ORBITAL PARAMETERS AND SEYFERT GALAXY TYPES

by

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ABSTRACT

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The rate of pairing of Seyfert galaxies is explored by utilizing a sample of 79 Seyfert galaxies selected from the "Catalog of Seyfert Galaxies and Related Objects" by N. Kaneko. Using computer simulations and data from the CfA Redshift Catalog, the fraction of Seyfert galaxies found in pairs or groups is observed to be significantly higher than that found in many previous investigations. The corrected pairing rate lies between 60 and 70 % for bright companions. This study supports the suggestion by Kollatschny and Fricke that many Seyferts reside in groups. Seyferts appear to have pairing rates similar to those for a sample of nearby normal spiral galaxies. An excess of projected angular momentum values was observed for the Seyfert pairs, implying the Seyfert companions are more bound than control companions. No evidence for Seyferts having a significant population of elliptical companions as compared to normal spirals was observed. In addition, no evidence that the physical separation between Seyfert 1 galaxies and their companions differs from that for Seyfert 2's.

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TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER 1: INTRODUCTION AND OVERVIEW OF PREVIOUS WORK

I. Introduction

The majority of galaxies we observe are ordinary galaxies which show little activity beyond what is expected for a collection of stars and gas. In a small percentage of observed galaxies, however, there is violent activity well beyond the norm. Seyfert galaxies, a particular class of active galaxy, emit strongly in the radio, infrared and X-ray. Unlike ordinary galaxies, which have a spectrum consisting of a thermal continuum plus absorption lines, Seyferts exhibit a nonthermal continuum plus emission lines.

Seyfert galaxies can be classified into two types depending on their emission spectra. Type 1 Seyferts have very broad H I, He I and He II emission lines with full widths at half maximum (FWHM) on the order of 1 to $5 \times 10^3 kms^{-1}$. The forbidden lines, like [O III]$\lambda\lambda$4959, 5007, [N II]$\lambda\lambda$6548, 6583 and [S II]$\lambda\lambda$6716, 6731 have FWHMs of order $5 \times 10^2 kms^{-1}$. The forbidden lines, therefore, are broader than the emission lines in most starburst galaxies.

Type 2 Seyferts have permitted and forbidden lines with approximately the same FWHMs, typically of order $500 kms^{-1}$. This is similar to the FWHMs of the forbidden lines in Seyfert 1's. Seyfert 2's also possess relatively strong [O III] emission lines, with [O III]λ 5007/H$\beta \geq 3$.

There are, however, lower-ionization Active Galactic Nuclei (AGN) called Low-Ionization Narrow Emission-Line Regions (LINERs). These can be distinguished from starburst or HII galaxies in that LINERs have relatively strong [O I] and [S II], and seem to be photoionized by the same type of hard spectrum as other AGNs. LINERs, however, seem to have a smaller ionization parameter, Γ, which is the ratio of number densities of ionizing photons $[for H^0]$ to free electrons. This sets the general level of ionization (Osterbrock 1989).

In it's most general sense, an "active galaxy" refers to those few percent of all galaxies which display an anomalous energy output from their nuclei compared to that from a "normal" galaxy. It is generally accepted that this activity arises from the interaction of matter with a supermassive black hole with a mass of $\sim 10^3 - 10^{10} M_{\odot}$. The problem which exists is in "fuelling" the AGN. This is a two-fold problem; we need to know what the fuel source is and how the fuel is transported to the black hole. In this work, the question of fuel transportation is addressed, with a focus on companion galaxies acting as possible mechanism in sustaining nuclear activity.

II. Overview of previous work

Almost a decade ago, the morphological similarities between patterns seen in Seyfert galaxies and those produced by gravitational forcing led to the suggestion that Seyfert activity might be fueled by material inflow induced by either a central bar or a perturbing companion (Simkin, Su, and Schwarz, 1980). More recent theoretical calculations suggest that such a feeding mechanism may involve a central bar-like structure even if initially induced by the tidal effects of a companion galaxy (Noguchi, 1988a,b).

The recent literature on the prevalence of Seyfert galaxy companions, however, is somewhat confusing and, at initial glance, contradictory (Byrd, et al., 1987, Dahari, 1984, 1985, Fuentes-Williams, and Stocke, 1988, Keel, et al., 1985, Kennicutt, and Keel, 1984, Kollatschny and Fricke, 1989, Petrosian and Turatto, 1982, 1986). Most studies find either a weak correlation between excess companions or none at all. All of these studies involve complex (and incommensurate) selection criteria. Most authors have attributed their disparate conclusions to selection effects (op. cit.). It would be instructive to look at the literature in greater detail.

Dahari (1984) has examined the region of the sky between $-45\,\mathrm{deg} \leq \delta \leq 90\,\mathrm{deg}$ and $z \leq 0.03$ for companions of 103 Seyfert galaxies, 18 of which were marginal or uncertain Seyferts. The redshift limit was chosen so that cosmological evolutionary effects would be umimportant. Dahari searched the Palomar Observatory Sky Survey (hereafter POSS) plates for possible companions within three times the major axis to the Seyferts (S=3D). This criterion was chosen specifically to avoid finding multiple companions. 15% of the Seyferts had physical companions, compared to an upper limit of 3.1% for the control sample. Calculating a factor denoted Q, which is the gravitational interaction strength between two galaxies, Dahari found that 7.5% of the Seyferts have very close companions, as opposed to 1% for the controls. Q will be large for close and large companions.

One hundred sixty seven systems of interacting and asymmetric galaxies were observed spectrophotometrically by Dahari (1985) in the range 4700-7100 Å . Results were compared with a sample of isolated galaxies. No Seyfert nuclei were found in elliptical or dwarf irregular galaxies. An excess of Seyfert nuclei among interacting spirals was observed at the 90% confidence level. This became statistically significant (98%) when only *strongly* interacting spirals were included.

Byrd et al. (1987) found (unlike Dahari) that Seyferts are more likely to have close and/or more massive companions to perturb them, rather than simply being more likely to have companions. Using the list of Dahari (1985) as their sample, surroundings more distant than S=3D were studied using different catalogs. 12/14 Seyferts were found to have probable companions and 7/12 are confirmed by their radial velocity. They conclude that 19/26 (73%) or even 24/26 (92%) of Dahari's Seyfert sample have companions. This seems to indicate that tidal interaction may be the predominant cause of Seyfert activity.

Fricke and Kollatschny (1988) analyzed 113 galaxies: 15 groups around Seyfert galaxies and 9 control groups around non-Seyfert galaxies of the same morphological type. Membership in these groups was confirmed spectroscopically. It was found that on average near the Seyfert galaxies, companions are more active (*strong emission-line activity*) than further out. They interpreted this in terms of interactions of closer companions with their Seyfert galaxy.

Fuentes-Williams and Stocke (1988) have measured the density of galaxies within 1 Mpc of 53 Seyfert galaxies chosen from the list of Weedman (1977) and 30 control galaxies chosen from the CfA redshift survey. The selection criteria used were:

1. $\delta \geq -10\,\mathrm{deg}$
2. $|b^{II}| \geq 20\,\mathrm{deg}$
3. $0.009 \leq z \leq 0.05$

Criterion 1. was chosen so that the galaxies were accessible on the POSS plates on which measurements were made; 2. allowed for the avoidance of areas of high extinction and confusion with foreground galactic objects and 3. excluded members of the local supercluster and less luminous but significant galaxies. The controls matched the morphology, absolute magnitude and redshift distribution of the Seyferts. They found that the Seyferts didn't possess a clear excess of luminous ($M_v \leq -18$) companions relative to the control sample of normal spirals. No statistically significant difference was observed between the Seyfert and control samples in any of the quantities measuring local galaxy density. When companion galaxies with diameters less than 15 kpc. were included, the Seyferts showed a statistically significant excess of companions, however this significance was less dramatic than found by Dahari or MacKenty.

Using the same selection criteria as Dahari, MacKenty (1989) constructed a sample of 51 Seyfert and 51 control galaxies from the Markarian and NGC catalogues, and compared their environments. He found that 71% of the Seyferts had apparent companion galaxies within 10 galaxy diameters as opposed to only 26% for the controls. Since no explicit correction for background noise was made, the true fraction of companions will be lower in both samples by similar amounts. MacKenty also found a higher fraction of Seyfert 2's had close companions than Seyfert 1's, however the statistical significance is marginal. In addition, he found that the non-Seyfert Markarians had the same frequency of companions as the Seyfert Markarians.

Heckman (1989) expressed several possiblities for reconciling the differences in the results found by Fuentes-Williams and Stocke with those of Dahari and MacKenty. These are:

1. "Bad Luck" at the 2-3σ level.
2. A true excess of companions to Seyferts exists, but only for intrinsically faint companions.
3. The stronger excesses of companions found by Dahari and MacKenty are (in part) artifacts of the way they defined a control sample.
4. An excess of close companions may be stronger for Seyfert 2's than for Seyfert 1's.

Kollatschny and Fricke (1989) systematically studied the occurrence and qualitative properties of Seyfert 1 and Seyfert 2 galaxies as a function of the galaxy environment. They selected 242 galaxies from the Catalogue of Quasars and Active Nuclei (Veron and Veron 1989) with the criteria:

1. $m_v \leq 15$

2. Listed as Seyfert 1, 2 or 3

3. $v_{rad} \leq 2000 kms^{-1}$

The environments of the Seyferts were inspected on the POSS and ESO/SRC plates. A search for companions was made out to 0.5 Mpc. A companion was defined as having a size between 20-200% the Seyfert size. The galaxy density within an environment of 500 kpc radius was considered. No size dependence of morphology on density class was observed. They concluded that a suitable group environment provides only a necessary condition for the development of Seyfert activity which in addition requires favorable conditions in the host galaxy itself.

MacKenty et al. (1989) have investigated the morphologies of the Markarian sample of 1500 UV excess galaxies and their environments using the 20 minute V plates obtained for the construction of the Hubble Space Telescope Guide Star Catalog. They find that the type of nuclear activity present in the Markarian sample is not dependent on either the morphology or the local environment of the galaxy.

An independent analysis of the material in many of these papers (Simkin, 1990) seems to suggest an excess of nearby companions for Seyfert 2 galaxies, but not for Seyfert 1 galaxies. On the other hand, two of the cited studies show no significant difference in excess companion density between the two Seyfert classes (Byrd, et al., 1987, and Kollatschny and Fricke, 1989). Both of these latter studies, however, deal with small numbers of objects. In addition, all of the studies use different criteria to define the term "*companion*."

