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THE HUBBLE DIAGRAM FOR SEYFERT GALAXIES AND RELATED OBJECTS

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Nous présentons les diagrammes magnitude-décalage spectral et diamètre angulaire-décalage spectral pour les galaxies de Seyfert. Tous deux montrent des corrélations indiquant que les décalages vers le rouge sont cosmologiques. Les luminosités des noyaux des Seyfert de classe I sont comparées à celles des QSO en utilisant des nouvelles mesures de flux de raies en émission. La continuité des luminosités, bien établie, avec des galaxies de Seyfert couvrant un intervalle de luminosité plus grand que les QSO est une indication que les décalages vers le rouge des QSO sont aussi de nature cosmologique.

I. INTRODUCTION AND DEFINITIONS

Anything happening in the nucleus of a galaxy may be related to the Seyfert galaxy phenomenon, but our review is restricted to the Seyfert galaxies themselves and the QSOs. This leaves us only with the problems of defining what is a Seyfert galaxy and of defending the implication that QSOs are "related objects". This review discusses the observational data only as it relates to the redshift problem. We make no attempt to review the extensive spectroscopic observations which are now being used to describe the physical conditions in Seyferts and QSOs. Such studies are fundamental, of course, to attempts to understand the energy sources involved. Recent examples of such work, which is accomplished with the new generation of multi-

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channel spectrophotometers, can be found in Osterbrock et al. (1976) and Boksenberg et al. (1975). These studies are being reviewed elsewhere (Weedman 1977). There are other recent reviews of observational data which discuss how the Seyferts fit into the more general problem of emission-line galaxies (van den Bergh 1975a, Weedman 1976a). We defer to previous discussions of the various theoretical alternatives for explaining why some galactic nuclei are active (e.g. Burbidge 1970, Saslaw 1974).

There are simple reasons why Seyfert galaxies are used as a step toward understanding QSOs. These reasons include the extraordinary similarities between their spectra, both in the emission lines and the continua, and the fact that both have such compact luminosity sources that they are variable. Unfortunately, all objects called Seyfert galaxies are not alike, and this can confuse attempts to relate them to the QSOs. The only indisputable definition of a Seyfert galaxy is that it be one of the six galaxies described in Seyfert's original study. Preferring to go beyond this, we define a Seyfert galaxy as any object that appears non-stellar in direct photographs and which has broad emission lines in its spectrum (Khachikian and Weedman 1974, hereinafter KW). This includes various sorts of N-galaxies, a number of radio galaxies, and even those "QSOs" that are surrounded by nebulosity. According to the classical definition, such emission lines should arise in a bright, semi-stellar nucleus. However, we know of no object with broad emission lines which does not have such a nucleus. We have tried to avoid classifications based upon further details of the photographic appearances because such classifications are so distance dependent. A conventional spiral galaxy containing a bright nucleus is virtually impossible to resolve if it has a redshift beyond about 0.1, but we have to worry about objects with redshifts above 3.0. It is therefore important to rely upon a distance-independent classification, which requires a spectroscopic classification.

There are other advantages to a spectroscopic classification. It refers only to that part of a galaxy where most of the luminosity arises which, for Seyfert nuclei, is the region we want to probe. The conditions in this region have little relation to those in the more extended parts of the galaxy. Additionally, the spectroscopic classification which we have used in the past is simple, requiring only two groups to accomodate all Seyfert galaxies (Khachikian and Weedman 1971, 1974). This classification is based only on relative emission line widths, as the presence of broad emission lines is incorporated into the definition of a Seyfert galaxy. The class 1 Seyferts (Sy 1) have Balmer lines that are broader than the forbidden lines, whereas the class 2 Seyferts (Sy 2) have the same widths for both Balmer and forbidden lines. This simple classification is designed for the observer, who can easily compare the width of Hβ to that of an adjacent [OIII] line. Starting from this classification, a number of other correlations become evident that lead to astrophysical conclusions (Neugebauer et al. 1976, Stein and Weedman 1976, Adams and Weedman 1975, Osterbrock et al. 1976). The Balmer line strengths are generally greater than forbidden line strengths in Sy 1, so Hβ $\gtrsim$ [OIII]λ 5007 whereas the converse is true for Sy 2, and even [OIII]λ4959>Hβ. The continuous spectra have stronger ultraviolet excesses in Sy 1 and appear to be power-law spectra, extending into the infrared. Class 2 continua also are often strong infrared sources but seem to be contaminated by starlight and are interpreted as being heavily reddened by dust. The difference in the nature of the continua leads to a strong correlation between the spectroscopic classes and the UBV colors. This correlation is good enough that a nearly equivalent classification of Seyfert galaxy nuclei can be achieved using the UBV colors alone (Markarian 1973).

