SECTION III

SEYFERT GALAXIES

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SEYFERT GALAXIES: CLASSIFICATION, MORPHOLOGY, OBSERVATIONS AT OPTICAL WAVELENGTHS, ENVIRONMENTAL FACTORS

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ABSTRACT. Recent optical work on Seyfert galaxies is summarized, particularly on their spectral classification, morphology, companions, and presence in clusters of galaxies. Their general continuity with QSOs and with Liners is emphasized. Methods of finding additional Seyfert galaxies and of assembling a complete sample for investigating the luminosity function of AGNs are also discussed.

1. INTRODUCTION

I was very pleased and honored to have the opportunity to present this paper at an IAU Symposium held at Byurakan Observatory, where so much important work on Seyfert galaxies has been done. Director V. A. Ambartsumian is responsible for many important concepts concerning the physical nature of these objects. With the 1-m Schmidt telescope, the late B. E. Markarian and his coworkers discovered very many Seyfert galaxies in the First Byurakan Spectral Survey; in fact most of the Seyfert galaxies on which my colleagues and I have worked are Markarian galaxies. The present generation of observational astronomers who were trained or are now working at Byurakan are making great strides toward understanding these objects.

2. CLASSIFICATION

Seyfert galaxies according to their original definition are characterized as galaxies having a bright, semistellar nucleus, and "broad" emission lines covering a wide range of ionization (Seyfert 1943). Seyfert galaxy nuclei appear to be continuous in many of their physical properties with the more luminous quasistellar objects (QSOs). Morgan and Dreiser (1983) have illustrated very clearly in their Figure 1 (Plate 11) how the brightness of the nucleus grows with respect to the brightness of the underlying galaxy or "fuzz" along a sequence from the Seyfert galaxy NGC 4151 to the quasar 3C 48.

The classification scheme of Khachikian and Weedman (1974) divides Seyfert galaxies into two groups. Seyfert 1 galaxies have broader H I emission lines (and other permitted lines, including He I, He II and Fe II), typically with full widths at half maximum (FWHM) of several thousand km s^{-1}, and narrower forbidden lines, typically with FWHM of several hundred km s^{-1}. Seyfert 2 galaxies, on the other hand, have H I and forbidden emission lines with comparable widths, similar to those of the forbidden lines in Seyfert 1s.

We (Osterbrock and Koski 1976; Osterbrock 1977) have extended this classification by dubbing objects whose H I emission-line profiles are clearly composite, made up of strong broad *and* narrow components, as Seyfert 1.5 objects. Cohen (1983) has studied many of these objects in detail, but has emphasized that *all* Seyfert 1s have composite H I line profiles to some degree. The Seyfert 1.5 galaxies are simply the objects in which the characteristic is most easily recognizable, be-

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cause the narrow H I emission-line components are so strong. That the Seyfert 1.5 classification is physically significant is shown by the fact that these objects are intermediate between Seyfert 1 and Seyfert 2 galaxies in other respects, in particular in the strength of their nonthermal radio emission (Osterbrock 1984). Though the typical narrow emission-line spectra of Seyfert 1 and 2 galaxies are similar, there are subtle but real differences between them, as shown quantitatively by Cohen (1983) and as will be discussed further below.

The classification scheme can be further extended to Seyfert galaxies with very weak broad H I emission-line components. The name Seyfert 1.8 has been used for objects which have an easily visible broad component of Hα, but only a very weak broad component of Hβ, while Seyfert 1.9 has been used for objects with an easily broad component of Hα, but with broad Hβ not visible at all (Osterbrock 1981). In their narrow-line spectra these Seyfert 1.8s and 1.9s tend to be more similar to Seyfert 2s, while the Seyfert 1.5s tend to be more nearly similar to Seyfert 1s. Dust almost certainly plays an important role in reddening the broad-line spectra of Seyfert 1.8 and 1.9 galaxies, for they typically have *broad* component intensity ratios Hα/H$\beta \approx 8$, considerably larger than the ratios in typical Seyfert 1 and 1.5 ratios. However Seyfert 1.8 and 1.9 galaxies are *not* simply edge-on objects with nuclei reddened by dust in their galactic planes. Instead, NGC 4235 *is* such a nearly edge-on Seyfert 1 galaxy (Abell, Eastmond, and Jenner 1978). Probably in Seyfert 1.8s and 1.9s the dust is near the central accretion disk and is associated with it. Quite possibly the disk is tipped with respect to the plane of the galaxy in which it lies (Tohline and Osterbrock 1982).

