6. SPECTROSCOPIC EVIDENCE BEARING ON THE DISTRIBUTION OF GAS IN EXTRA-GALACTIC SYSTEMS*

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Six years ago, in a joint paper with W. Baade [1], I presented certain spectrographic data bearing on the distribution and motions of gaseous masses in spiral nebulae. Since then progress in this special field has been unspectacular and relatively slow by conventional optical means, mainly because of the considerable faintness of the sources. Nevertheless, the optical data now seem sufficiently representative to warrant a review directed toward an eventual comparison of optical and radio results. For there can be little doubt that the new radio astronomy techniques give every indication of revolutionary new advances. Highly significant results have been obtained for the Magellanic Clouds, a beginning has been made in the local group spirals such as the Andromeda nebula, and it is reasonable to expect, as more powerful installations come into operation, that the nearer field and great cluster nebulae will come under detailed radio observation. But these matters have been considered at the recent Jodrell Bank symposium on radio astronomy, in Manchester. For this reason and because I am not a radio astronomer I shall proceed, without further discussion of these exciting new developments, to a description of the more prosaic optical data obtained from spectrographic observations.

When the slit of a spectrograph is placed on the optical image of an extra-galactic nebula to learn something about the distribution of gas in the system, the resulting spectrogram is examined for evidence of emission lines. These come from interstellar gas that has been ionized by the far-ultra-violet radiation from imbedded hot stars. Although the principal constituent and source of free electrons in the gas is hydrogen, other much less abundant elements reveal their presence by forbidden radiations. Among these is a close-doublet emission line normally at wave-length λ 3727, which is due to [O II]. From the spectra of more than 800 extra-galactic nebulae observed during the past twenty years at the Mount Wilson-Palomar and Lick Observatories, this particular emission feature

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has been found to occur with higher frequency than all others, including Hβ and Hγ, in the blue-violet spectral region [2,3]. In the red, Hα with its flanking companions of [N II] at λ 6548 and λ 6584, may rival λ 3727 as persistent emission [4], but spectrographic observations in the red are not nearly so numerous. With this limitation, λ 3727 is presently the best-known optical indicator of ionized gas in extragalactic systems.

To begin this discussion of gas in extra-galactic systems, it should be emphasized that observations of emission lines in their spectra show where the *combination* of hot stars and ionized hydrogen gas exists. There may be cases of systems in which the gas is present, but unless there are also hot stars mixed with it to effect the ionization required to produce the emissions, the optical spectra do not show directly the presence of gas. Thus the optical data give information chiefly on the distribution of Strömgren's H II regions, whereas the radio observations at 21-cm yield results on the distribution of neutral hydrogen, H I. Indirectly, the gas in extragalactic systems may be included in estimates of mass obtained from spectrographic measurements of rotational and internal motions. These optical data, however, are at present too scanty and of too low precision for a discussion of the mass ratio between stars and the interstellar matter that contains gas and dust.

One of the principal impressions obtained from detailed study of extragalactic systems is the great diversity of structural forms. These range from smooth, featureless elliptical systems, through the regular and barred spirals of varying degrees of complexity, to irregular objects of chaotic and contorted shapes. Although almost every combination of elliptical, spiral and irregular systems can be found, Hubble has proposed a classification scheme that has been generally useful for a large majority of the brighter and nearer nebulae. These are the ones best adapted for detailed spectrographic study of emission radiations, and this discussion is mainly based on the distribution of λ 3727 radiation according to Hubble's classification. The frequencies of occurrence, from the Mount Wilson-Palomar and Lick spectrographic data [5], are shown in the table on p. 25.

This table confirms with appreciably more material a result previously obtained from fewer data, namely, that there is a definite increase in the frequency of occurrence of λ 3727 for a progression from elliptical to spiral systems. The fifth and sixth columns show as a percentage the order of the increase. They also show some systematic differences between the two sets of data, but these differences are not so large as to invalidate the trend, and they may reasonably be ascribed to the different circumstances of observation [1]. If averages are taken, the frequency increase is from about 15 % for ellipticals to nearly 80 % for spirals, or by a factor of approximately 5.

The foregoing overall statistics, however, give little hint as to how the ionized gas, as indicated by the presence of λ 3727, may be distributed in the various types of extra-galactic systems. The Lick spectrographic material has been examined for this purpose, with details given in a table of red-shifts [5]. For the present discussion, it seemed most practicable to present typical results in a series of illustrations, first individually described and then collectively considered as to some possible general conclusions. The procedure is according to Hubble's nebular types, beginning with ellipticals, followed by normal spirals, barred spirals, apparently close doubles, and finally two streamer-connected pairs.

Frequency of occurrence of λ 3727

	Lick				Mount Wilson-Palomar	
Type	λ 3727/all	(%)	λ 3727/total	(%)	(%)	λ 3727/all
E	5/41	12	5/41	12	18	15/82
So	6/23	26	9/33	27	48	25/52
SBo	3/10	30				
Sa	7/16	44	9/20	45	62	23/37
SBa	2/4	50				
Sb	31/46	67	40/65	62	80	53/66
SBb	9/19	47				
Sc	73/106	69	81/118	68	85	35/41
SBc	8/12	67				
Irr	16/17	94	20/23	87	—	—
Spec, Pec; Sab, Sbc	4/6	67				
All	—	—	164/300	55	55	151/278

Fig. 1 shows in the upper panel spectra of two ellipticals, in one of which, NGC 5846, λ 3727 may be faintly present, because measurement of the feature marked with an arrow gave a red-shift in agreement with those for the H- and K-absorption lines. The spectrum of the uncatalogued companion above 5846 shows a similar emission feature (of a little shorter wave-length) that is not λ 3727 because it does not give a red-shift in agreement with a larger red-shift measured for the H- and K-lines. In both cases, however, these features that appear as faint emission in the general region of λ 3727 could be only intensifications in the continuous spectra, and further observations are needed to reach a decision. In the central panel, λ 3727 is clearly present in the isolated elliptical NGC 1453; the smaller direct image is due to a too-weak exposure. The lower panel shows the non-typical but interesting case of NGC 4486 (M 87), which has been discussed as a radio source by Baade and Minkowski [6]. Here the slit was on the nucleus and along the ray or jet, which may be seen projecting downwards in the direct photograph. The spectrogram shows

λ 3727 fairly strong in the nucleus, and probably absent in the ray. The emission lines extending entirely across the spectrum are 4047 and 4358 of Hg I, which come from the low, western horizon sky-glow produced by city lights in the Santa Clara valley.

Fig. 2 shows how λ 3727 appears in three early-type spirals, two classified by Hubble as So and one as Sa. In all three cases λ 3727 is not only present in faint (NGC 3169) to strong (NGC 3998) intensity, but it likewise shows rotational inclination comparable to the principal absorption lines. These spectra also show the tendency, only suggested by the ellipticals, for the λ 3727 radiation to be concentrated toward the center of the systems. For all three of these systems the spectrographic exposures were long enough to have shown λ 3737 well beyond the nuclei, if it were present.