An indiscriminant compilation of all of the data for objects with $cz \leq 4000$ kms^{-1}, taken from all of the studies noted above, seems to suggest that Seyfert 1 galaxies are found preferentially in wide pairs while Seyfert 2's have companions which are closer (Simkin, 1990). This is shown in Figure 1, where most of the Seyfert 2 galaxies appear to lie within 100 Kpc of their companions while most of the Seyfert 1's are found at distances beyond 100 Kpc (with H_0=100). If this effect is real, it would explain the apparent deficiency of paired Seyfert 1 galaxies found in those studies which selected only companion candidates within a few galactian diameters of the target Seyfert.

Using a galaxy diameter approach to find companions may bias the number of companions found if the mean diameters of the galaxies in the samples differ. That is, if one sample has a mean galaxy diameter that is larger than another, the sample with the larger mean galaxy diameter will have a greater number of companions associated with it. An approach using galaxy diameters would be better suited for potential tidal effects. Chapter 2 outlines the use of velocity and physical separation as constraints on determining companionship to the Seyfert galaxies. This gives a physical basis for defining companionship. A comparison with non-Seyfert pairs is discussed.

In Chapter 3, the morphologies of the companions to Seyfert and control spirals is discussed. Fuentes-Williams and Stocke (1988) found a nonnegligible population of ellipticals as companions to Seyfert galaxies as opposed to mostly spiral companions for a control sample of normal spirals. It is demonstrated that no evidence was observed for Seyferts having an overabundance of ellipticals as companions compared to a sample of normal spirals.

In Chapter 4, the question of galaxy pairing is readdressed with a focus on the frequency of pairing given different selection criteria. Also discussed are the results of multiple simulations using randomly selected control samples. Chapter 5 summarizes the results found in this study.

Figure 1: Plot of multiple pairs to the Seyfert galaxies of Simkin (1990). Note that the companions of the Seyfert 2's lie closer to their host than for the Seyfert 1's

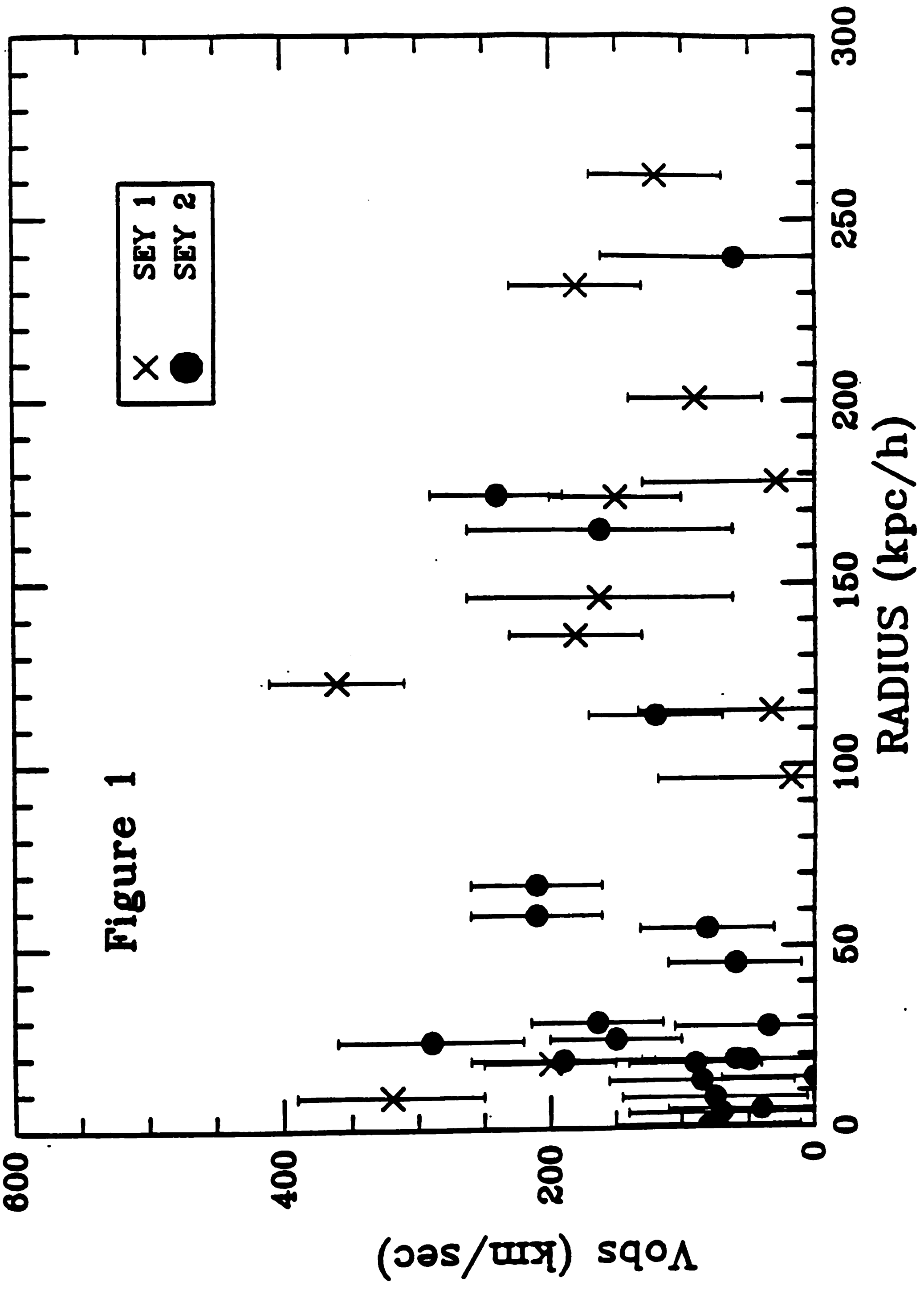


Figure 1
SEY 1
SEY 2
RADIUS (kpc/h)
Vobs (km/sec)
0
50
100
150
200
250
300
0
200
400
600

CHAPTER 2: ANALYSIS OF GALAXY PAIRING

I. Seyfert Companions from the CfA catalog

To investigate more rigorously the apparent differences in results, possibly due to selection effects, found in the studies listed in Chapter 1, a sample comprised of 79 Seyfert galaxies was selected from the "Catalog of Seyfert Galaxies and Related Objects" by N. Kaneko (see Table 1). This was chosen to include all Seyferts with $cz \leq 4000$ kms^{-1} and excluding the Virgo cluster. The ratio of Seyfert 1's to Seyfert 2's in this sample (approximately 1:2, Table 2) is similar to that found for nearby, volume limited samples of Seyfert galaxies irrespective of their status as companions (Simkin, Su, and Schwarz, 1980).

After experimenting with the various criteria used to characterize "companions" in the studies noted above, the following selection rules were adopted to identify possible physical pairs for these Seyferts from amongst all other galaxies with known redshifts in the CfA catalog:

Table 1: Table of Seyferts from list of Kaneko

Object	Sy type	RA	Dec	V_r (km/s)	Dim (')
N 424	2	1 9 9.8	-382056	3496	2.2 1.1
N1052	2	23837.0	- 828 6	1475	1.8 1.0
N1068	2	240 7.1	- 01331	1153	9.0 8.0
N1097	2	24412.0	-3029 0	1275	5.0 4.5
M1066	2	25649.0	363718	3600	1.0 0.5
N1241	2	3 848.0	- 9 7 0	2168	3.3 2.2
N1358	2	33112.0	- 51530	4013	2.0 1.5
N1365	1	33142.0	-3618 0	1652	7.0 3.2
N1386	2	335 0.0	-3610 0	924	2.0 0.8
N1566	1	41854.0	-55 4 0	1487	13.0 9.0
N1808	2	5 6 0.0	-3734 0	977	10.0 7.0
N2110	2	54948.0	- 718 0	2311	0.7 0.5
MK3	2	6 948.4	71 311	3900	0.5 0.4
N2273	2	64538.4	605416	1842	3.6 2.4
0722-095	2	72234.4	- 934 5	2400	1.8 1.6
MK1210	2	8 127.0	51522	3900	0.2 0.2
N2639	1	840 6.0	5023 0	3226	2.0 1.5
N2691	1	85130.0	3944 0	4048	1.6 1.0
0942+098	2	94248.8	95048	3600	1.1 0.9
N2992	2	94317.0	-14 549	2305	1.1 0.5
0945-307	2	94528.4	-304257	2500	1.6 0.6
N3031	1	95130.0	6918 0	350	26.0 14.0
N3081	2	95712.0	-2235 0	2413	1.1 0.9
N3079	1	95836.0	5555 0	1114	8.7 1.6
N3185	2	101454.0	2156 0	1218	2.0 1.2
N3227	1,2	102048.0	20 7 0	1138	6.5 4.5
N3281	2	102936.0	-3436 0	3460	2.1 0.6
1034+061	2	1034 0.0	6 9 0	3600	0.6 0.4
N3312	1	103441.4	-271814	2863	2.5 1.0
N3393	2	1046 0.0	-245347	3730	4.0 4.0
N3516	1	11 322.8	725020	2602	2.1 1.8
N3718	1	112948.0	5321 0	987	11.0 5.0
N3783	1	113630.0	-3728 0	2550	0.9 0.8

Table 1 (cont'd).

Object	Sy Type	RA	Dec	V_r (km/s)	Dim (')
N3786	1	1137 4.9	321111	2723	2.2 1.1
MK745	2	113720.6	171355	3000	1.0 1.0
N3982	2	115353.0	5524 0	1188	2.4 2.2
N3998	1	115520.9	554355	1028	3.0 2.5
N4051	1	12 036.4	444835	710	6.0 5.0
N4117	2	12 512.0	4324 0	958	2.5 0.9
N4151	1	12 8 1.1	3941 2	962	7.0 6.0
N4253	1	121555.6	30 526	3876	0.9 0.9
N4258	2	121630.0	4735 0	449	22.0 9.0
N4278	1	121736.2	293331	643	3.5 3.5
N4507	2	123254.0	-3938 0	3523	1.0 0.9
N4594	1	123724.0	-1121 0	1128	6.0 2.5
F312	2	1238 9.0	-362920	3300	0.7 0.7
N4968	2	13 424.0	-232440	2957	2.5 1.4
N5005	2	13 836.0	3719 0	1022	6.3 3.0
N5033	1	1311 9.2	365130	892	11.5 5.5
N5077	1	131652.8	-122342	2823	1.0 0.9
1331-234	2	133151.2	-232526	2600	1.1 0.6
1333-340	1	1333 1.8	-34 228	2300	1.3 0.7
MK270	2	133941.2	675536	2700	0.6 0.6
N5273	1	133955.1	355421	1089	2.8 2.3
N5347	2	1351 5.4	3344 0	2335	1.7 1.4
N5427	2	14 049.0	- 54726	2730	1.2 1.1
N5506	1	141042.0	- 258 0	1753	2.0 0.5
MK670	2	1412 0.2	265849	1700	1.0 1.0
N5643	2	142728.0	-435712	1180	2.1 2.0
N5728	2	143936.0	-17 2 0	2834	2.0 0.9

Table 1 (cont'd).