It is important to realize that virtually all QSOs have emission line and continuous spectra similar to those of Sy 1 nuclei, except for their systematically higher redshifts. It is also only the Sy 1 whose optical luminosity, like the QSOs, is variable. The emission-line spectra of Sy 2 resemble those of many emission-line radio galaxies, such as Cygnus A (Osterbrock and Miller 1975). The same is true for most objects that have been called N-galaxies. This is because the N-galaxies were usually identified optically in searches for radio sources. We make no distinction between N-galaxies and Seyferts if the former have broad emission lines in their spectra. But, because of the selection effect, most N-galaxies are also radio galaxies. Only a small minority, about 10%, of the total Seyfert sample are strong radio sources. Among the remainder, it is interesting that a higher proportion of Sy 2 are weak sources than of Sy 1 (Sramek and Tovmassian 1975).

We are intrigued by the apparent distinctions between Sy 2 and radio galaxies on the one hand, and Sy 1 and QSOs on the other. If we associate objects in this way, QSOs would not in general be distant radio galaxies. They would instead have to be identified with distant Sy 1, which means with spiral or proto-spiral galaxies. This is because there is a definite deficiency of ellipticals among the Seyferts (van den Bergh 1975b, Adams 1977). In fact, no Sy 1 can be classified as a bona fide elliptical galaxy although a few have amorphous envelopes. Adams (1977) has suggested that a non-thermal source turning on in the nucleus of a spiral galaxy might look like a Seyfert nucleus, with emission lines, whereas an analogous event in an elliptical might look like a BL Lacertae object, with a featureless spectrum. This is consistent with the identification of at least a few BL Lac objects with elliptical galaxies (Stein et al. 1976).

Because of our conclusion that the properties of Sy 1 identify closely with the QSOs, we will use only them when making comparisons with QSO luminosities. For now, we proceed to consider the nature of the redshifts for the general sample of Seyfert galaxies.

II THE HUBBLE DIAGRAM

To construct the Hubble diagram for Seyfert galaxies, we simply take the photometric data and redshifts referenced by KW. When multi-aperture photometry exists in the references given, data from the largest apertures are used. Most of the galaxies have been observed only once, with one aperture. No corrections have been applied to any of the magnitudes. The reason is that the most important correction - the aperture correction - cannot be calculated for most Seyfert galaxies. This is because the luminosity profiles are not the same; some Seyferts have nuclei that are much brighter relative to the surrounding galactic disks than do others. Only when extensive and accurate multi-aperture photometry exists will reliable total magnitudes be available. A few attempts have been made to study carefully the luminosity distributions in some of the brighter Seyferts (e.g.Penston et al. 1974, Zasov and Lyutyi 1973, de Vaucouleurs 1973). Even this tedious work is hampered by the fact that the nuclear magnitude can vary with time. It does not seem feasible to expect a set of corrected magnitudes for Seyfert galaxies that will ever be as homogeneous as those for the first-ranked cluster ellipticals (Sandage and Hardy 1973.)

Nevertheless, a magnitude-redshift correlation does exist for the Seyfert galaxy sample. This is illustrated in figure 1. There is a lot