Fig. 3 shows three intermediate-type normal spirals, all Sb in Hubble's classification scheme. One of these, NGC 2841, has a prominent nuclear bulge, while the other two, with less extensive central parts, instead have well-developed, inner spiral-ring structure. In the upper panel, λ 3727 appears in moderate intensity only in the nuclear region, as was the case in the elliptical and earlier-type spirals considered in Figs. 1 and 2. On the original spectrogram of NGC 2841 the night-sky spectrum shows strongly enough to suggest that, if λ 3727 were present in appreciable intensity in the outer parts of this spiral, the exposure was long enough to have recorded it. The central and lower panels are intended to show that λ 3727 may sometimes be stronger in an interior spiral-arc ring, as in NGC 4736 (M 94), or sometimes in the nucleus, as in NGC 4750. While λ 3727 is also present in the nuclear region of M 94, its intensity there appears to be less than in the part of the ring that was on the slit. In all three spirals emission and absorption lines are measurably inclined because of rotation of the systems.

Figs. 4 and 5 show six examples of Sc or late-type normal spirals, which, as is well known, have a great variety of structural features. These systems were selected from more than 100 observed with the Crossley nebular spectrograph in order to illustrate the considerable variation in the distribution pattern of λ 3727.

In the upper panel of Fig. 4, this emission is fairly strong in the short, bar-like nucleus of NGC 925 and in one knot, but faint elsewhere. In the central panel, λ 3727 is present in good strength throughout NGC 2748, possibly because the principal plane of the system is tilted not far out of the line of sight and the light path is longer in the spiral. For the nearly square-on spiral NGC 2835 in the lower panel, λ 3727 is present in a pronounced patchy distribution that corresponds closely with the light

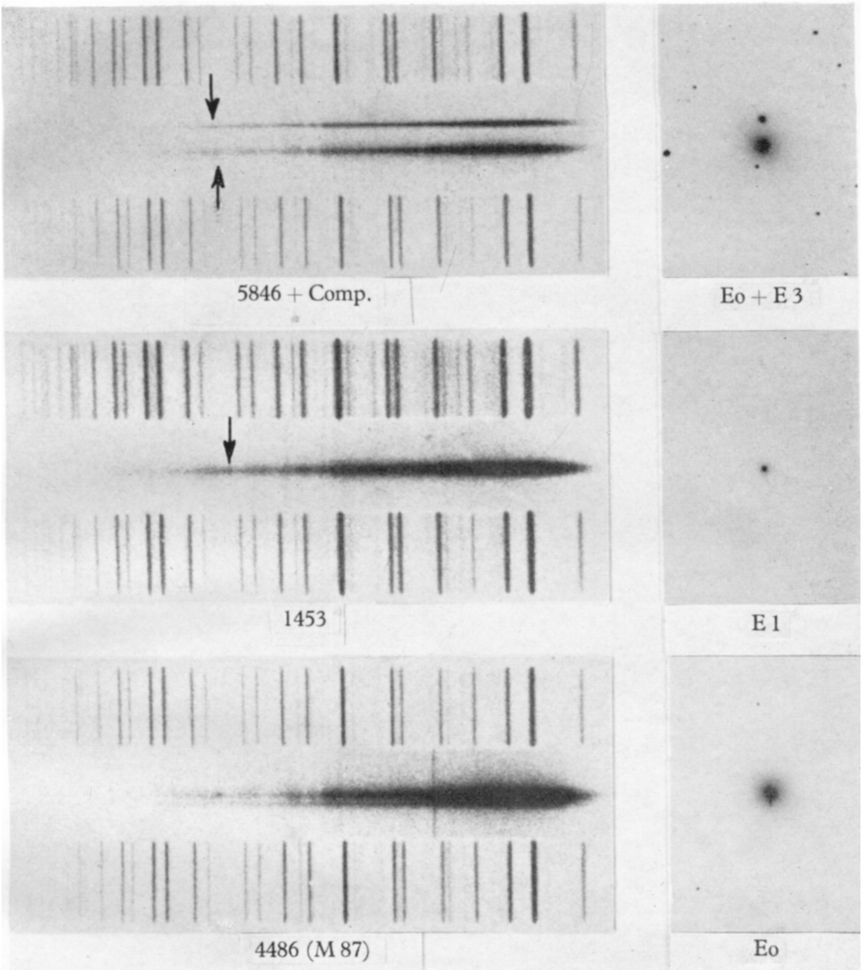

Fig. 1.

facing p. 26

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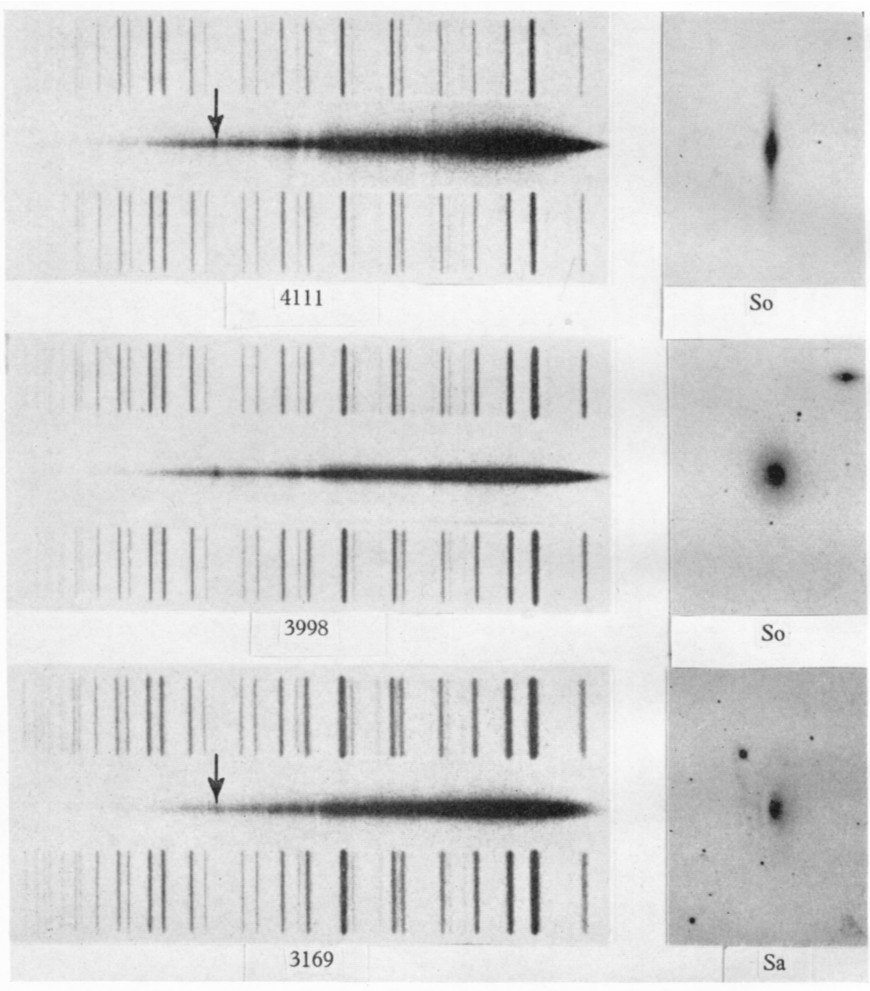

Fig. 2.