Object	Sy Type	RA	Dec	V_r (km/s)	Dim (')
N5899	2	151312.0	4214 0	2554	2.8 1.2
N5929	2	152418.9	415041	2550	1.0 0.9
N5953	2	153212.0	1522 0	1983	1.7 1.3
N6217	2	1635 0.0	7818 0	1370	3.6 3.6
N6221	2	164825.0	-59 8 0	1478	6.2 5.0
N6300	2	171217.0	-624554	1107	7.1 5.3
I4870	2	193248.0	-6556 0	852	2.2 1.2
N6814	1	193954.0	-1027 0	1552	1.3 1.1
N6890	2	201448.0	-445748	2419	1.4 1.2
F348	2	203324.0	-501550	2400	0.7 0.6
I5063	2	204812.0	-5716 0	3402	4.4 3.0
N7213	1	22 612.0	-4725 0	1769	2.5 2.5
I5201	2	221755.0	-4617 0	915	14.4 7.9
N7314	2	2233 0.0	-2618 0	1430	3.0 1.0
N7450	1	225810.0	-131114	3100	1.6 1.6
N7496	2	23 7 0.0	-4342 0	1657	2.1 1.2
N7582	2	231536.0	-423836	1576	8.0 3.0
N7590	2	231612.0	-4231 0	1509	1.9 0.6
N7672	2	232459.8	12 635	4010	0.5 0.4

$$|cz_{sey} - cz_{comp}| \leq 600 \quad kms^{-1}$$

and

physical separation $\leq$ 720 kpc.

An upper limit of the physical separation of 720 kpc was selected based on measurements of Schneider and Salpeter (1989). They constructed a detailed model in which they traced orbital parameters for a full population of galaxy pairs from the time of their formation, at which time they would have been expanding with the Hubble flow. It was observed that an upper limit of the physical separation of 720 kpc is a naturally occurring quantity. The characteristics of candidate pairs chosen with the criteria listed above are shown in Table 2.

Table 2: Statistics of companions for Kaneko Seyferts

Galaxy Type	Sy1+2	(%)	Sy1 (%)	Sy2 (%)
Total Sample ($cz \leq 4000$ kms^{-1})	79	(100)	26 (33)	53 (67)
Number with Companions	61	(77)	22 (85)	39 (74)
Number with $\geq$ 1 Companions	46	(58)	20 (77)	26 (49)

II. Comparison with Non-Seyfert pairs

To assess the significance of the results in Table 2, various tests were devised to estimate the probability that a suitably chosen "random" sample of galaxies from the CfA would exhibit a similar companion density. These are described below:

CASE A:

An ensemble of 25 sets of 79 galaxies was constructed from objects chosen at random from the CfA (with the only restriction that their radial velocity be less than 4000 kms^{-1}). The Virgo cluster dominates the velocity distribution at lower redshifts and strongly biases towards finding companions. It has, therefore, been excluded in this analysis. The CfA was then searched with the same technique as was used to identify Seyfert companions, using each simulated set in place of the original Seyfert list. The mean number of companions found for these sets is shown in Table 3 and the distribution in this number is shown in Figures 2, 3 and 4 respectively. The velocity distribution of this sample is (as expected) similar to that of the CfA (Figures 2A and B).

CASE B:

To assess the possibility that galaxies with velocities chosen "at random" from the CfA catalog exhibit more than average clustering, an ensemble of 25 sets of 79 galaxies was constructed from objects chosen at random from the CfA with the further restriction that the radial velocity of each galaxy chosen match that for its corresponding Seyfert to within 50 kms^{-1}. The velocity distribution for this case and the Kaneko Seyferts with Virgo excluded is shown in Figure 2C. Using the same search technique as above, yields the mean number of companions for the galaxies in this ensemble shown in Table 3 and the corresponding distribution plotted in Figure 3. The companion density is slightly higher for this case than for the unconstrained random sample.

CASE C:

To test the possibility that the areas surounding nearby Seyfert galaxies have been surveyed more extensively and thus have a higher percentage of measured redshifts than areas not graced by Seyferts, the following tests were set up:

a. C1: Catalog limit = 4000 kms^{-1}

The CfA catalog was searched for all galaxies with measured redshifts less than 4000 kms^{-1} in a conical solid angle of 6 deg, centered on each Kaneko Seyfert. Of the 163 objects which fit these restrictions, 24 fit the criteria for 'pairing' with the Kaneko Seyferts. The remaining 139 (distributed over 40 fields) were then used to construct an ensemble of 25 sets of 40 "random" galaxies which were analyzed for pairing as before. This simulation yielded a significantly lower percentage of "pairs" than did either Case A or Case B (Table 3, and Figure 4).

b. C2: Catalog limit = 6000 kms^{-1}

The CfA catalog was then searched for all of the galaxies with measured redshifts less than 6000 kms^{-1} in a conical solid angle of 6 deg, centered on each Kaneko Seyfert. Of the 229 objects which fit these restrictions, 24 fit the criteria for 'pairing' with the Kaneko Seyferts. The remaining 205 (distributed over 52 fields) were then used to construct an ensemble of 25 sets of 52 "random" galaxies which were analyzed for pairing as before. This simulation again yielded a significantly lower percentage of "pairs" than did either Case A or Case B (Table 4). This, along with C1 above, suggests that galaxies in the Seyfert fields are not over-represented in the catalog.

Table 3: Mean Number of Companions (25 runs)

Galaxy Type	Sy1+2	(%)	Sy1 (%)	Sy2 (%)
Kaneko Seyferts	61	(77.2)	22 (84.6)	39 (73.6)
Case A (Random)	49.2	(62.3)	15.9 (61.2)	33.3 (62.8)
Case B (restricted V_r)	52.8	(66.8)	18.3 (70.4)	34.5 (65.1)
Case C1 (restricted sky positions)	53.3	(67.5)	22.9 (72.5)	30.4 (64.2)
Case C2 (restricted sky positions)	35.3	(44.7)	15.7 (57.3)	19.6 (38.)

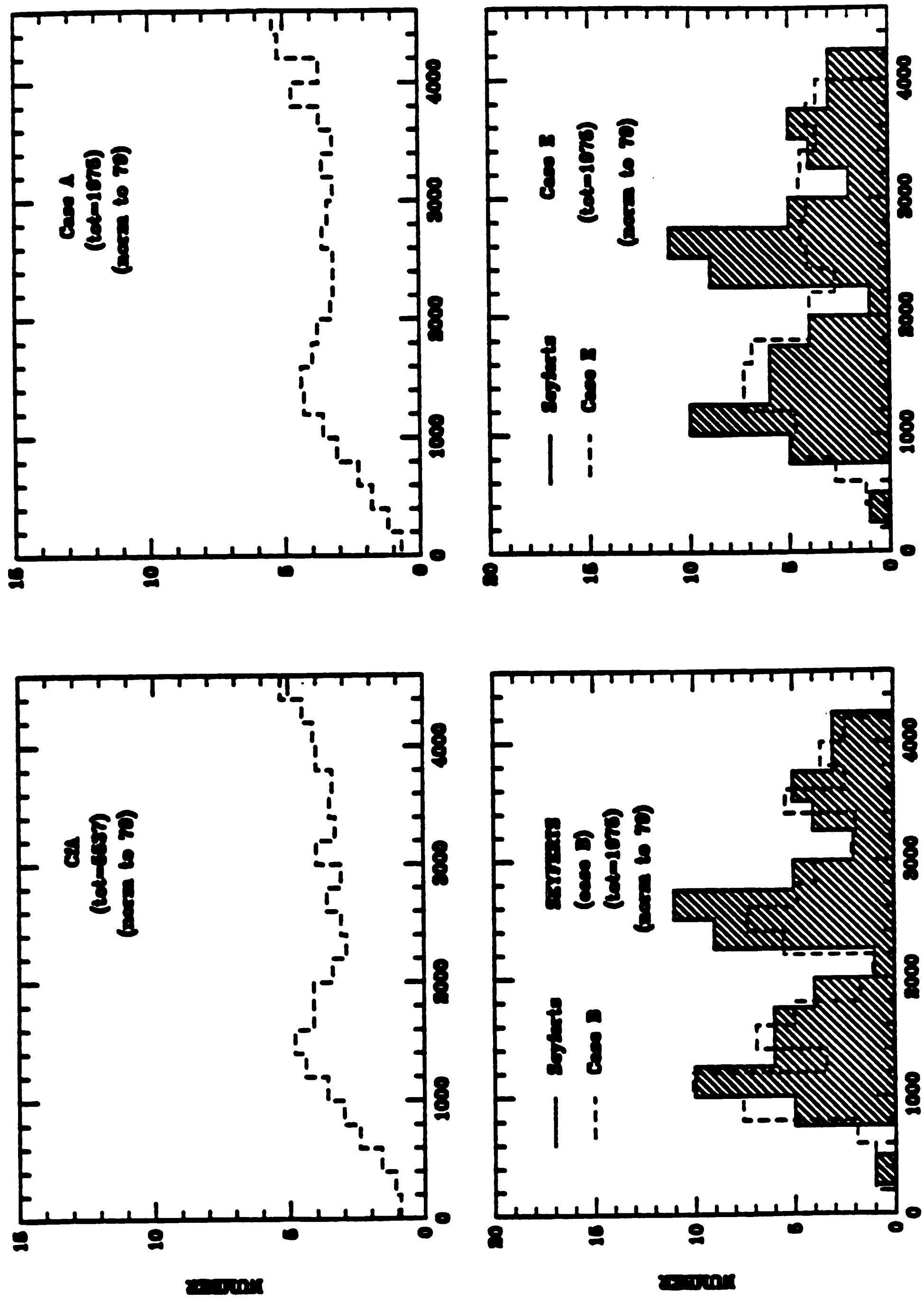
Case D

An ensemble of 25 sets of 79 galaxies was chosen at random from the CfA with the restriction that the morphology and inclination of each galaxy match that for its respective Seyfert. The velocity was constrained to $v_r \leq 4000 kms^{-1}$ for the controls. The CfA was searched for companions as before. The results for the average velocity and pair average is shown in Table 4. The average velocity is higher than that for the Seyferts.