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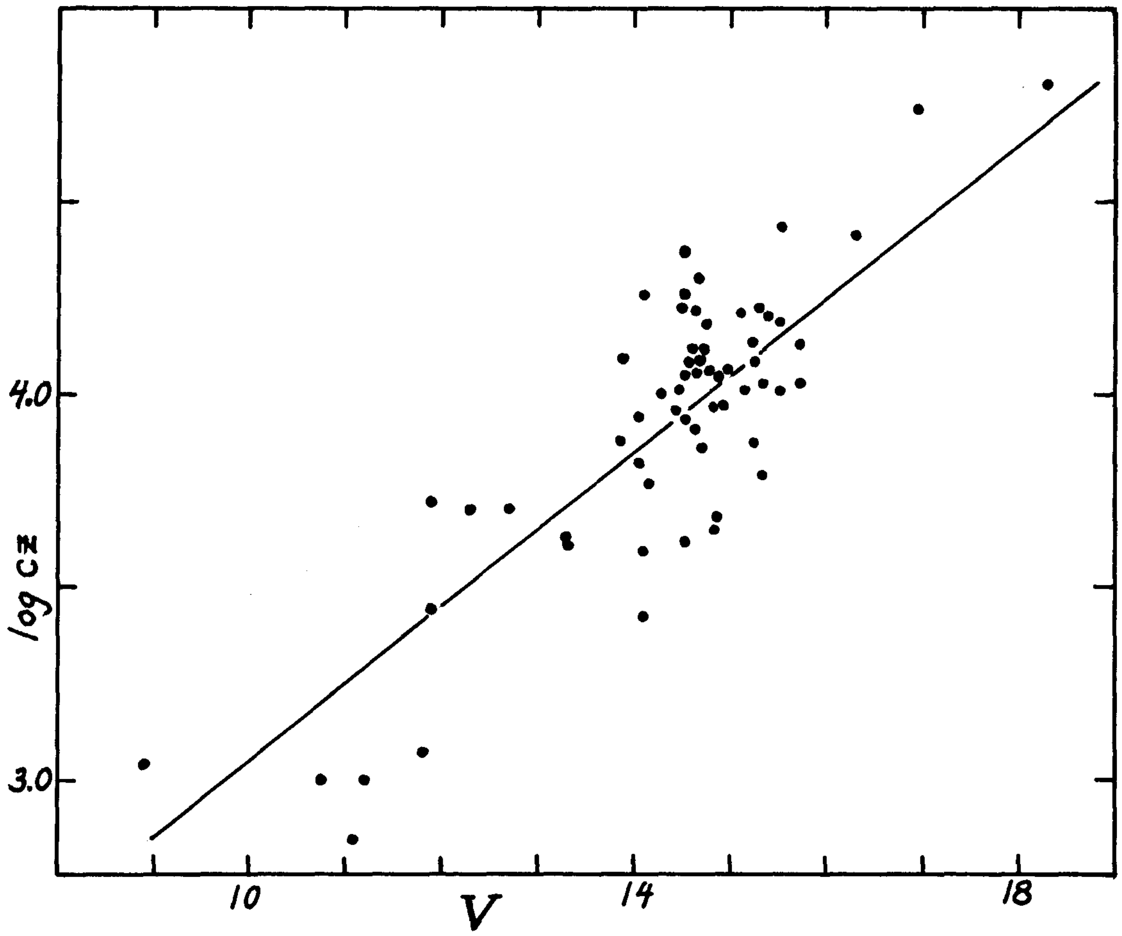

Figure 1: Magnitude - redshift diagram for Seyfert galaxies. Observed V magnitudes are plotted without applying any corrections. The σ(Δm) = 1.04 mag. compared to 0.28 mag. for first ranked ellipticals.

of scatter, and the Seyferts concentrate in the apparent magnitude range 14 mag. to 16 mag. This is a consequence of selection effects. Most Seyfert galaxies are from the Markarian objective prism survey, which is only complete to about 16 mag. Spectroscopic surveys are now underway which go fainter (Smith 1975), but there has not yet been time to confirm many additional Seyfert galaxies. The Seyferts in figure 1 include both Sy 1 and Sy 2, so as to show the most complete Hubble diagram that can be constructed at the moment for the general sample of Seyferts. A line of slope 5, i.e. that expected for a linear redshift - distance relation, is shown as fitted to the data by eye. The σ(Δm) about this line is 1.04 mag. Recall that Sandage's best fit for the totally corrected magnitudes of first ranked ellipticals gives $\sigma(\Delta m) = 0.28$ mag. (Sandage and Hardy 1973). The Seyferts certainly cannot be considered as standard candles; on the other hand, the existence of a redshift - distance relation would probably be inferred from figure 1 even if it were the only sample of galaxies available. No one should expect Seyfert galaxies to yield a well defined Hubble diagram, because the nuclei encompass a range in intrinsic luminosity of more than 7 magnitudes (see below).

An alternative method for demonstrating a redshift - distance relation is to use the angular diameters of galaxies. For the Seyferts, such measures refer only to the galactic disks and so are not affected nearly so much by the nuclei as are the magnitude measures. At redshifts above about 0.1, conventional photographs become difficult to measure because the image of the bright nucleus spreads over the surrounding disk. We measured the angular diameters of the Seyfert galaxies in KW from the *Sky Survey* prints, as these are still the most homogeneous photographic data for these galaxies. The resulting angular diameter - redshift diagram is shown in figure 2. The Sy 1 and Sy 2 are shown separately. Relative to first ranked ellipticals, the dispersion for the Seyferts is significantly less than in the magnitude - redshift diagram. The dispersions about the line shown, $\sigma(\Delta \log \theta)$ for θ in arcseconds, are 0.21 for the Sy 1 and 0.23 for the Sy 2. Sandage's (1972) measures of first ranked ellipticals on plates taken with the same telescope have a dispersion of 0.11. If we accept as a consequence that the redshifts of elliptical galaxies are cosmological, the results in figure 2 are evidence that Seyfert galaxies also have redshifts which are proportional to their distances.