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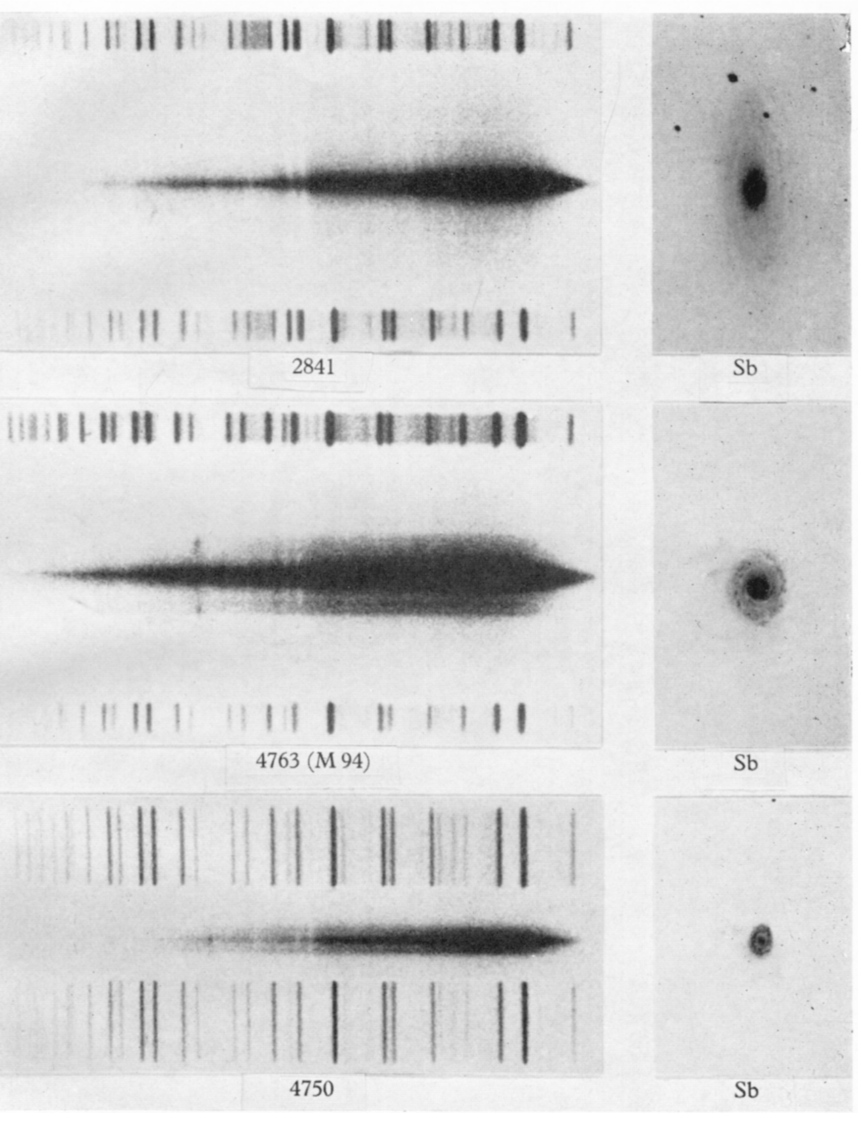


Fig. 3.