Case E

Again an ensemble of 25 sets of 79 galaxies was selected at random from the CfA, in this case matching morphology and recessional velocity to within $600 kms^{-1}$. The average velocity and average number of pairs is shown in Table 4. The velocity and number distributions are plotted in Figures 2, 3 and 4. It is apparent from Figure 2 that the velocity distribution for this case is not as good a match as that for Case B. This is due to the fact that the velocities of the controls in Case B were matched

Figure 2: Velocity distributions of the CfA and Cases A, B and E. Also plotted is the velocity distribution of the Seyferts.



VELOCITY DISTRIBUTIONS (km/s)
NUMBER
Case A
Case E
Seyferts
Case B
SEYFERTS
(norm to 70)
0
1000
2000
3000
4000
5
10
15
20

Figure 2

Figure 3: Plot of the mean number distribution of companions found for the ensembles in Case A, B, D and E. Also plotted is the mean number distribution of the Seyferts.

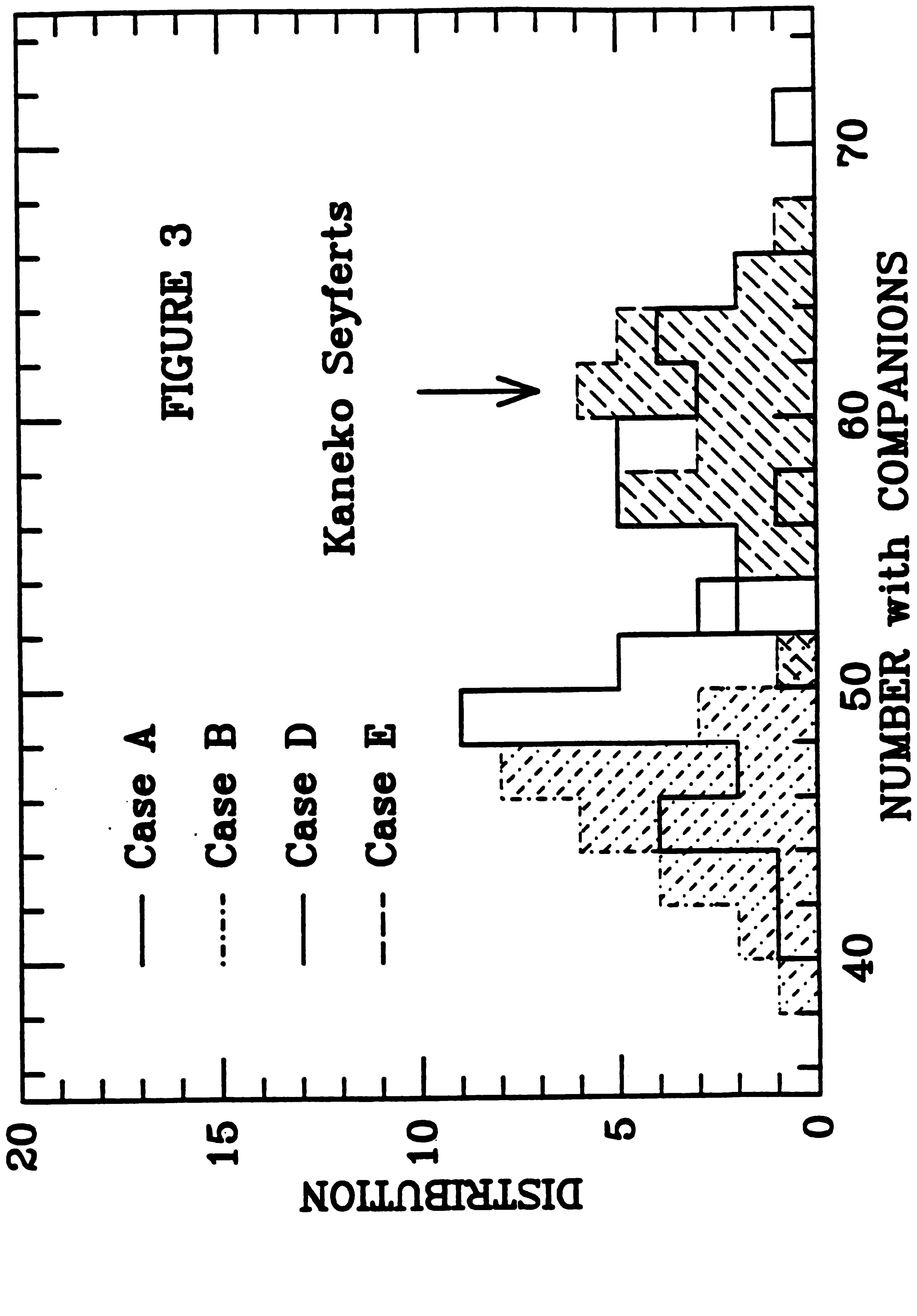


FIGURE 3
Kaneko Seyferts
Case A
Case B
Case D
Case E
40
50
60
70
NUMBER with COMPANIONS
0
5
10
15
20
DISTRIBUTION

Figure 4: Plot of the mean number distribution of companions found for the ensembles in Case A, C1, E and F. Also plotted is the mean number distribution of the Seyferts.

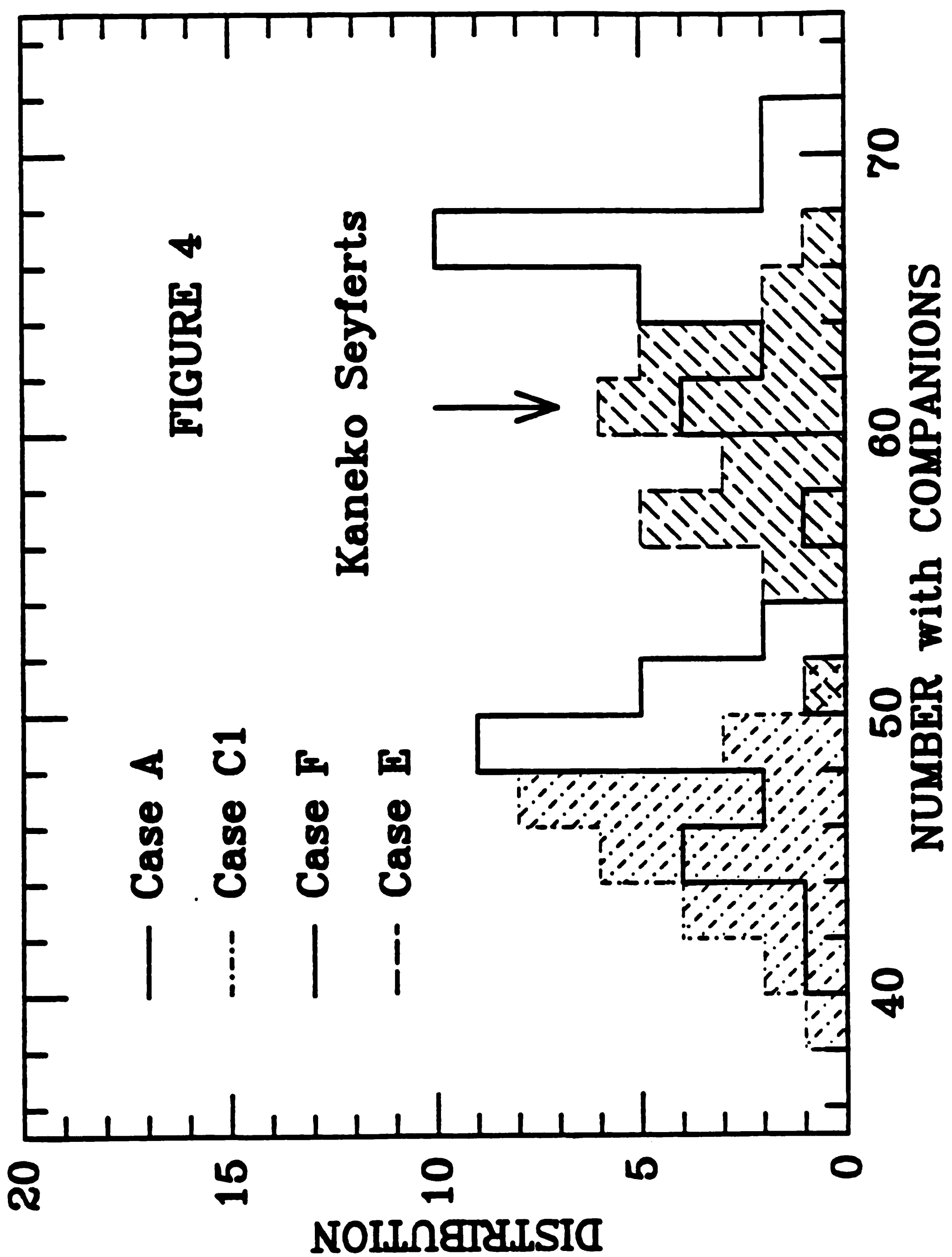


FIGURE 4
Kaneko Seyferts
Case A
Case C1
Case F
Case E
NUMBER with COMPANIONS
DISTRIBUTION
40
50
60
70
0
5
10
15
20

to within $50 kms^{-1}$ of their respective Seyferts, whereas in this case a velocity range of $600 kms^{-1}$ was allowed. This produced a smearing of the three peaks found in the Seyfert velocity distribution. The velocity and pair average match that for the Seyferts very well. This was concluded to be the correct control sample in modelling Seyfert companionship.

Case F

In order to examine the effect of morphology on finding companions, an ensemble of 25 sets of 79 galaxies was chosen at random from the CfA which match their respective Seyfert in recessional velocity but have a large difference in morphology. In this case, elliptical galaxies were selected. See Table 4 and Figure 4 for results.

Case G

The same analysis has been done here as in the previous case, but now the morphologies were selected to be late type spirals. The results are shown in Table 4.