The question has been asked, however, how we can be confident that the extended envelopes associated with Seyfert galaxy nuclei are really the disks of galaxies (Burbidge 1973). It has been suggested that if the redshifts are non-cosmological, there could be some correlation between the compactness of an object and its redshift, which would lead to the results in figure 2. To answer this objection, it is necessary to consider the morphological appearance of these envelopes. All of the original Seyfert galaxies have sufficient structure to be classifiable using existing classification systems for normal galaxies. Virtually all of these Seyferts are spirals (van den Bergh 1975b), and spiral arms are the best morphological signature that one indeed is seeing an object of galactic

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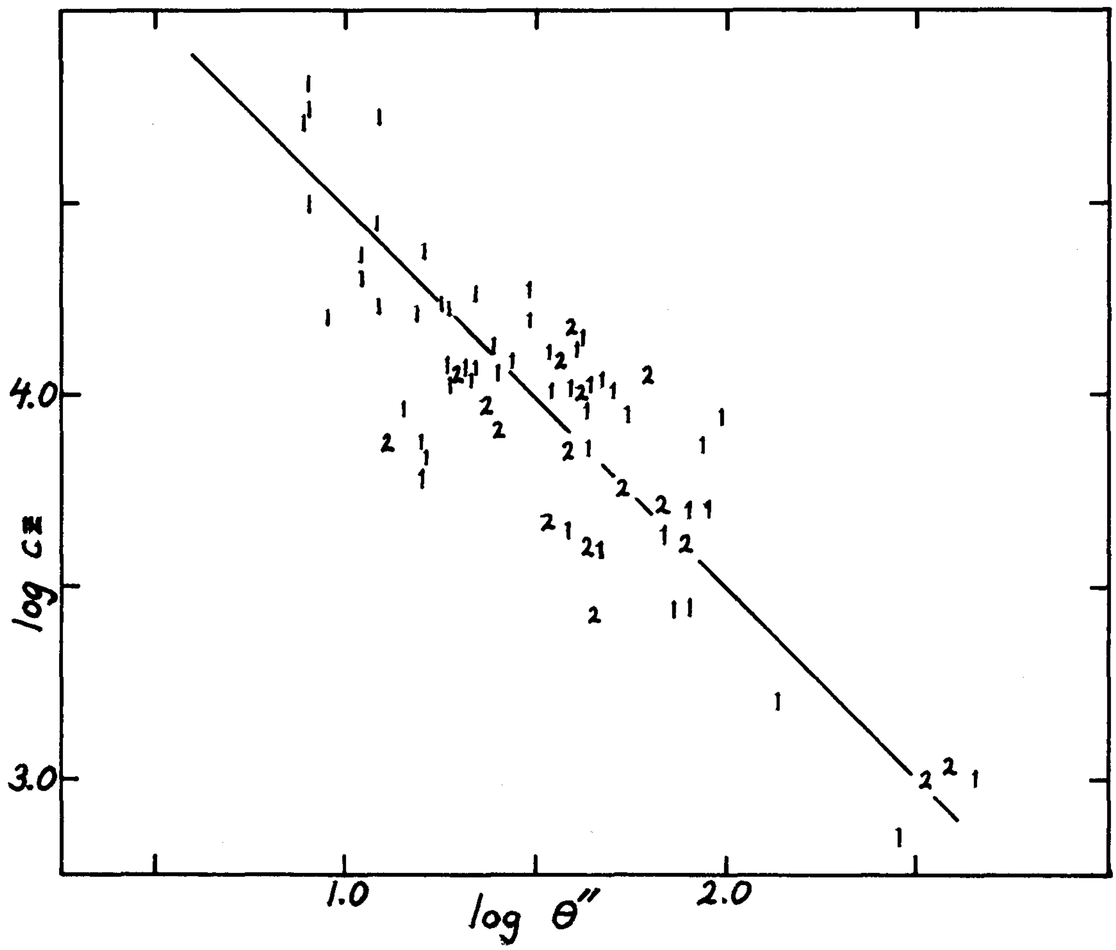