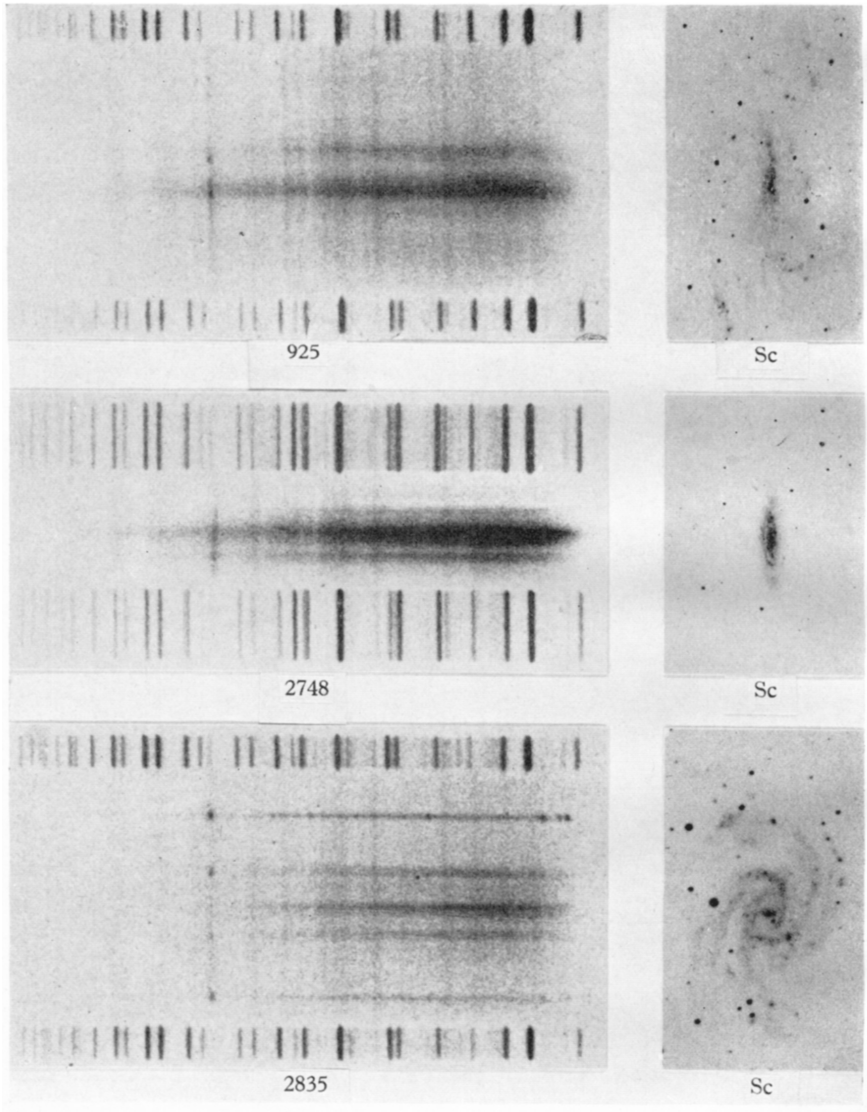
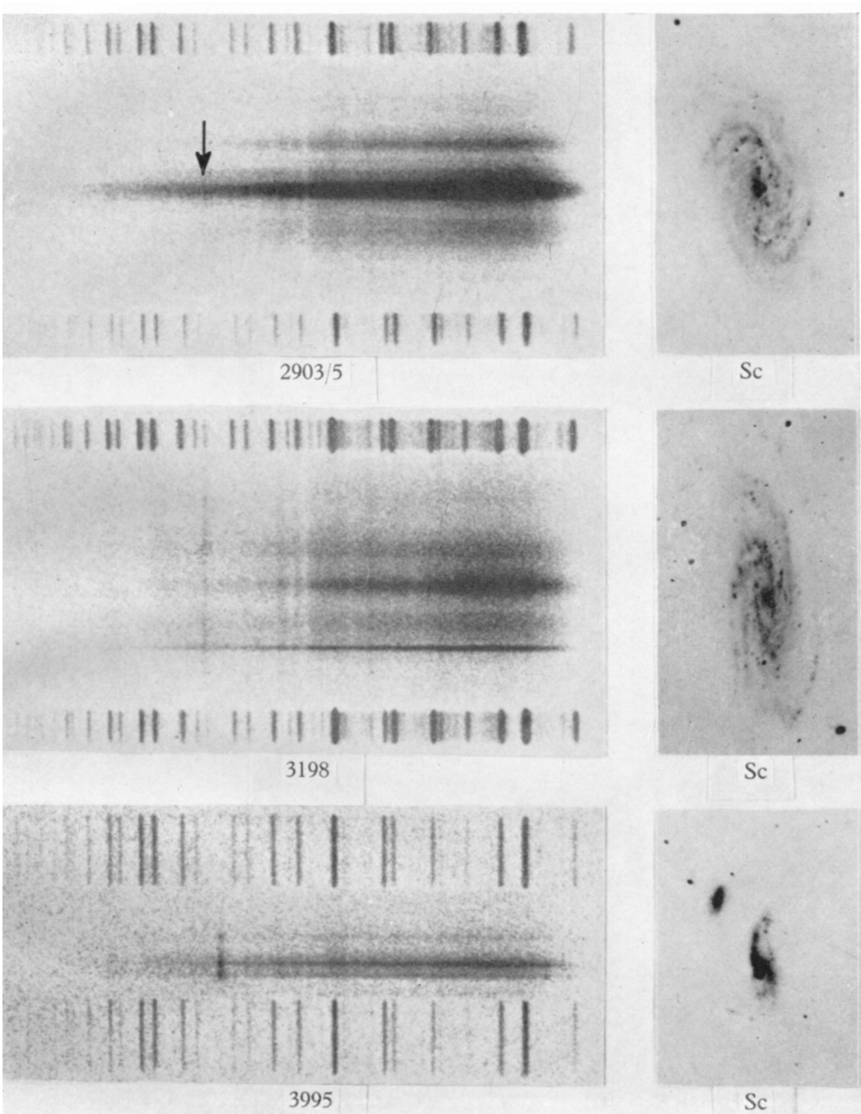


Fig. 4.



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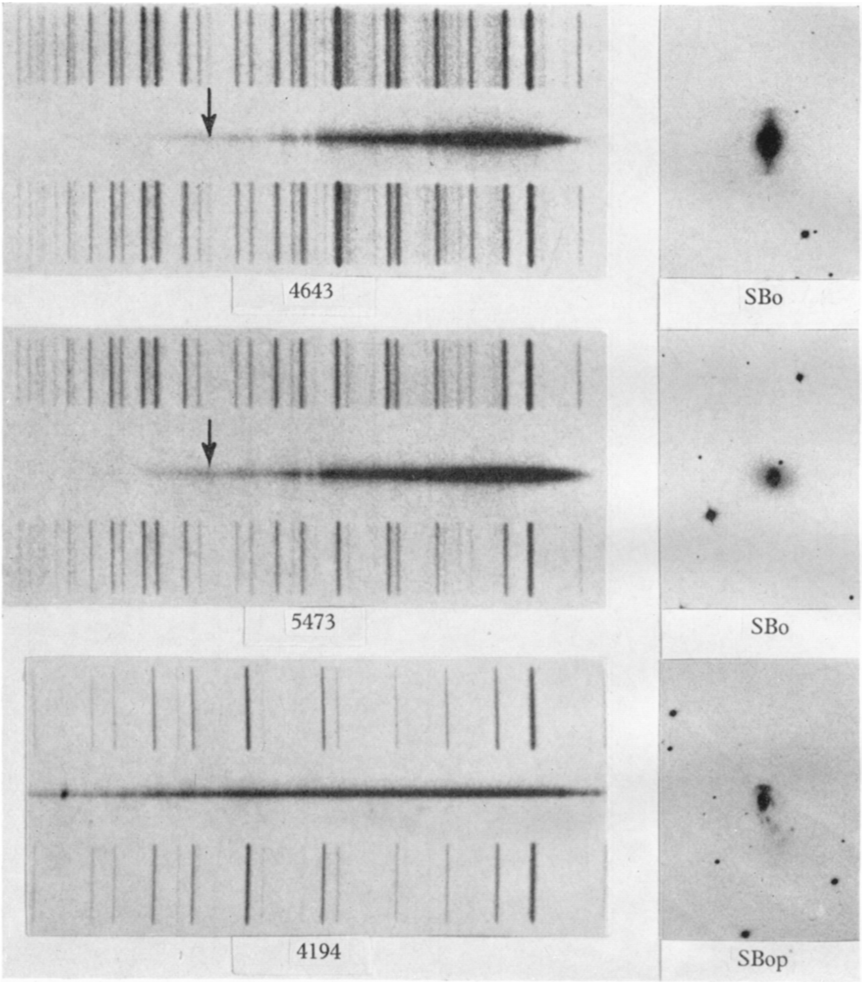

Fig. 6.