Table 4: Average velocity and pair average for 25 runs

Case	Average v_r	pair average
A	2585	49.2
B	2131	52.8
C1	2690	53.3
C2	3508	35.3
D	2321	60.04
E	2176	60.16
F	2180	66.4
G	2096	55.56
Kaneko	2131	61.

III. Analysis of results in section II.

Number distributions for Cases A, B, D and E and Cases A, C, E and F are plotted in Figures 3 and 4 respectively. Again, it is concluded that Case E was the best match for the Seyferts and is the correct control sample to use when modelling the Seyfert pairing rates. The lower average pair values found in Cases A, B and C is postulated to be due to a combination of:

1. The higher mean velocity in Case C2 implies that there are fewer high velocity galaxies in the CfA catalog.

2. Random picks with random morphologies include late type spirals which yield fewer pairs.

The Seyfert type distribution for Case E is plotted in Figures 5 and 6 respectively. Figure 5 shows all companions while Figure 6 plots only multiple companions. Also shown is the distribution for the Kaneko Seyferts. It is concluded that the distribution of single pairs is the same for the Seyferts and controls, BUT there may be a deficiency of multiple pairs for the Seyfert 2's and an excess for the Seyfert 1's.

The "projected angular momentum", J, for the pairs in Case E was then examined. Plotted in Figure 7 is the distribution of "projected angular momentum" for pairs with the minimum J. There appears to be an excess of low J values for the Seyfert pairs as opposed to the control pairs. The total number of companions for the controls and Seyferts is plotted in Figure 8. The average number of Seyfert pairs with $J \leq 2000$ km/s*kpc is 24 as compared to 13.8 for pairs in Case E. The probability

Figure 5: Number distribution for all companions in Case E.

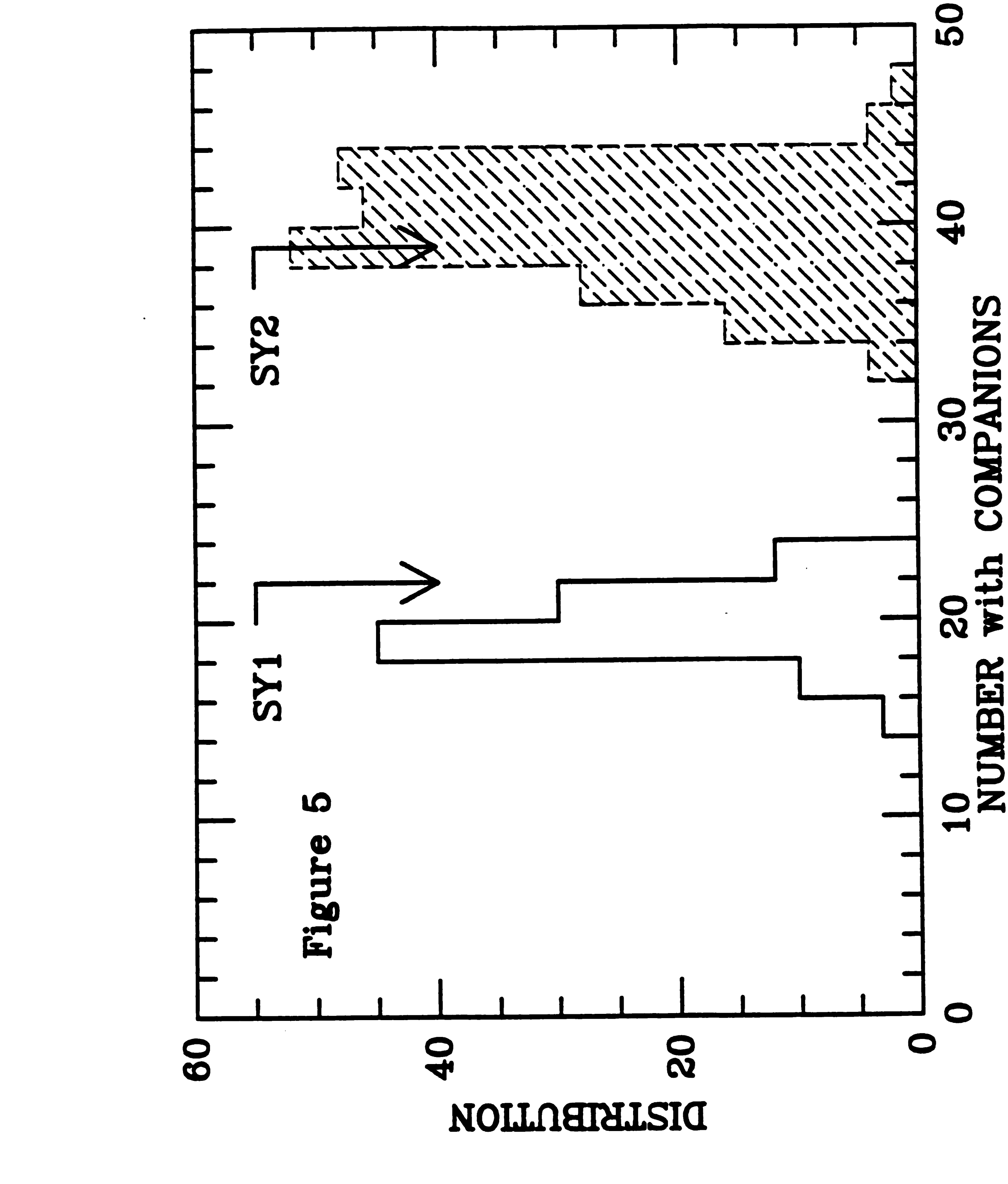


Figure 5
SY1
SY2
DISTRIBUTION
NUMBER with COMPANIONS
0
20
40
60
0
10
20
30
40
50

Figure 6: Number distribution for multiple companions in Case E.

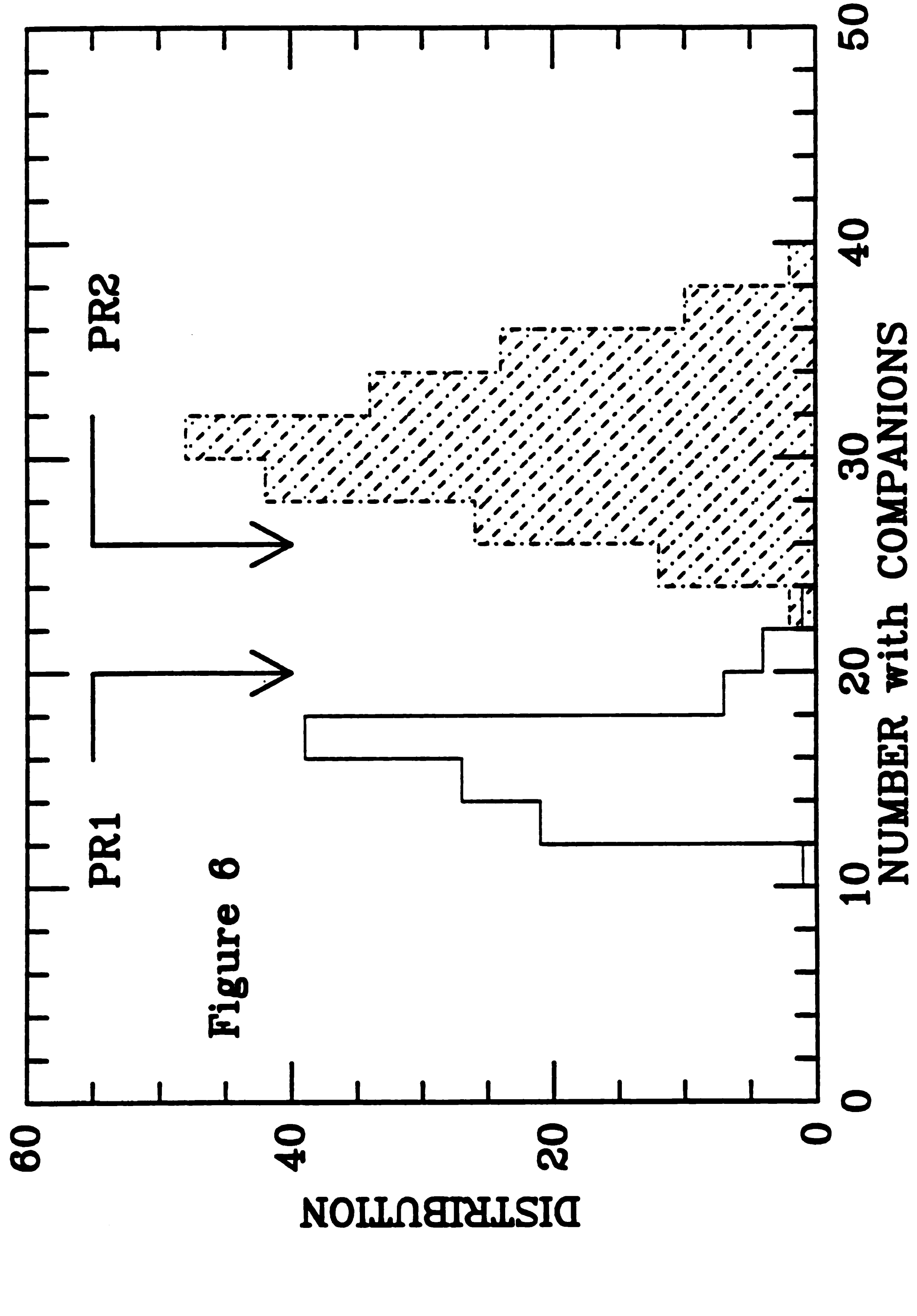

PR1
PR2
DISTRIBUTION
NUMBER with COMPANIONS
0
20
40
60
0
10
20
30
40
50

Figure 6

Figure 7: Plot of "projected angular momentum" for the Seyferts and Case E.