Figure 2: Angular diameter - redshift diagram for Sy 1 and Sy 2 galaxies. Diameters are measured from the Sky Survey prints. The $\sigma(\Delta \log \theta) = 0.21$ for Sy 1 compared to 0.11 for first ranked ellipticals.

dimensions. A systematic morphological study of a much larger sample of Seyfert galaxies has recently been completed by Adams (1977), using photographs obtained with the 2.1-m reflector at McDonald Observatory. Although many Seyferts, primarily those with high redshifts, have such small angular sizes as to be unclassifiable, Adams comments, ". . . . it seems clear that Seyfert nuclei occur in a broad distribution of ordinary and barred spirals along the Hubble sequence."

It is particularly significant that some Seyferts whose nuclei have luminosities approaching those of cosmologically redshifted QSOs have envelopes which appear the same as would normal spiral galaxies at comparable redshifts. Examples of such galaxies are Markarian 79 and 618, NGC 7469, IC 4329A, I Zw 1 and II Zw 136. At the moment, the "proof"

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that these objects are galaxies is based strictly upon their morphological appearance. There is as yet no spectroscopy showing that the envelopes have absorption lines, required by some as evidence that the light really is coming from stars. Such observations in the proximity of a very luminous nucleus are extremely difficult and may not be done convincingly for some time. We would point out, however, that absorption lines have been detected in the outer disks (as opposed to the nuclear bulge) of only very few spirals. Rotation curves in the outer parts of spiral galaxies, for example, usually depend on emission lines from the H II regions in the arms. This simply means that it is hard to see absorption lines in faint galaxy envelopes under the best of circumstances. A recent study by Simkin (1975) of the disk of the famous Seyfert galaxy NGC 4151 is interesting in this regard. She finds that, "Deep-sky limited isodensitometry shows it to have the structure of a giant barred spiral. Spectra of the bright part of the bar, however, show no evidence for the normal red giant stellar population usually associated with this type of barred spiral." In fact, she saw no absorption lines in the disk of NGC 4151 and found it to have an unexpectedly blue color. This means either that NGC 4151 is not a galaxy of stars or that the disks of Seyfert galaxies do not necessarily have readily detectable absorption lines. We would rather not contemplate the consequences of suggesting that the spiral nebulae are not galaxies, after all. Fortunately, multi-aperture photometry of Seyferts gives disk colors corresponding to those from galaxies of stars (e.g. Penston et al. 1974, Zasov and Lyutyi 1973).

The majority of the higher redshift, more luminous Seyfert galaxies have images that are too small and too dominated by the nucleus for classification with existing photographic data. Quantitatively, Adams (1977) finds that only 21% of all Seyferts are unresolved or have amorphous main bodies, but that this fraction is 80% for those with redshifts above 0.07. Consequently, we cannot prove even morphologically that these are distant galaxies. If they are not, we have two different sorts of "Seyfert galaxy". One is a spiral galaxy with cosmological redshift. The other is a compact object with non-cosmological redshift surrounded by a nebulosity whose diameter is inversely proportional to its redshift. Other than redshift, there are no systematic spectroscopic differences, within existing data, between Sy 1 which are surrounded by spiral arms and those surrounded by unclassifiable nebulosity. Beyond a redshift of about 0.1, the nebulosity is invariably unclassifiable (plate 1).

One can only come to an evaluation of the redshifts for Seyfert galaxies by a personal judgment of the data presented above. Our own prejudice, based on both the magnitude-redshift and angular diameter-redshift diagrams, is that the redshifts of all objects called Seyfert galaxies are cosmological. Perhaps we can best summarize these arguments with a proverb from the Tennessee hills: "If it looks like a chicken, walks like a chicken, and squawks like a chicken, it probably _is_ a chicken."