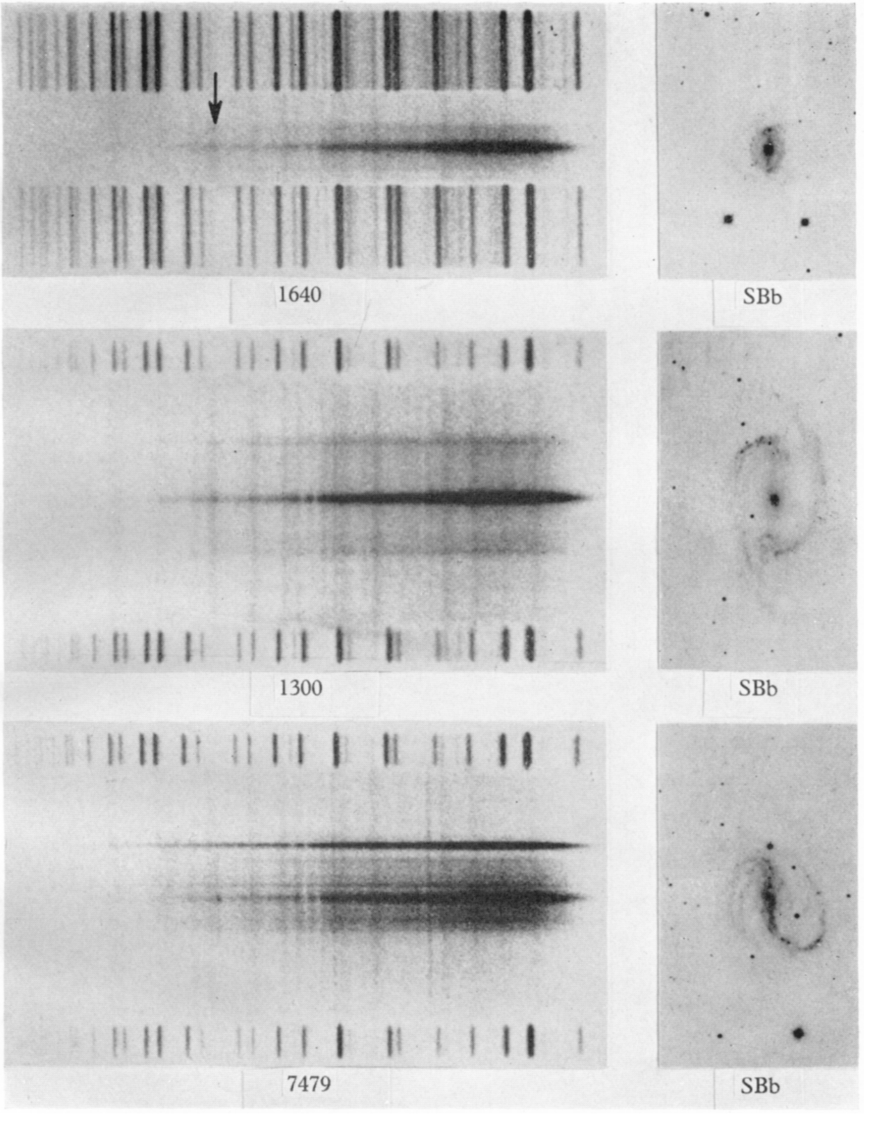

Fig. 7.

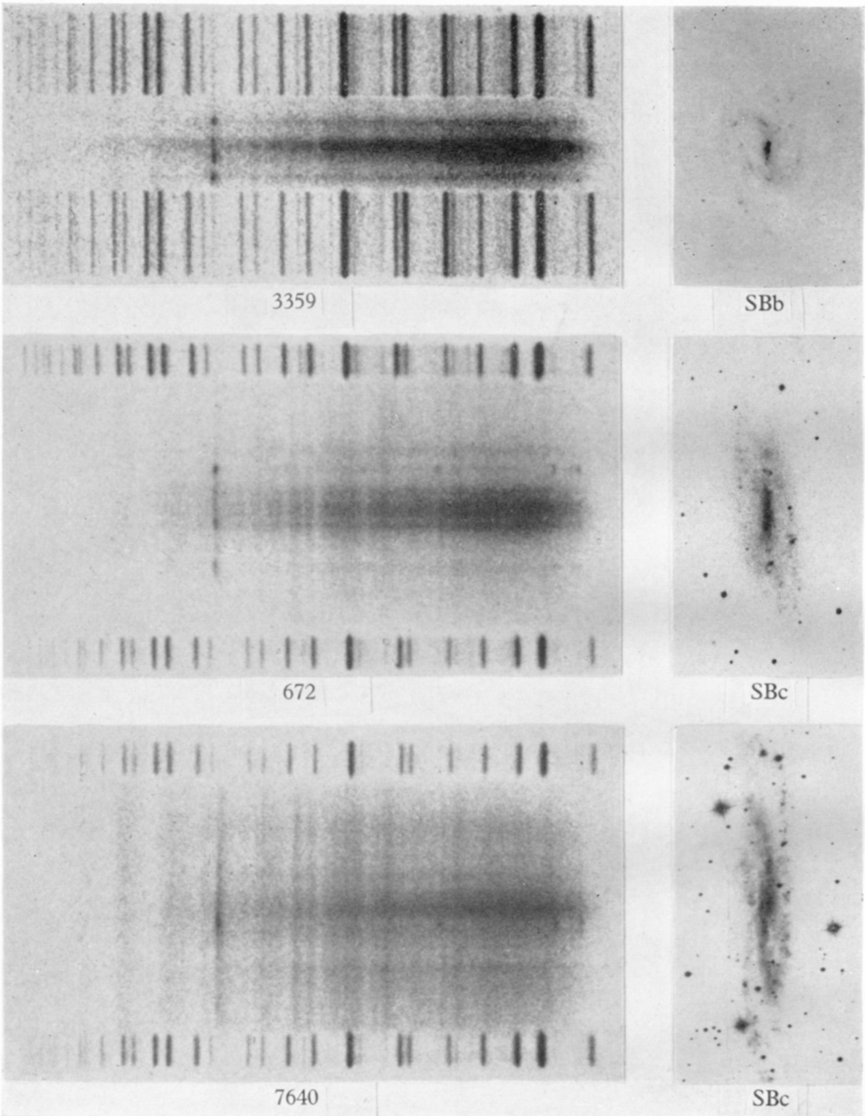

Fig. 8.