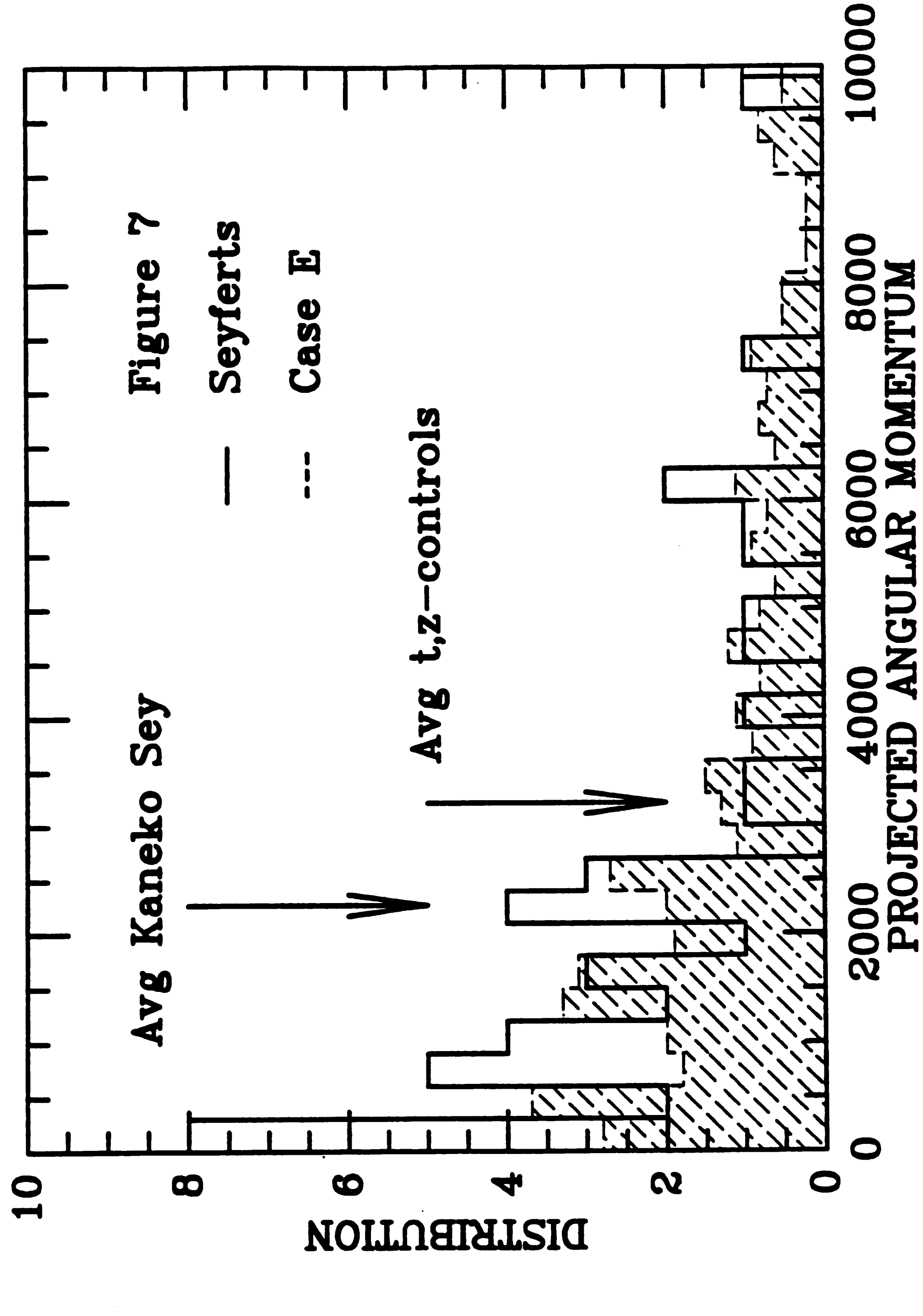


Figure 7
Seyferts
Case E
Avg Kaneko Sey
Avg t,z–controls
PROJECTED ANGULAR MOMENTUM
DISTRIBUTION
0
2000
4000
6000
8000
10000
0
2
4
6
8
10

Figure 8: Number distribution of companions of Seyferts and Case E with total angular momentum $\leq 2000 kms^{-1} * kpc$. There is an excess of low J values for the Seyferts as opposed to the control sample.

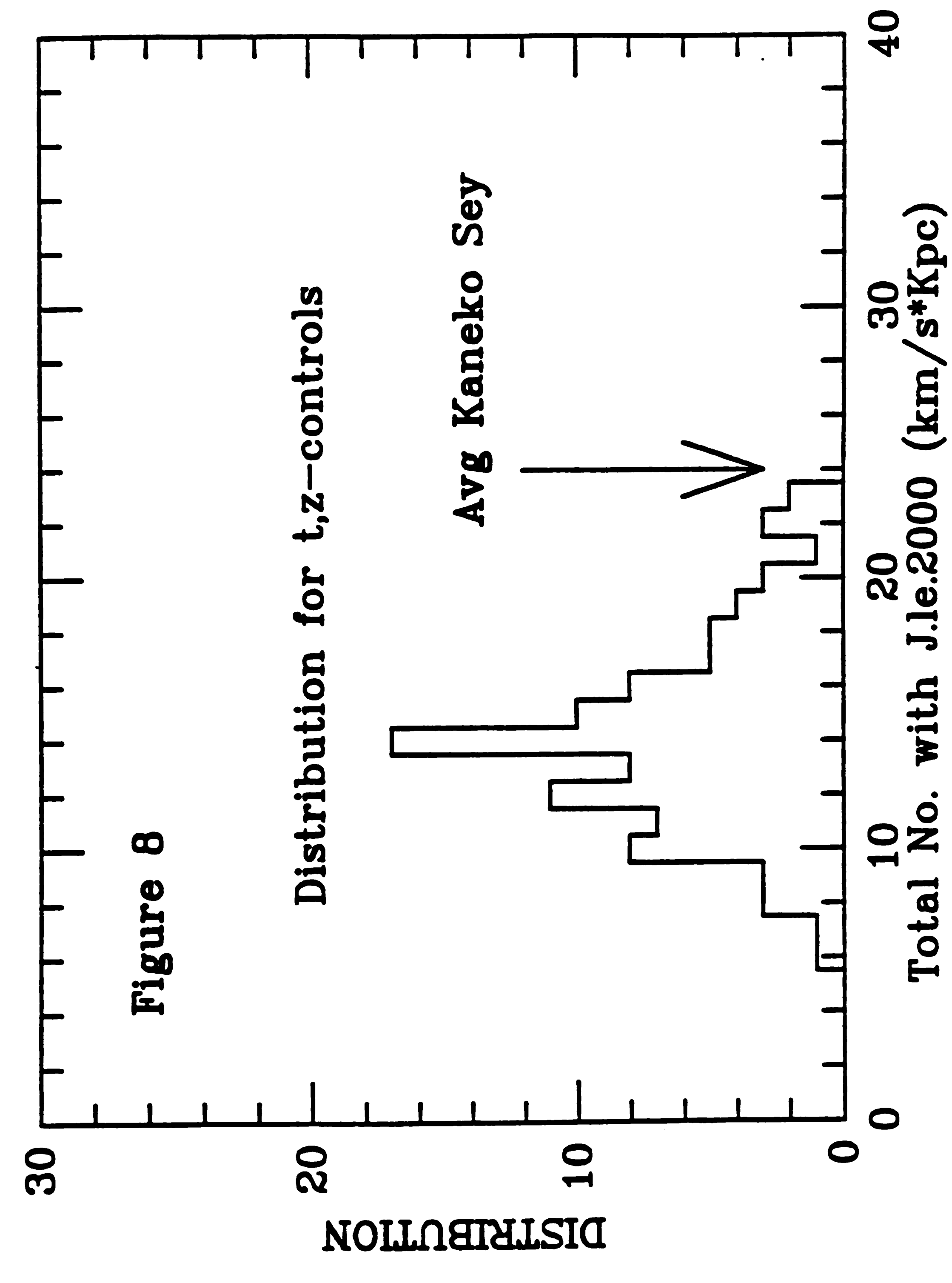


Figure 8
Distribution for t,z-controls
Avg Kaneko Sey
DISTRIBUTION
0
10
20
30
Total No. with J.le.2000 (km/s*Kpc)
0
10
20
30
40

that this occurs by chance is less than 4%. This implies that the companions to the Seyferts are different in some respect to those for the controls. One possibility is that the companions of the Seyferts are more bound than the control companions.

IV. Angular Separation

Converting to projected physical separation using a distance based on H_o = 100, the Seyfert galaxy pairs were examined for any evidence of a difference in radial separation as a function of Seyfert class (such as appears in in Figure 1). No such distinction was found. Plotting projected separation against radial velocity difference for each Seyfert galaxy and its closest companion gives the results shown in Figure 9. Again, this plot shows no evidence for any difference in projected separation between Seyfert 1 and Seyfert 2 galaxies. Figure 10 plots the pairs with the smallest J values. Note the resemblance to Figure 9. Since the data in Figure 1 represent a compilation of **multiple** pairs subject to incommensurate selection effects, while those in Figure 9 represent only **closest** pairs from a much larger sample with uniform selection, it was concluded that there is no evidence for a kinematic distinction between Seyfert 1 and Seyfert 2 galaxies.

Figure 9: Plot of projected separation against radial velocity difference for each Seyfert galaxy and its closest companion. No evidence for a kinematic distinction between Seyfert 1 and Seyfert 2 galaxies is observed.