3. LOWER ACTIVITY

Many emission-line galaxies are not Seyfert galaxies. An example is NGC 7714, the so-called "starburst" galaxy studied in detail by Weedman *et al.* (1981). It has very weak (if detectable at all) [O I] and [N I] emission lines, relatively weak [N II] and [S II], and generally fairly strong He I λ5876, all indicating photoionization by OB stars similar to those in H II regions. Most (about 90%) Markarian galaxies are of this type. A small fraction of them have high ionization, leading to large values of the emission-line ratios [O III] λ5007/Hβ. Some examples are included among the "extragalactic H II regions" studied by French (1980). Thus it is not correct simply to classify all emission-line galaxies with $\lambda 5007/\mathrm{H}\beta > 3$ as Seyfert 2s, as Shuder and Osterbrock (1981) did. A better scheme is to use several different line ratios, as suggested by Baldwin, Phillips, and Terlevich (1981). They recommended plots of [O III] λ3727/[O III] λ5007 vs. [O I] λ6300/Hα, [S II] ($\lambda 6716 + \lambda 6731$)/H$\alpha$ and [N II] λ6583/Hα. All three of the latter ratios are enhanced under conditions of photoionization by a "hard" spectrum, with a relatively high fraction of high-energy photons, compared with photoionization by ordinary OB stars, which have exponential cutoffs in their spectra at high energies.

Heckman (1980) pointed out that many low-ionization galaxies are not photoionized by OB stars, but rather appear to form a natural extension of Seyfert 2s to smaller values of λ5007/Hβ. He called these objects Liners. Many of them are objects in which the emission clearly results from photoionization by a hard spectrum (Ferland and Netzer 1983, Halpern and Steiner 1983, Osterbrock and Dahari 1983). Thus it is useful to distinguish between AGNs (Seyfert 2s and Liners photoionized by a hard spectrum) and H II region galaxies (photoionized by OB stars). Veron (1981) and Keel (1983a,b) have emphasized the importance of using [O III] $\lambda 5007/H\beta$ rather than [O II] $\lambda 3727$/[O III] $\lambda 5007$ as the line ratio to be compared with the various line ratios in the red to make this classification. The $\lambda 5007/H\beta$ ratio is equally sensitive to ionization, but is much less affected by interstellar extinction or by calibration problems. Veilleux and Osterbrock (1986) have recently collected and rediscussed a large body of homogeneous spectrophotometric measurements in these terms, and have delineated the areas occupied by AGNs and H II region galaxies in the various line-ratio diagrams.

It is impossible, from the strongest emission lines alone, to distinguish between photoionization by a hard spectrum and "shock-wave heating" (or conversion of kinetic energy of mass motion to heat) as the energy input mechanism. The analyses quoted above show that the fainter lines in many Seyfert 2s and Liners agree much better with the predictions of photoionization by a hard spectrum than by shock-wave heating. Very probably this conclusion applies to all Seyfert 2 galaxies and Liners in which the emission lines are observed to arise in ionized gas in a small central nucleus. But it is quite possible, and even likely, that the Liners with extended regions of emission, often distorted, *are* examples of shock-wave heating, as Heckman has suggested at this Symposium.