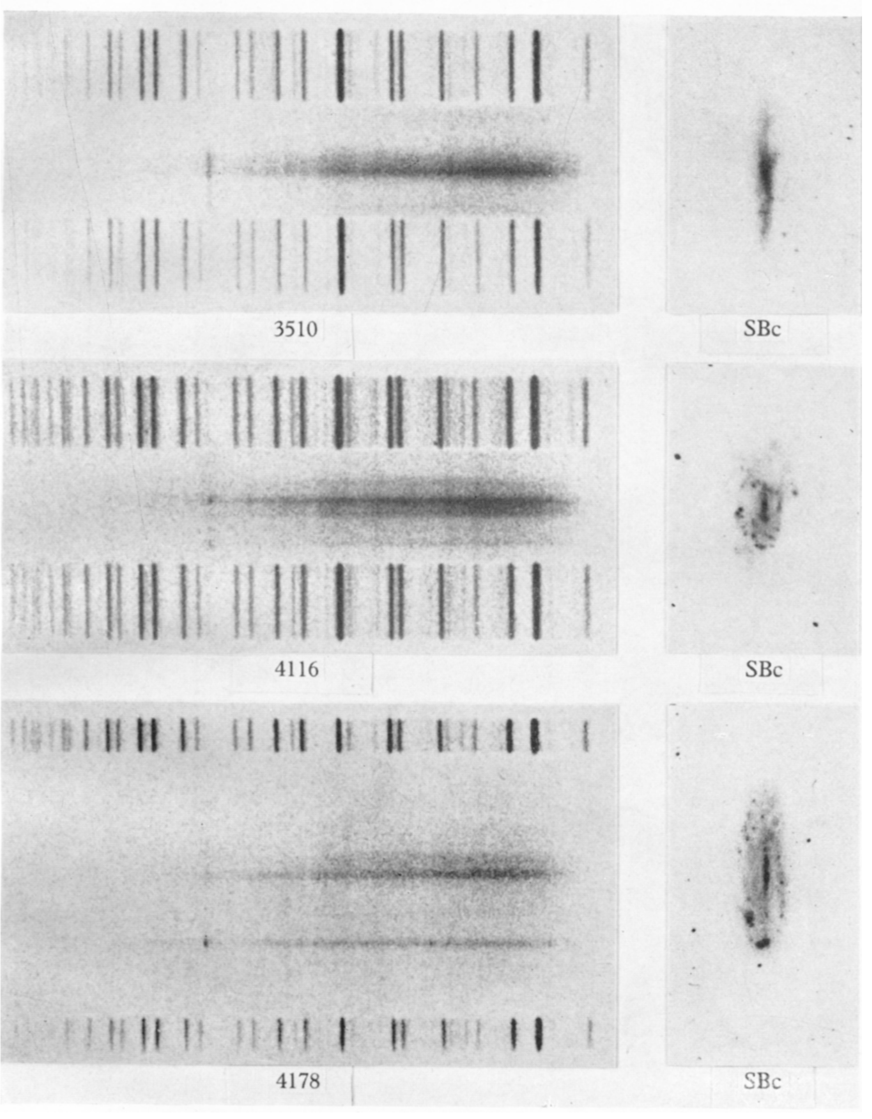

Fig. 9.

Facing Fig. 8

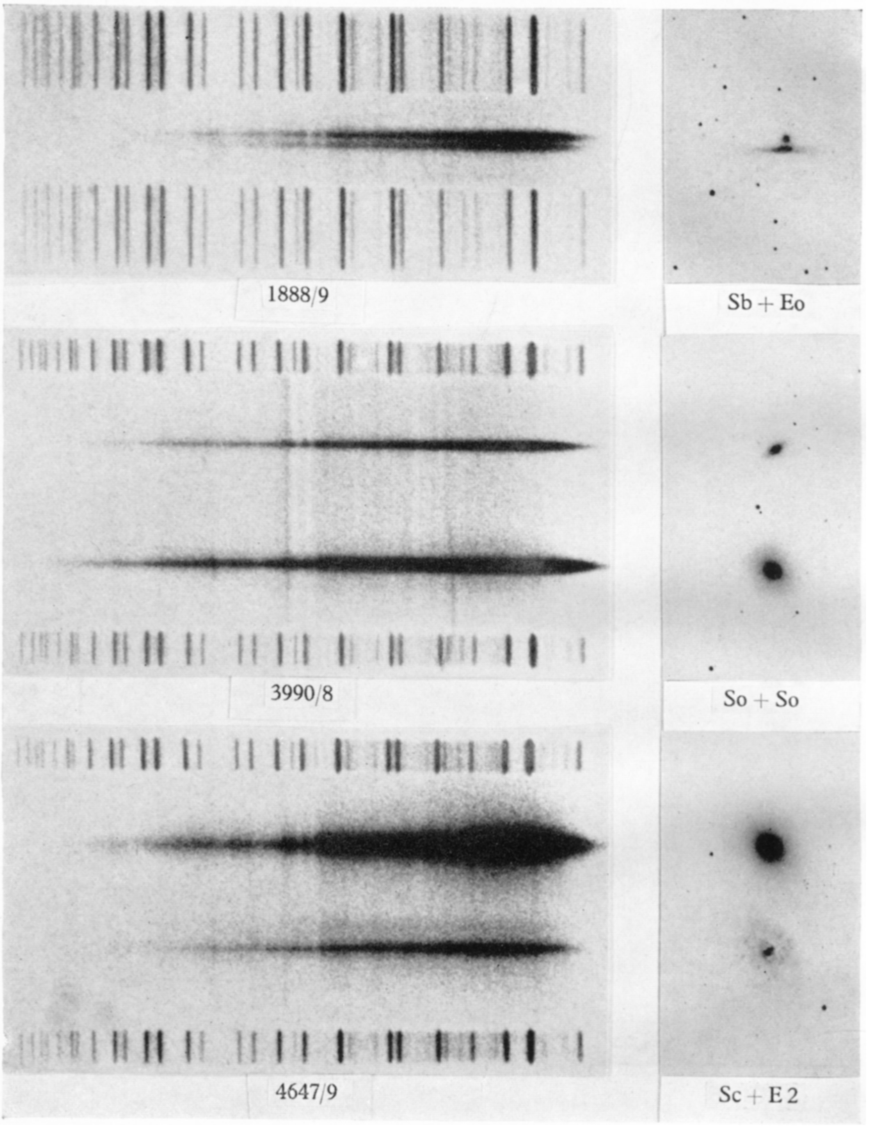

Fig. 10.

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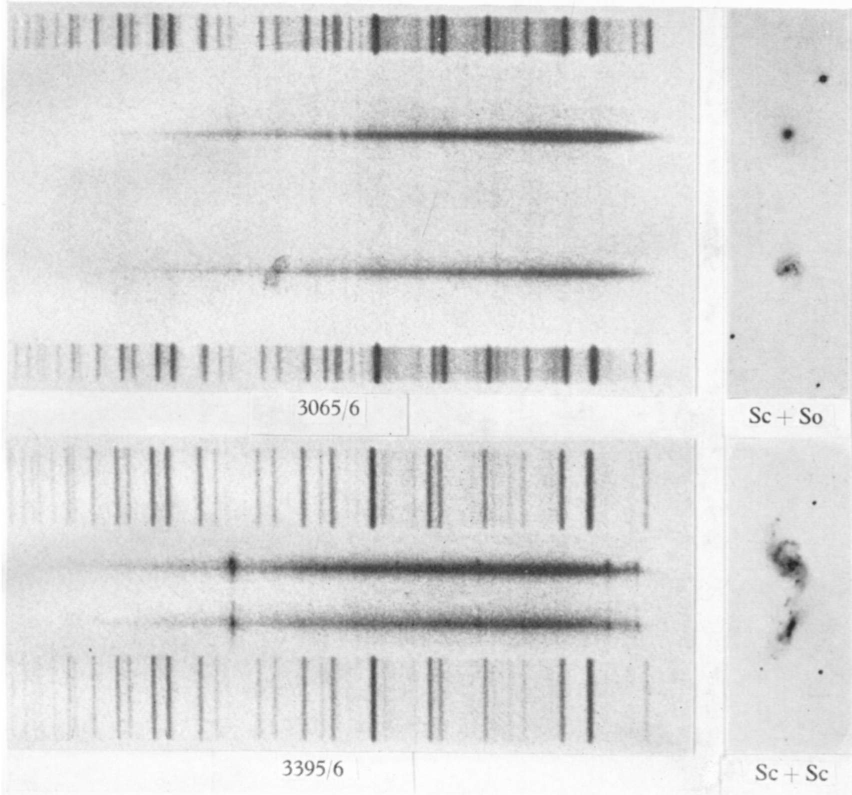