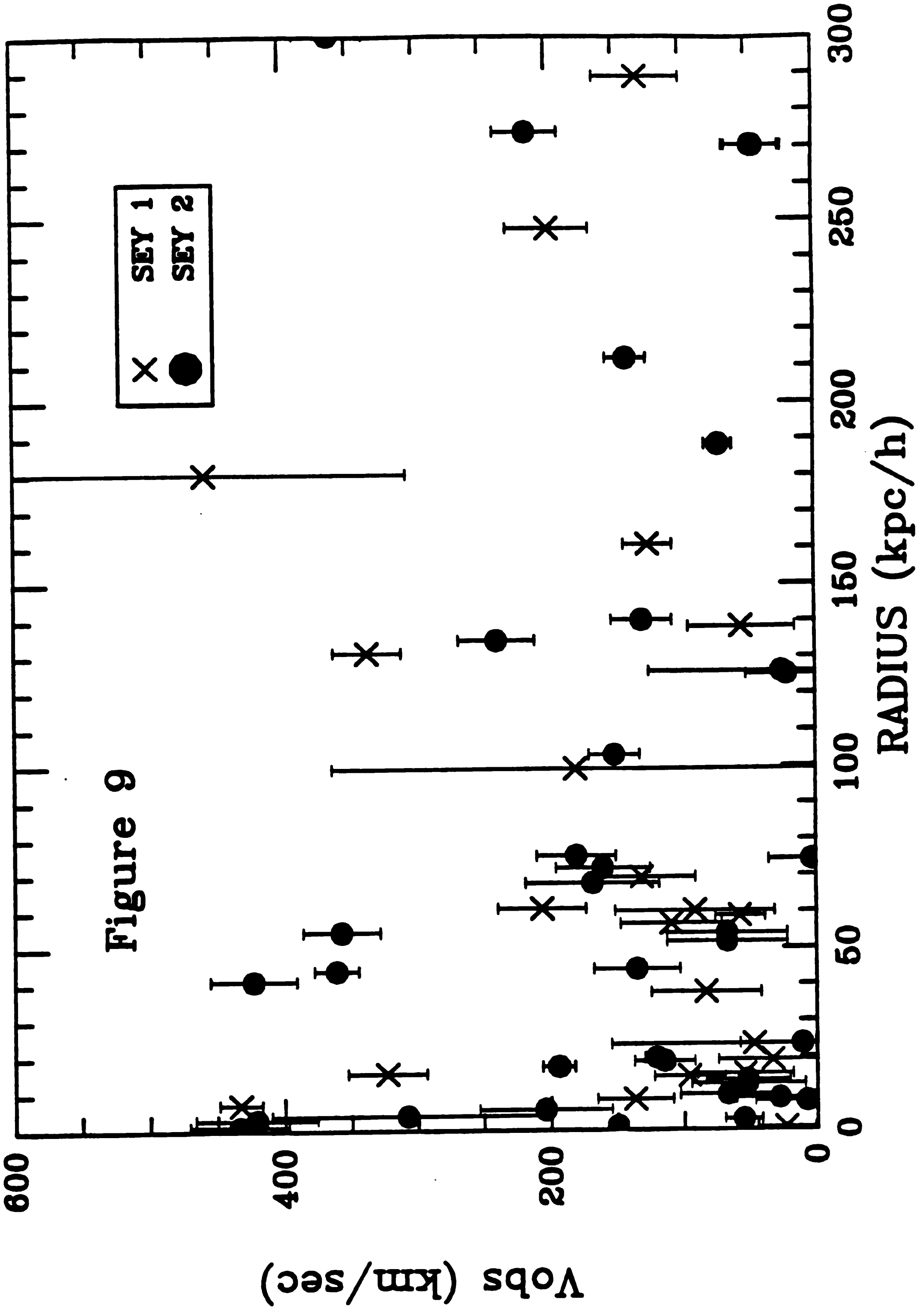


Figure 9
SEY 1
SEY 2
RADIUS (kpc/h)
Vobs (km/sec)
0
50
100
150
200
250
300
0
200
400
600

Figure 10: Plot of the companions with the smallest "projected angular momentum" in Case E.

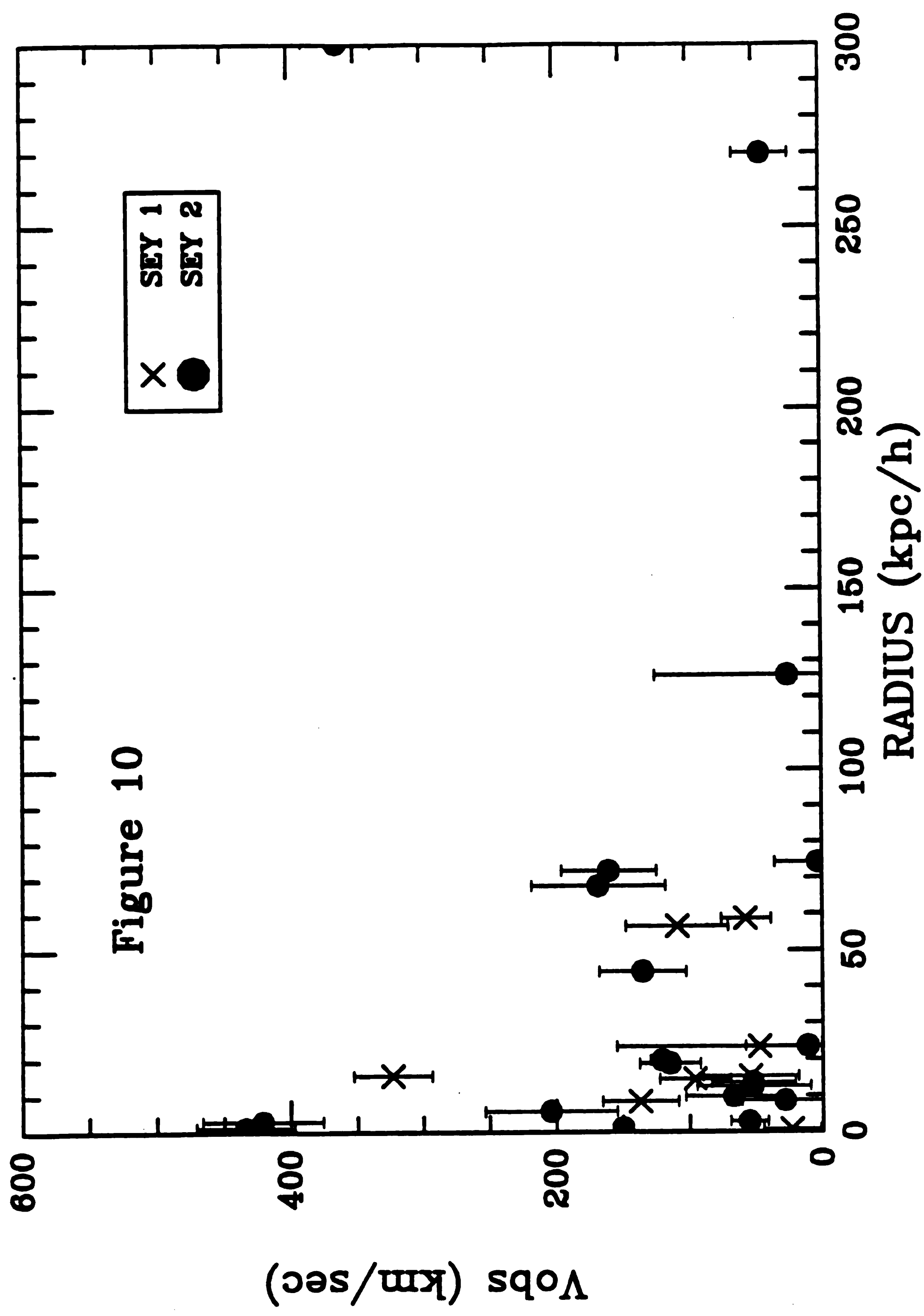

SEY 1
SEY 2
RADIUS (kpc/h)
0
50
100
150
200
250
300
Vobs (km/sec)
0
200
400
600

Figure 10

CHAPTER 3: MORPHOLOGY OF THE COMPANIONS FOR SEYFERT AND CONTROL GALAXIES

Fuentes-Williams and Stocke (1988) have measured and compared the galaxian environment around their sample of Seyferts and control spirals. Measurements were made using the two-dimensional Grant measuring engine at the Kitt Peak National Observatory on the blue copies of the Palomar Observatory Sky Survey. They considered a circle of 1 Mpc projected radius centered on each Seyfert or control and measured only those galaxies whose sizes were greater than about 1/4 the size of the central galaxy. Morphologies of these galaxies were classified as either spiral or elliptical and a rough determination of Hubble types for galaxies with small angular diameters ($\leq$10 arcsec) was made simply by looking at apparent ellipticity. It was observed that there was a nonnegligible population of ellipticals as companions to the Seyferts as opposed to mostly spiral companions for normal spiral galaxies.

To investigate this effect in greater detail, a sample of 51 normal spiral galaxies was constructed using the CfA redshift survey with $cz \leq 4000 kms^{-1}$. The control sample was matched with the Seyfert sample so that the only differentiating characteristic was nuclear activity. To be precise, a good match was sought between redshift, morphology and inclination to the line of sight. A search for companions was performed in the same manner as for the Seyferts. The Virgo cluster is excluded in this analysis as it will bias the results in preferentially finding elliptical companions. The morphologies of all companions for the Seyferts and controls were found using the NASA Extragalactic Database through the IRAS Processing and Analysis Center (IPAC). Morphologies were able to be determined for 277 of the Seyfert companions and 192 of the control companions. The results are shown in Table 5.

Table 5: Comparison of morphologies of Seyfert and control companions

Morphology	Seyfert Number	(%)	Control Number	(%)
Spiral	156	(56)	112	(58)
S0	71	(26)	65	(34)
Elliptical	29	(11)	18	(9)
Spiral + Ellip.	185	(67)	130	(68)
Spiral + S0	227	(82)	177	(92)

No evidence for a significant population of ellipticals as Seyfert companions as opposed to control companions is observed. One possibility is that many of the ellipticals observed by FW-Stocke were really S0's mistaken for ellipticals due to their rough determination of morphologies. The Seyferts do exhibit 2.5 times more S0's than ellipticals as companions. S0's (or lenticulars) are smooth and featureless, like elliptical galaxies, but obey the exponential surface-brightness law characteristic of spiral galaxies. This is given by:

$$I(R) = I_0 exp(-R/R_d),$$

where R_d is the disk scale length. The surface-brightness profiles for most ellipticals, on the other hand, are fit by the $R^{1/4}$ or deVaucoulers law,

$$I(R) = I(0)exp(-kR^{0.25}) \equiv I_e exp\{-7.67[(R/R_e)^{0.25} - 1]\},$$

where the effective radius R_e is the radius of the isophote containing half of the total luminosity and I_e is the surface brightness at R_e (Binney and Tremaine, 1987). This approach to determining morphology may eliminate the effect observed by FW-Stocke.

The lack of a significant population of elliptical companions around Seyferts seems to suggest that the similarity in Seyfert and control environment, which is demonstrated in the following chapter, is real. The percentages of galaxies in a given location that are elliptical seem to decrease monotonically from the central regions of rich clusters to the "field" (Dressler 1984). Had an overabundance of elliptical companions been observed around Seyferts, the environment of the Seyferts would have been expected to be of a higher density than that for normal spiral galaxies. A higher density environment around Seyferts was observed by FW-Stocke in their analysis because they found a significant population of ellipticals as companions to the Seyferts.