III EXTENSION TO QSOs

Many astronomers have long been aware of the physical similarities between QSOs and the nuclei of Seyfert galaxies. Both seem characterised by the generation of extraordinary luminosity by some non-thermal mechanism within a volume that is very small by galaxy standards. It was pointed out nearly a decade ago that the luminosities of some objects called Seyfert galaxies would be comparable to those of some QSOs, if cosmological redshifts were used for both. This so-called "continuity argument" provides one of the few empirical evidences for cosmological redshifts of QSOs, assuming Seyfert galaxy redshifts are cosmological. Reviews of earlier work attempting to relate Seyferts to QSOs can be found in Burbidge (1970) and Sandage (1971). We now consider such luminosity comparisons further, with a few refinements. The primary motivation for making such comparisons anew is the conclusion reached above, that the Seyfert galaxy redshifts are indeed cosmological. We also now have available a large and homogeneous subset of Seyferts, the Sy 1, whose spectroscopic and photometric properties unquestionably resemble those of QSOs. New data also exist that make it easier to restrict our consideration only to the nucleus of a Seyfert, which of course is the compact, non-thermal source that resembles a QSO. In contrast to our analyses in the preceding sections, we would now rather ignore the outer parts of Seyfert galaxies as they serve only to contaminate data from the nucleus.

To accomplish this, we use as a luminosity indicator the energy radiated in the hydrogen emission lines. There are a number of advantages to this. One is that the broad hydrogen emission lines are well correlated with the non-thermal continuous spectrum which radiates most of the luminosity from the nucleus of an Sy 1 or a QSO. This association probably comes about because the hydrogen emission arises following ionization caused by the continuum. An approximate but empirical rule of thumb is that the bolometric luminosity of an Sy 1 nucleus is 10^3 times the luminosity of the Hβ emission line. A further advantage of using the hydrogen lines is that easy comparisons can be made between low redshift Seyfert nuclei and high redshift QSOs. The Lα emission is the strongest line seen in QSOs and is so dominant that it can be used to discover faint, high redshift QSOs in optical surveys (Smith 1975, 1976). Theoretical models of QSOs as well as empirical composite spectra are sufficient to predict the Lα/Hβ ratio with reasonable confidence, to within a factor of two anyway, even though this ratio has not been observed in any one object. The Hβ luminosity of a QSO can then be deduced from an observation of Lα, thus reducing everything to one luminosity indicator without needing the K corrections applied for broad band photometry. Such emission-line observations are now easy with the availability of multi-channel spectrophotometers.

If we assume that the redshifts of Sy 1 and QSOs are all cosmological, the Hβ luminosities can be compared. Such a comparison is shown in figure 3, assuming a zero pressure cosmological model with $\Lambda = q_o = 0$. We also assume that the QSOs in which Lα was measured have an intensity ratio Lα = 40Hβ (Davidson 1972). The data used are mostly from Weedman (1976b), but a very important addition has been made. This is the sample of nine high redshift, radio quiet QSOs discovered in an objective prism survey with the 61-cm Schmidt at Cerro Tololo (Smith 1976, Osmer and Smith 1976). These QSOs were selected because of the observed Lα flux and so represent a strongly biased sample of those QSOs with the brightest Lα of all. We can therefore be reasonably confident that the sample of QSOs in figure 3 includes examples of the most luminous ones in the universe, for cosmological redshifts.

Figure 3 shows the details of the Sy 1 - QSO continuity argument. The Sy 1 nuclei span a luminosity range of about 10^3, as do the QSOs. There is an overlap in luminosity such that the brightest Sy 1 is 10 times more luminous than the faintest QSO, whereas the brightest QSO is 10^2 more luminous than the brightest Sy 1. A representative QSO luminosity is almost 10^2 that of an average Sy 1 but less than 10 times the brightest Sy 1. The entire phenomenon, from faintest Sy 1 nucleus to most luminous