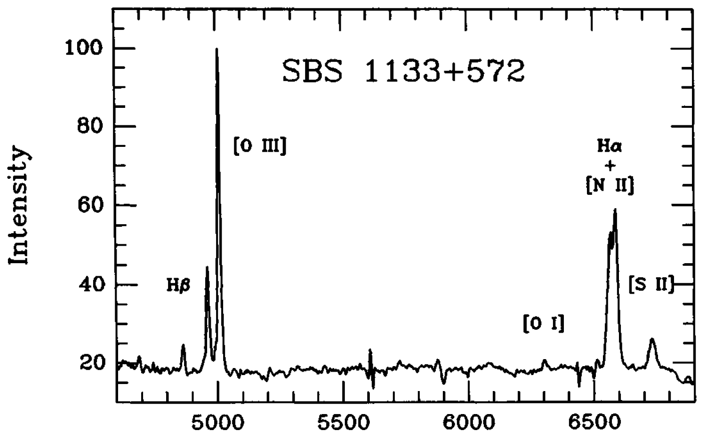

Figure 1. Lick Observatory CCD spectrum of Seyfert 2 galaxy SBS 1133 + 572 from Second Byurakan Survey.

4. FINER DETAILS

In general, Seyfert 1 galaxies often exhibit higher ionization, in quite a few cases to [Fe X] $\lambda 6375$, than most Seyfert 2 galaxies. This suggests that there is a general very rough correlation between high internal velocity (perhaps at the inner edge of an accretion disk, or perhaps in an outward flow from the central nucleus) and high-energy photons. Correlations between line width and both ionization potential (Wilson 1979) and critical density for collisional deexcitation (Pelat, Alloin, and Fosbury 1981) have been observed in numerous Seyfert galaxies. More recently the line profiles of fairly large numbers of Seyfert 1 and Seyfert 2 galaxies have been examined systematically by De Robertis and Osterbrock (1984, 1986a) and by Whittle (1985a,b,c). In a general way, these show that in Seyfert 1 galaxies there is more often a correlation of line width with *ionization potential*, while in Seyfert 2s there is more often a correlation of line width with *critical density*. Since the degree of ionization falls off proportionally to $N_e^{-1}r^{-2}$ with electron density and distance from a point photoionizing source, these results suggest that the velocity decreases outward, and that in Seyfert 2 galaxies the typical electron density decreases outward more steeply (perhaps approximately as r^{-2}) than in Seyfert 1 galaxies (perhaps more nearly constant).

However, there are clearly many exceptions to this general trend. Phillips, Charles, and Baldwin (1983) found several Seyfert 2 galaxies with [O III] $\lambda5007$ FWHM ≈ 200 km s^{-1}, and Whittle (1985a) has found many more with FWHM $\approx$ 250 km s^{-1}, smaller than the 300 km s^{-1} often considered a lower limit for such objects. Yet adopting the primary definition of a Seyfert 2 galaxy as an object exhibiting a wide range of ionization, physically linking the class to photoionization by a hard spectrum, these galaxies clearly belong to it. Two extreme examples of Seyfert 2 galaxies with both unusually high ionization and unusually narrow lines are Mrk 1388 (Osterbrock 1985) and NGC 1320 = Mrk 607 (De Robertis and Osterbrock 1986b).

Another interesting group of objects are the narrow-line Seyfert 1 galaxies studied by Osterbrock and Pogge (1985). They are not a separate group, but show that the general phenomena of Seyfert 1 galaxies, including a strong featureless continuum and often strong Fe II emission lines, extend down to objects whose H I lines are only slightly broader than their forbidden lines.

5. MORPHOLOGY

Nearly all Seyfert nuclei that are in galaxies close enough to be classified are in spirals (Adams 1977). Note we here do not include strong radio galaxies, which have optical emission-line spectra very similar to Seyferts, in that class. The radio galaxies are nearly all N, cD, D, and E in morphological classification. Many Seyfert galaxies, if close enough to be examined carefully, turn out to barred spirals (Simkin, Su, and Schwarz 1980). The Seyfert galaxies' forms are often mildly distorted, but seldom violently (Adams 1977). We shall continue with this point after discussing the companions of Seyferts.

