure 6 can all be approximately fitted by profiles derived from triangular-shaped emission coefficient distribution functions. We show only the additional case of NGC 6826 (see Fig. 7) which is interesting because the expansion velocity is relatively small, smaller than the Doppler thermal width of the hydrogen lines, so that the observed $\text{H} \, \lambda$ profile appears single, while the observed $[\text{O} \, \text{III}]$ profile is double. The calculated $\text{H} \, \lambda$ and $[\text{O} \, \text{III}]$ profiles of Figure 7, which were both calculated with identical triangular-shaped distribution functions, reproduce this property very well. Note that among the observed nebulae, NGC 6572 also has a low velocity of expansion and an apparently single $\text{H} \, \lambda$ line, like NGC 6826.

We believe that other assumed forms of the emission distribution function, such as parabolic, or double exponentials of the form

\begin{equation}
E(U) = a \exp(-a |U - \frac{1}{2} \Delta V|) \quad \text{for} \quad U > 0
\end{equation}

\begin{equation}
= b \exp(-a |U + \frac{1}{2} \Delta V|) \quad \text{for} \quad U < 0
\end{equation}

would also reproduce the observed profiles about as well as the triangular forms assumed above. We do not believe it is worthwhile to try to get the best fit, since not only the observational errors but also the variation of ionization through the nebula (which implies that different ions have different expected emission distribution functions) contribute to the lack of definiteness of this procedure. At this stage it appears to us it would be more profitable to try to construct physical models, such as those of Mathews (1966) and Turoff (1965), and compare the profiles predicted by these physical models with the observational profiles, rather than to analyze further the observational data. However, the sample models we have considered indicate that the distribution function must have a fairly well-defined peak to fit the observed profiles well.

The physical meaning of the emission distribution function cannot be derived from these profiles alone, since they all refer to the projected centers of the nebulae. If no other information were available, they could be interpreted as resulting from turbulent velocities within the nebula, or from a gradient of expansion velocity. However, since Wilson's observations of a larger number of lines show that the expansion velocities of ions with high ionization potential (that is, of material situated close to the central star) tend to be small, while the expansion velocities of ions of low ionization potential (that is, of material situated relatively far from the central star) tend to be large, there is no doubt that a gradient of expansion velocity exists. Such a gradient is predicted by all published models, because in all of them the expansion velocity goes to zero at the center of the symmetric nebula. Therefore it is probable that at least a large part of the emission distribution function is determined by the expansion of the nebula. However, it is not possible from these observations alone to say whether or not turbulent velocities also have some influence on the velocity profiles. Analysis of the profiles near the edges of a spherically symmetric nebula would be necessary to give a definite answer to this question, and we hope to return to this problem in a later paper.

Finally, it should be emphasized that the observational data given here are selected in the sense that the nebulae observed were the most nearly symmetric bright objects that could be observed in the summer sky, and that from among these selected nebulae the profiles that were reduced were further selected as the most nearly symmetric forms. This selection was made so that the observational data could be compared with theoretical models, which will undoubtedly be highly idealized and therefore completely symmetric, in contrast to even the most nearly symmetric among the observed nebulae.
However, in nature, in addition to the nebulae with nearly symmetric double lines, nebulae with asymmetric and distorted profiles also exist. An example of a nebula with a symmetric profile, NGC 7662, is reproduced in Figure 8, along with an example of a nebula with a more highly distorted profile, NGC 7027. It can be seen that there is some fairly complicated velocity structure in the faint outer ring of NGC 7662, which shows best in the densest long exposure of λ 5007. Also the complications in the structure of the profiles of NGC 7027 largely disappear in the lightly exposed [N II] λ 6583 line of this rather chaotic-appearing planetary.

The observational data on which this paper is based were obtained by one of us (D. E. Osterbrock) as a guest investigator at the Mount Wilson and Palomar Observatories, and he is very grateful to Director H. W. Babcock for the opportunity to work there, to Dr. O. C. Wilson for many practical suggestions, help, and advice on planetary nebulae and on the use of the coude spectrograph, and to Mr. E. L. Hancock, Mr. A. L. Olmstead, and Mr. J. L’Ecuyer for assistance in obtaining the plates. We are also grateful to the National Science Foundation for partial support of this research, and to the Space Astronomy Laboratory of the University of Wisconsin for the use of the IBM 1620 computer in reducing the observational profiles and calculating the model profiles.

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———. 1950, ibid., 111, 279.
Fig. 8.—Enlargements of emission lines in planetary nebulae. (a), (c), and (d): \([\text{O} \text{III}] \lambda 5007\) in NGC 7662, successively longer exposures. (b): \(\text{H} \alpha\) in NGC 7662, for comparison with (a). (e), (f), and (g): \([\text{O} \text{III}] \lambda 4959\), \(\text{H} \alpha\), and \([\text{N} \text{II}] \lambda 6583\) in NGC 7027.