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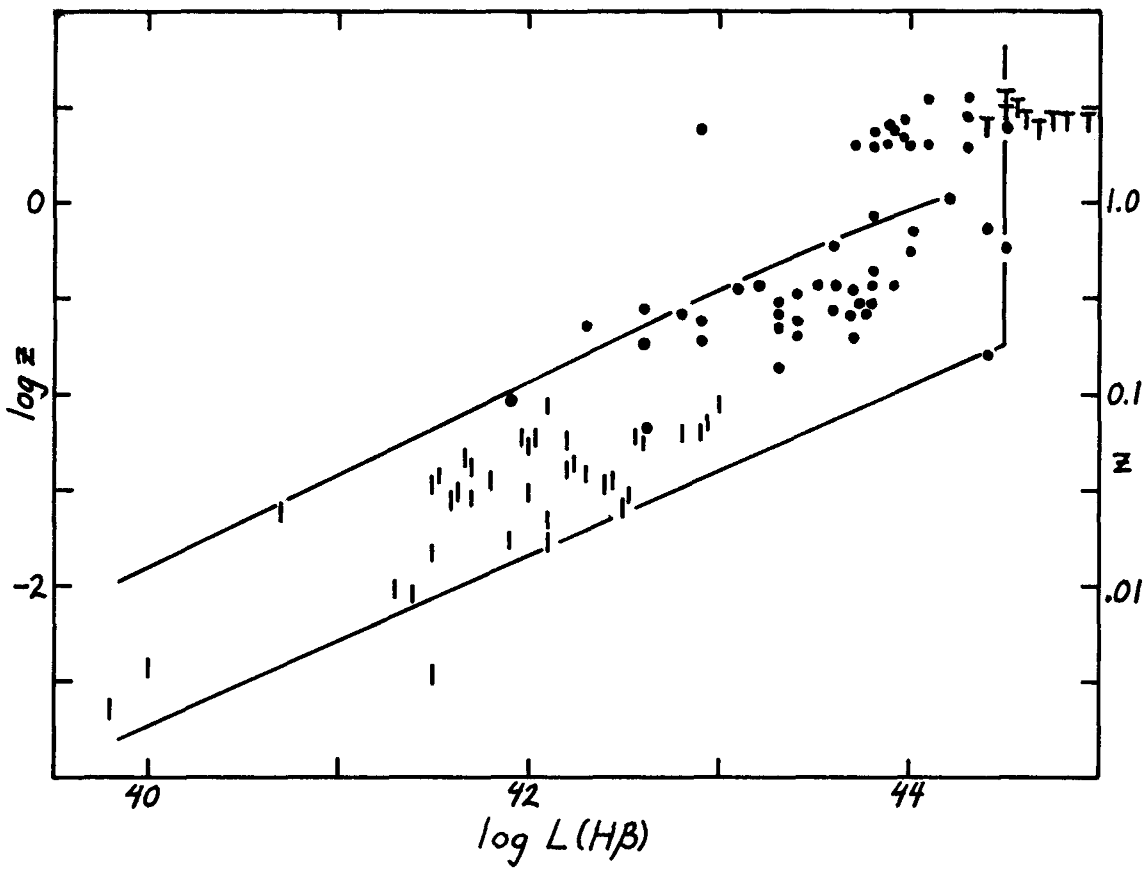

Figure 3: Luminosity - redshift diagram for Sy 1 nuclei and QSOs. Filled circles are QSOs, symbols "l" are Sy 1 nuclei and symbols "T" are QSOs discovered because of their strong Lα emission in Tololo objective prism spectra. Luminosities calculated for $\Lambda = q_o = 0$ and $H_o = 50$ km s^{-1} Mpc^{-1}. Curves represent boundaries to distribution of points expected from flux limits of observations and a hypothesized luminosity function.

QSO ranges over a factor of 10^5 in luminosity. Using the estimated relation between Hβ and bolometric luminosity, this corresponds to a luminosity range of 10^{43} ergs s^{-1} to 10^{48} ergs s^{-1}, which certainly gives the theoreticians a lot of flexibility. If they can cover a factor of 10^3 to explain the Sy 1 nuclei, they should have no difficulty in finding an extra factor of 10 to encompass the majority of QSOs.

The distribution of points in figure 3 can be explained by simple selection effects. A curve corresponding to a constant observed Hβ flux of 1.6×10^{-14} ergs cm^{-2} s^{-1} is shown (upper curve). This is close to the effective limit for the observations available at present. It is determined

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both by the selection effects contained in the identification of Seyferts and QSOs as well as the limitations on emission-line spectrophotometry. The absence of Hβ points to the left of this curve is because of this flux limit. Because the Hβ fluxes at high redshifts are deduced from observations of the strong Lα, they have an effective observational limit that is 40 times fainter. But why are there no points in the lower right of the diagram? That can be explained by adopting a luminosity function for Sy 1 nuclei and QSOs such that the more luminous objects are sufficiently rare that they are not found until a large volume of space is surveyed. For example, the lower curve shows the luminosity expected for the most luminous Sy 1 nucleus or QSO as a function of redshift under the following conditions: a) There is an upper limit to QSO luminosities such that log L(Hβ) < 44.5 anywhere in the universe. b) For redshifts less than unity, there is neither density nor luminosity evolution for Sy 1 nuclei and QSOs. c) The luminosity function N(L) is proportional to $L^{-1.33}$. We have normalized to 3C 273, which is close to the assumed luminosity limit, by making the lower curve pass through it. It has L(Hβ) = 2.5×10^{44} ergs s^{-1} and z = 0.158. Using the N(L) given, QSOs or Sy 1 nuclei with L(Hβ) = 10^{42}ergs s^{-1} would be 1500 times as numerous, per unit volume, as objects like 3C 273. Then only $(1500)^{-1}$ of the volume of space out to 3C 273 should have to be surveyed to find an object with L(Hβ) = 10^{42} ergs s^{-1}. This corresponds to a redshift $(11.4)^{-1}$ that of 3C 273, or z = 0.014, which is what the lower curve in figure 3 shows. This highly simplified analysis is not a formal solution to the data and should not be considered as a literal result for the Sy 1 - QSO luminosity function. Our purpose is only to illustrate the reasoning by which the distribution of points in figure 3 can be understood.