6. ENVIRONMENT

There are relatively fewer Seyfert galaxies and AGNs in clusters of galaxies than in the general field (Gisler 1978). More recent spectra of Dressler and Gunn (1982, 1983), Dressler, Gunn, and Schneider (1985) and Dressler, Thompson, and Shectman (1985) confirm this. They believe that an exception is the 3C 295 cluster, with $z = 0.46$, with a high population of AGNs, but except for the radio galaxy itself and one Seyfert 1 galaxy this is not certain. As discussed above the emission lines in the red spectral region are crucial for distinguishing between Seyfert 2s or Liners and H II region galaxies, but in 3C 295 [S II] $\lambda\lambda6716, 6731$ are redshifted to $\lambda9800$, where the OH night-sky emission spectrum and the low sensistivity of the CCD make the spectra noisy. Dressler *et al.* use the criterion that an intensity ratio $\lambda5007/\mathrm{H}\beta > 1$ implies the object is AGN, but the examples collected by Veilleux and Osterbrock (1986) show that many H II-region galaxies have such ratios. Dressler, Thompson, and Shectman (1985) report that according to their spectra AGNs occur at a frequency of about 5% in their sample of field galaxies, but only about 1% in their sample of cluster galaxies. The latter percentage may be too large, for the reasons stated above.

Although a few years ago no Seyfert galaxies were known in the Virgo cluster, there are now two, NGC 4388, a relatively low-luminosity Seyfert 2 galaxy (Phillips and Malin 1982), and NGC 4639, a Seyfert 1.8 (Filippenko, this symposium). NGC 4235 is evidently not a Virgo cluster member, but a projected background object (Abell, Eastmond, and Jenner 1978).

Adams (1977) called attention to the relatively large fraction of Seyfert galaxies that are disturbed or interacting systems. Petrosian, Saakian, and Khachikian (1978, 1979) pointed out the relatively high fraction of Seyfert galaxies with double nuclei. Several other authors have confirmed these correlations. Most recently Dahari (1984, 1985), Kennicutt and Keel (1984) and Keel, Kennicutt, Hummel and van der Hulst (1985) studied this problem statistically, using complete samples of Seyfert galaxies, control samples of galaxies that are not Seyferts, and quantitative definitions of what they mean by double nuclei, companion galaxies, close companions, etc. One of their general conclusions is that there is an excess of companions to Seyfert galaxies, compared with a control sample of field galaxies, and that there is a great excess of *close* companions. Also an excess of interacting galaxies are Seyfert galaxies, but *strongly* interacting galaxies (such as the extreme Vorontsov-Velyaminov and Arp objects) tend *not* to be Seyferts.

These statistical results suggest that interactions are an important mechanism by which gas is delivered to the nucleus of a galaxy (requiring that it have almost zero angular momentum on the galactic scale). Probably in some cases this occurs by gravitational perturbations during the interaction of the two galaxies, modifying the flow of gas within one of them; in other cases by capture of gas from one galaxy to the other, in some of these by actual mergers. Evidently in the most strongly interacting pairs the result is more usually to tear one or both galaxies apart than to deliver gas with near-zero angular momentum to a nucleus. One of the most interesting remaining questions, then, is whether all the *apparently single* Seyfert galaxies in fact do either have companion galaxies (too faint to have been detected in the surveys to date), or have undergone an interaction or merger long enough ago so that its gross effects are no longer easily detectable, but recently enough so that the gas it delivered at the nucleus is still providing fuel for gravitational energy release.

Evidently in a cluster of galaxies the much smaller fraction of Seyferts shows that all the close, slow perturbations already occurred long enough ago so that the fuel they provided has been exhausted, and that the present high internal velocity dispersion works against effective perturbations or mergers.