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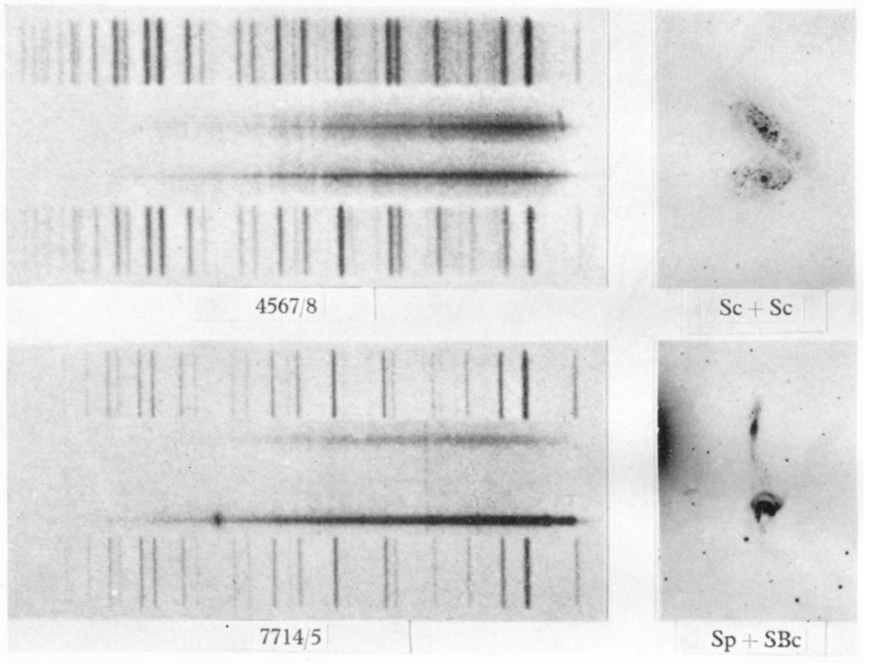

Fig. 12.

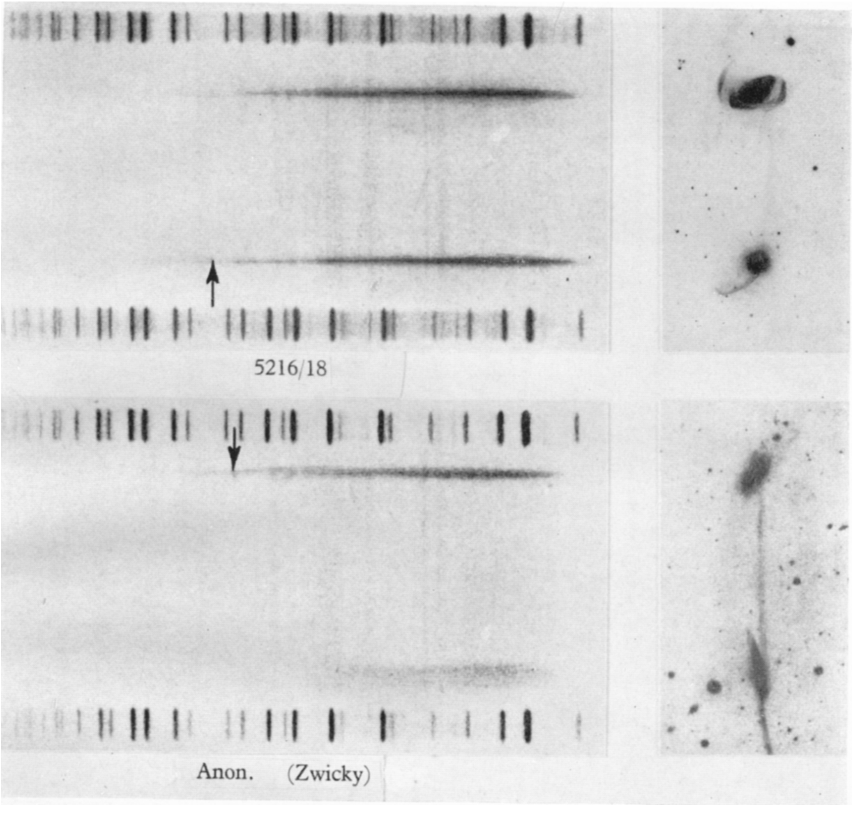

Fig. 13

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distribution in the direct exposure, except in the nucleus where it is much fainter or absent. For the brightest knot that was on the slit, the spectrum shows a number of other emission radiations that include those at λ 4957 and λ 5006 of [O III], with intensities relative to Hβ typical of galactic gaseous diffuse nebulae.

Fig. 5 shows examples of weakest and strongest appearances of λ 3727. In the upper panel this emission appears faintly present mainly in the nuclear region of NGC 2903/5, although a slightly different orientation of the slit might show it to occur with fairly uniform intensity throughout, as for NGC 3198 in the central panel; in the latter, the strong, narrow continuous spectrum at the lower end of the slit is that of a foreground star. In the bottom panel, λ 3727 shows in high intensity in the strongest arm and brightest condensation in NGC 3995, which appears to be the distorted member of a double system.

At this point we leave the so-called normal spirals and consider the barred spirals. Although the latter seem to have a characteristically different structure in direct photographs, spectroscopically they do not give much reason to think that they are systematically different. As indicated in the next group of illustrations, the same emission and absorption lines occur, with the same diversity in intensity, and with comparable complex relationship to structure, for the barred as for the normal spirals.

The upper and central panels of Fig. 6 show two earliest-type barred spirals, NGC 4643 and 5473, classified by Hubble as SB0. In these nebulae the very faint features marked with arrows were measured as λ 3727 and gave red-shifts corresponding to the absorption H- and K-lines. The result is thus the same as for ellipticals: if λ 3727 is present, it tends to be faint and concentrated toward the center. The case is quite different, however, for the nebula in the bottom panel. This shows a 3-prism spectrogram of the 'peculiar' SB0 system NGC 4194, in which λ 3727 is not only strong, but hydrogen lines of abnormal intensity and width are present. Here Hβ and Hγ are in emission, the higher members of the Balmer series are in absorption, and the [O III] pair can be seen. There is little doubt in this case that the qualification 'peculiar' is justified.

In the Crossley collection there are at present no spectrograms showing λ 3727 in SBa systems, not because none are known, but only because no systematic program for their observation has been undertaken. Therefore, we next consider the intermediate-type barred spirals—those denoted SBb in Hubble's classification.