It is possible that a real luminosity function including Sy 1 nuclei and QSOs can eventually be formulated that accounts even for evolutionary effects. Given that surveys for radio quiet, optically faint, high redshift QSOs are now underway, using well defined flux and redshift limits, we consider it premature at this time to worry further about the luminosity function. The important conclusion from the data displayed in figure 3 is that there is a valid empirical argument for a continuity of luminosity from Sy 1 nuclei through the brightest QSOs. We consider this as strong evidence for the hypothesis that QSO redshifts really are cosmological.

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DISCUSSION

I.E. SEGAL: Two points which suggest that Seyfert galaxies are more understandable from the standpoint of the chronometric cosmology: First, there is then no significant difference in intrinsic luminosity between Seyfert galaxies and quasars; they also both have about the same intrinsic dispersion in absolute magnitude, about 1^m. Second, with regard to the (m,z) relation of Seyfert galaxies, if the sample of 90 Seyfert-like galaxies published by Vorontsov-Vel'yaminov in 1974 is fair, then the Hubble law deviates from expectation by 15σ; while the chronometric prediction deviates by $\sim 0.1\ \sigma$. Moreover the deviations from the Hubble line have a dispersion slightly greater than that in the apparent magnitudes, $1\overset{m}{.}5$; while that from the chronometric law is considerably less, $1\overset{m}{.}0$.

M. BURBIDGE: In your third slide, you had log cz plotted against absolute magnitude and a line with a slope looking like a Hubble line through the points. I did not understand what was the significance of this line? A Hubble relation must have been used to derive the absolute magnitudes.

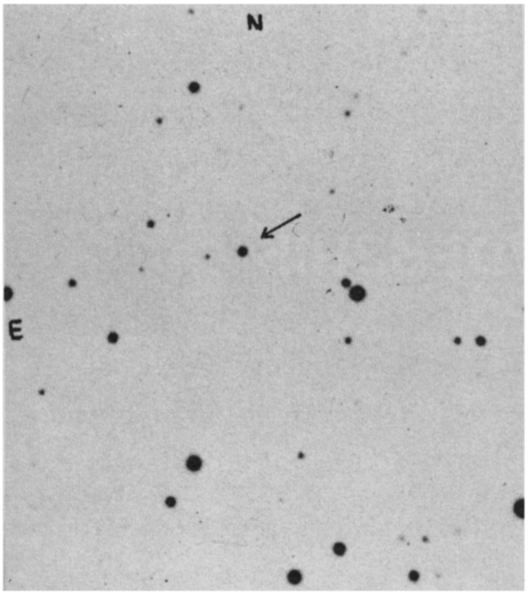
E. KHACHIKIAN: I wanted to show that large dispersion exists in M magnitudes of Seyfert galaxies. The line showed selection effect of observations.

H. ARP: A minor point: you showed a stellar appearing object with redshift $z \approx 0.1$. I would technically call that a quasar rather than a Seyfert galaxy as you did. Perhaps that is not an important point because I believe, as you do, that there is a continuity between quasars and compacts and Seyferts.

Of more consequence, I should point out that these objects usually appear isolated, not in clusters and groups as galaxies usually do.

E. KHACHIKIAN: The point is that Kazarian 102 spectroscopically is close to both Seyferts and QSOs. Actually it is one of the distant Seyfert galaxies or one of the nearest QSOs. Kazarian 102 is not connected with any nearby galaxy.

Plate 1: Kazarian 102, a blue "stellar" object with a spectrum like that of an Sy 1 or a QSO and a redshift of 0.136. This represents objects in the redshift range where their classification is ambiguous. Depending on the visibility of the nebulosity surrounding the bright nucleus, this would be called either an Sy 1 or a QSO. Photograph obtained with the 2.6-m reflector at Byurakan Observatory.



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