7. OBSERVATIONS AT OPTICAL WAVELENGTHS

The Markarian lists are by far the best source of Seyfert galaxies. About 10% of the Markarian galaxies are Seyferts, many of them Seyfert 1s, and the fractions of both increase strongly at the highest luminosities (Huchra and Sargent 1973, Huchra 1977, Meurs 1982, Meurs and Wilson 1984). The Second Byurakan Survey (Markarian, Lipovetsky, and Stepanian 1983) goes much deeper. It provides the opportunity to study observationally the luminosity function of Seyfert galaxies to a fainter magnitude in the areas of the sky it has covered. We have obtained spectra of several of the objects from the SBS, and in all cases to date our spectra agree with the classifications published by Markarian and Stepanian (1983, 1984). An example is the Seyfert 2 galaxy SBS 1133 + 572, whose spectrum, obtained with our CCD lens-grism spectrograph at Lick Observatory, is shown in Figure 1.

However, it is also important to obtain spectra of every galaxy in selected fields in order to find the complete luminosity function of Seyfert galaxies. Experience has shown in particular that many Seyfert 2s are missed, or are not easily recognized, in objective-prism surveys based primarily on ultraviolet excesses (Huchra, Wyatt, and Davis 1982). The complete luminosity function undoubtedly contains a considerably higher proportion of Seyfert 2s than the Markarian lists alone (Phillips, Charles, and Baldwin 1982). Higher dispersion objective-prism surveys, aimed at recognizing Seyfert galaxies by their emission lines, can be very fruitful, as Wasilewski (1983) and the SBS papers mentioned above have shown.

Most recently the IRAS infrared measurements have provided yet another method of discovering Seyfert galaxies not recognized in the spectral surveys (Carter 1984, de Grijp *et al.* 1985). A large fraction of them are Seyfert 2s, and on the average they are more heavily reddened than the previously known Seyferts found mostly on objective-prism surveys (Osterbrock and De Robertis 1985).

8. CONCLUSIONS

Optical classification of Seyfert galaxies, other AGNs, and other emission-line galaxies can be used to sort these objects into physically significant groups. Interactions with other galaxies are highly significant in the AGN process, very probably in supplying fuel at their nuclei. Many different methods must be used to find all Seyfert galaxies in a given region, but objective-prism spectra provide one very important technique.

I am very grateful to many colleagues, especially at Lick Observatory, for many helpful discussions on Seyfert galaxies and AGNs. I am particularly indebted to Drs. J. S. Miller, L. B. Robinson, R. Stover, and E. J. Wampler for the superb spectrographs and data-handling systems that they provided at Lick Observatory. I am also grateful to the National Science Foundation for partial support of our Seyfert galaxy research under grant AST 83-11585.

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DISCUSSION

DULTZIN-HACYAN: Is the shape of the continuum energy distribution clearly different among Seyfert galaxies and HII galaxies?

OSTERBROCK: I have tended to stay away from trying to measure continuum distributions, and have concentrated my efforts on measuring emission-line intensity ratios.

BARTEL: What is the basis for your definition of an active galactic nucleus and how arbitrary is that definition?

OSTERBROCK: Optical astronomers customarily use "active galactic nucleus" to mean the observed "semi-stellar" nucleus of a Seyfert galaxy or "quasistellar" QSO. "Nucleus" does not mean, to optical astronomers, the absolutely smallest structure that can be resolved (say 0.001 of the VLBI), but rather the concentration of gas, stars, dust etc. at the centre of any galaxy - such as for instance M31, our galaxy, or a Seyfert galaxy. No doubt any definition has some arbitrariness connected with it, but it is intended to describe a part of physical reality.

FILIPPENKO: Of the IRAS "warm" galaxies for which you have optical spectra, have you found any correlations between the emission-line properties and the infrared properties?