Fig. 7 shows three SBb's that represent the range, for this class of system, of the degree to which the spiral arms seem to have uncoiled from a ring structure that often is present around the nucleus. With the possible exception of one very faint appearance in a knot in NGC 1640, λ 3727 is rather strongly concentrated toward the nuclei of these three spirals. While other slit positions in their outer parts might show λ 3727, these regions are so much fainter in these spirals that the nebular spectral features are likely to be confused with the night sky spectrum. There is better evidence, from other cases, that λ 3727 shows no general tendency to be confined to the nuclear regions of SBb and SBc systems; some examples are given in the next two illustrations.

Fig. 8 shows, in the upper and central panels respectively, intermediate-type and late-type barred spirals, NGC 3359 and 672, in which λ 3727 is strong just beyond the ends of the bar, localized in knots or condensations, in addition to being present in the bar. For NGC 3359 the direct photograph is a too-weak exposure that fails to show details of the outer spiral structure where the slit crossed it. Thus the spectrogram seems to show strong emission where there is little light recorded in the direct image. In the lower panel the nearly edge-on late-type barred spiral NGC 7640 shows λ 3727 present along the bar and major axis in fairly uniform intensity that corresponds closely with the distribution of light in the direct photograph.

Fig. 9 shows three more late-type barred spirals of which two, NGC 3510 and 4116, are irregular in appearance. In these two systems λ 3727 is distributed in patchy intensity both in the bar and in the outer irregular parts. The bottom panel reproduces a grainy spectrogram (pre-War 2) that shows λ 3727 in only one bright knot near one end of the system. This is a case where a better-quality plate, with IIaO emulsion and a narrower slit, is needed to determine the presence or absence of λ 3727 in the bar. From the other foregoing examples a positive result would be expected.

We next consider the distribution of λ 3727 in some double systems in which the components are of nearly the same type, of different type, or streamer-connected. As was the case for the single systems illustrated, the selection of doubles is but a small sample from the large number of known close pairs. The variety is so great that the following group of illustrations can only suggest the richness of the field.

Fig. 10 shows three pairs of systems in which one component in each appears to be an exception to the statistical result for λ 3727 to be stronger with advancing nebular type. In the top panel NGC 1888, Sb, seems to show little or none of this emission, in the center NGC 3998, the larger and brighter So, shows λ 3727 strongly, and in the lower NGC 4647, Sc, shows the radiation only faintly. These three exceptional cases are not intended, however, to show that double systems differ systematically from single ones. The purpose is to suggest that the relationship between structure and distribution of ionized gas probably is as complex for double as for single systems.

Fig. 11 illustrates two pairs of systems that show nearly the extremes of low and high intensities of λ 3727. In the upper panel, the components are not known from direct photographs to be connected by a streamer, but the appearance of the original spectrogram in the region of λ 3727 suggests a check of this possibility. For the spirals in the lower panel, T. L. Page [4] has reported λ 3727 connecting them. This result probably would have been obtained with the Crossley nebular spectrograph if the slit were placed slightly differently and if the exposure were longer.

Fig. 12 shows two close doubles for which the spectrographic data have unusual interest. In the upper panel, there is no certain evidence of emission radiation in either component, but in the lower panel the brighter member shows exceptionally strong λ 3727 and other bright lines. This spiral is classified as peculiar because of its distorted form. Thus the very different spectral features in these two pairs may indicate the effects on the distribution of ionized gas of little and much interaction.

Fig. 13 shows the result of attempts to find, in two streamer-connected systems [7, 8], spectroscopic evidence for an ionized gaseous constituent in the streamers. Examination of the original negatives, and experience with many others similarly exposed long enough to reach the background night-sky spectrum, leads to the conclusion that no emission lines are present in the blue and near ultra-violet spectra of these two pairs. Although this is a result for only two cases, the connecting filaments are among the brightest known.

In making generalizations from the spectrographic data reproduced as Figs. 1–13, it should be emphasized that any one spectrogram showing emission gives information regarding the distribution of ionized gas only in a single plane corresponding to the orientation of the slit. This, in many cases, was placed on the more conspicuous components such as nuclei, spiral arms, bars, knots, or doubles for red-shift or differential velocity measurements. These data therefore involve a great deal of observational selection, the effect of which is difficult to evaluate. A much better approach to the problem would be to use narrow-band color-filter photography, which would include a whole system. A comprehensive survey, carried out with moderate to large reflectors utilizing modern interference filters and fast plates, would place on a much firmer basis our knowledge of the distribution of H II regions in the nearer extragalactic systems of all classes. In the meantime, the spectroscopic evidence suggests the following summary conclusions regarding the distribution of ionized gas in extragalactic systems, as inferred from the occurrence of λ 3727:

(1) In the progression of nebular types from ellipticals to spirals, the gas tends to become less centrally concentrated and to occur more frequently by a factor of 5 or 6.

(2) While the H II regions are often related to such structural features as nuclei, spiral arms, bars or rings, the relationship is not very close; there appears to be little systematic difference between normal and barred spirals.

(3) For close doubles, there is some indication of increased ionization when the components either are of very late or irregular nebular type, or when peculiar structure suggests strong interaction.

(4) In two cases of wider pairs having relatively bright connecting streamers, there is no evidence for an ionized gaseous constituent in the joining filaments.

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Discussion

Page: It is worth mentioning similar observations of double galaxies made with a small grating spectrograph at the McDonald Observatory. Many of these same objects were observed in the red region, including Hα and the forbidden N II doublet 6548 and 6584 Å. These plates showed many of the same aspects that Dr Mayall has described. As might be expected, among about 100 spectra, Hα appeared in every case where 3727 appeared, with one exception. However, in two cases, the bridge between double galaxies showed emission both in 3727 (which generally seems more extended than Hα) and in the forbidden nitrogen lines, which are similarly extended, but *not* in Hα.

Oort: Can Dr Mayall give more details about the rotation periods of the barred spirals he has measured?

Mayall: Only ten nebulae of type SBc were measured. The measurable inclinations of the spectral lines give rotation periods that vary from about 50 to

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250 million years, for inclinations ranging from 1° down to about 0°.2 or 0°.3. However, there are some smaller inclinations of the lines which could not be measured. I assumed 200 km/sec/1,000,000 pc for Hubble's red-shift parameter in order to obtain distances to compute periods.

Oort: Does Dr Mayall mean that there is a big selection effect and that he could not measure the period of rotation in many cases?

Mayall: There is a big selection effect in the sense that only those nebulae were observed in which the bar was nearly normal to the line of sight and for which the spiral was favourably tilted. However, under these conditions, we get a measurable but small inclination whenever the spectrogram is well enough exposed. Since only ten late-type barred spirals have been observed, it would be very hasty to draw any generalization on the basis of our present data.