OSTERBROCK: A weak correlation between the power-law indices between the various IRAS bands, and whether the galaxy is a Seyfert 2, a Liner , or an HII region galaxy. However, the spread among each type of objects is much larger than the differences between the mean relations.

FAIRALL: I would be interested in your comments of Seyferts of high luminosity versus those of low luminosity. In terms of morphology, I seem to have found a number of high luminosity Seyfert 1s in E/S0 galaxies or galaxies with very weak spiral structure - rather than conventional spirals. I also have the impression that low luminosity Seyferts favour clusters, whereas high luminosity Seyferts prefer to be out in the open.

OSTERBROCK: The main statement I can make is that Seyfert 1 and 1.5 galaxy nuclei tend to be more luminous than Seyfert 2 nuclei, on the average. At the largest luminosities there are essentially no Seyfert 2s and practically all QSO's can be classified on the basis of their spectra as Seyfert 1's.

PASTORIZA: In how many objects have you observed the correlation between the critical density and the width of the lines?

OSTERBROCK: I don't remember the exact number but it is given in the paper by M.M. De Robertis and myself. It is of the order of ten objects. One IRAS Seyfert 2 that we studied in some detail also showed this correlation.

PREUSS: You did not talk about BLRG's and NLRG's. Do you find the same intermediate (Sey) types among them, or are they different from the Seyfert galaxies you talked about?

OSTERBROCK: Most of the BLRG's would be classified as Seyfert 1.5 rather than Seyfert 1, if someone insisted they'd be considered Seyfert galaxies. But the BLRG's have much weaker FeII emission, and much stronger forbidden lines (and narrow HI emission components) than typical Seyfert 1 galaxies. The NLRG'S have emission line spectra nearly identical with Seyfert 2s.

MELNICK: Your initial definition of Seyfert 1.5 galaxies inspired the notion of a continuity of Seyfert-like activity (1,1.1...1.9,2) according to the relative strengths (energies) of the narrow and broad components. Now you have identified "narrow" line Seyfert 1 galaxies. Would you expect a continuity in the line widths of the broad component?

OSTERBROCK: Yes, the "narrow-line" Seyfert 1 galaxies are simply the Seyfert 1's with the smallest fullwidths at half maximum of their HI lines. Yet a large number of them have strong FeII emission and clearly are related to Seyfert 1's; no Seyfert 2 galaxies have strong FeII emission features.

KHACHIKIAN: I would like to make comment concerning the Sy 1.5 type galaxies. I argue against this type of Seyfert galaxies. As I understood correct the most intrinsic difference between Sy 1 and Sy 1.5 is the existence in Sy 1.5 of narrow components of H-lines superimposed on the very broad H-lines. These narrow components have the same structure and redshift as narrow forbidden lines. Many years ago when Dr. Weedman and I came to the idea to divide Seyferts to Sy 1 and Sy 2 (Astrofizika, 7, 389, 1971), we drew some examples of Hβ line profiles in Sy 1, (as I remember five different profiles). That of NGC 5548 looks like the same, as is described for Sy 1.5. The explanation of these two-component profiles of H-lines in Seyferts has been done by Dibay and Pronik (Soviet Astron.J. 44, 952, 1967) about 20 years ago. They suggested the model of two zones of ionized gas with

different physical properties in the nucleus of Sy. Within the framework of this model it is very easy to explain this type of profiles of Sy 1 galaxies. In other words the broad and narrow components of H-lines in Sy 1 have no connection from physical point of view: they are just mechanical superposition on each other.
So, it is not necessary to involve new symbols.

KOMBERG: What is your opinion on the possibility of the evolution of Sy 1 into Sy 2 and vice versa?

OSTERBROCK: I think that the transition of one type of Sy to another does not happen. But the strength on wings of permitting lines can be changed which is the base for classifying the galaxy as Sy 1 or Sy 2.

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