CHAPTER 4: FURTHER ANALYSIS OF GALAXY PAIRING

In order to examine the frequency of pairing of Seyfert galaxies as opposed to non-Seyferts, the following tests were set up:

CASE 1: MATCH T, z, i

As an initial selection criterion, a program was constructed to search the CfA Redshift Catalog and retrieve those galaxies which matched their respective Seyfert in morphology (denoted in the CfA by deVaucoulers T notation), recessional velocity and inclination to the line of sight. Histograms both including and excluding the Virgo cluster were made. These are shown as Figures 11 and 12 respectively. This was done for reference in the later cases. Each Seyfert had a list of potential controls after this was done. From this list, the best match for the Seyfert was obtained and the CfA was searched for companions of these galaxies. The "best" match refers to the galaxy which most closely matches the selection criteria (in this case, T, z and i). This definition applies for the following cases as well. The results are shown in Table 7. The number of control companions is observed to occur with relatively the same frequency as the Seyfert companions.

CASE 2: MATCH z, i

The CfA was again searched for possible controls matching recessional velocity

Figure 11: Velocity distribution of the Seyferts. The Virgo cluster is included.

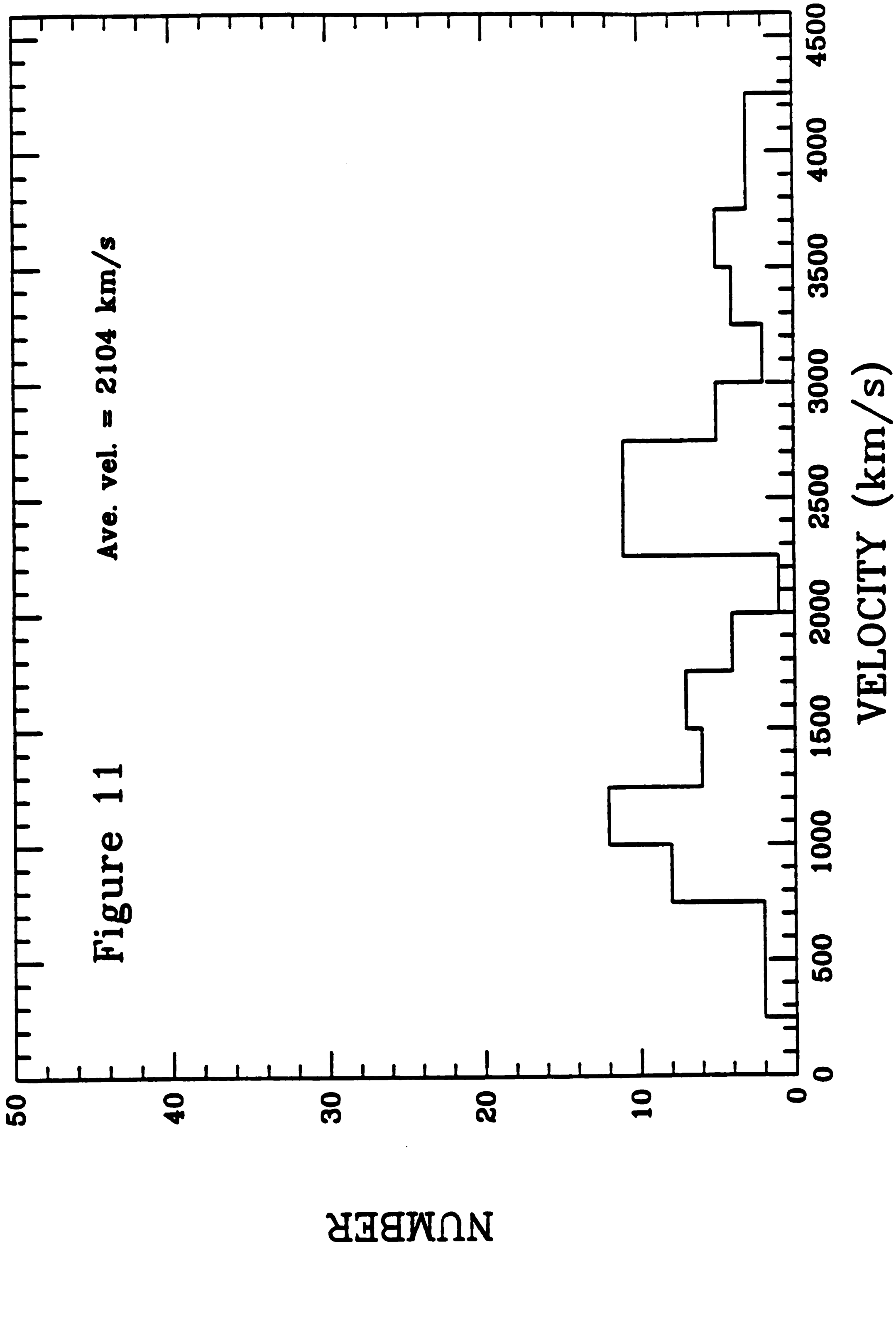

Ave. vel. = 2104 km/s
VELOCITY (km/s)
NUMBER
0
500
1000
1500
2000
2500
3000
3500
4000
4500
0
10
20
30
40
50

Figure 11

Figure 12: Velocity distribution of the Seyferts. The Virgo cluster has been excluded.

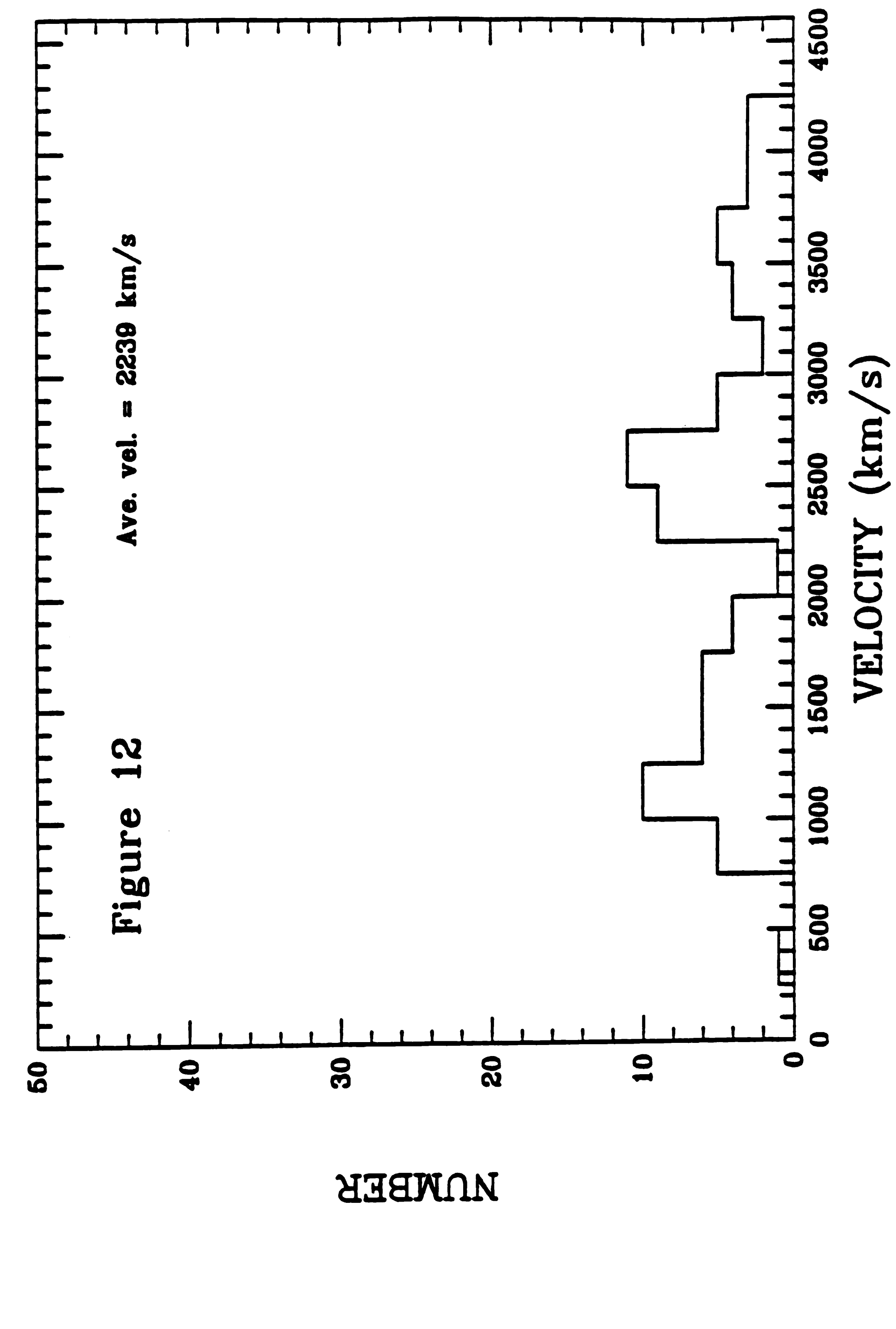

Ave. vel. = 2239 km/s
NUMBER
VELOCITY (km/s)
0
10
20
30
40
50
0
500
1000
1500
2000
2500
3000
3500
4000
4500

Figure 12

and inclination. The best match for each Seyfert was chosen and the CfA searched for companions. The results are listed in Table 7. Again the frequency of companions occurring is the same as in Case 1 above.

CASE 3: MATCH T, i

Again the CfA was searched for controls, this time matching morphology and inclination to the line of sight. The velocity was constrained to within $6000 kms^{-1}$ and the average velocity of the sample was over $1000 kms^{-1}$ greater than that of the Seyferts. The best match for each Seyfert was selected and the controls searched for companions as above (See Table 7). The number of controls with no companions as opposed to the Seyferts has increased.

CASE 4: MATCH i

The CfA was searched for controls as above, in this case matching only inclination to the line of sight. The velocity restrictions were the same as in Case 3 above. Companions were found for the best match and the results outlined in Table 7. There are more galaxies that were found to have no companions.

It should be noted that the Virgo cluster has been excluded in the above analysis, as it introduces a bias toward finding multiple companions. Histograms of the apparent and absolute magnitudes of the companions in each of the above cases were made and are shown in Figures 13 and 14 respectively. Each histogram has been normalized to 100 galaxies. As can be seen, the average apparent magnitude in the velocity constrained cases is brighter than for the unconstrained cases. The average absolute magnitude is brighter for the case matching T and i. This was due to the

Figure 13: Histograms of the apparent magnitude of the companions for the given cases. The apparent magnitudes of the companions at greater velocities are fainter as is expected.

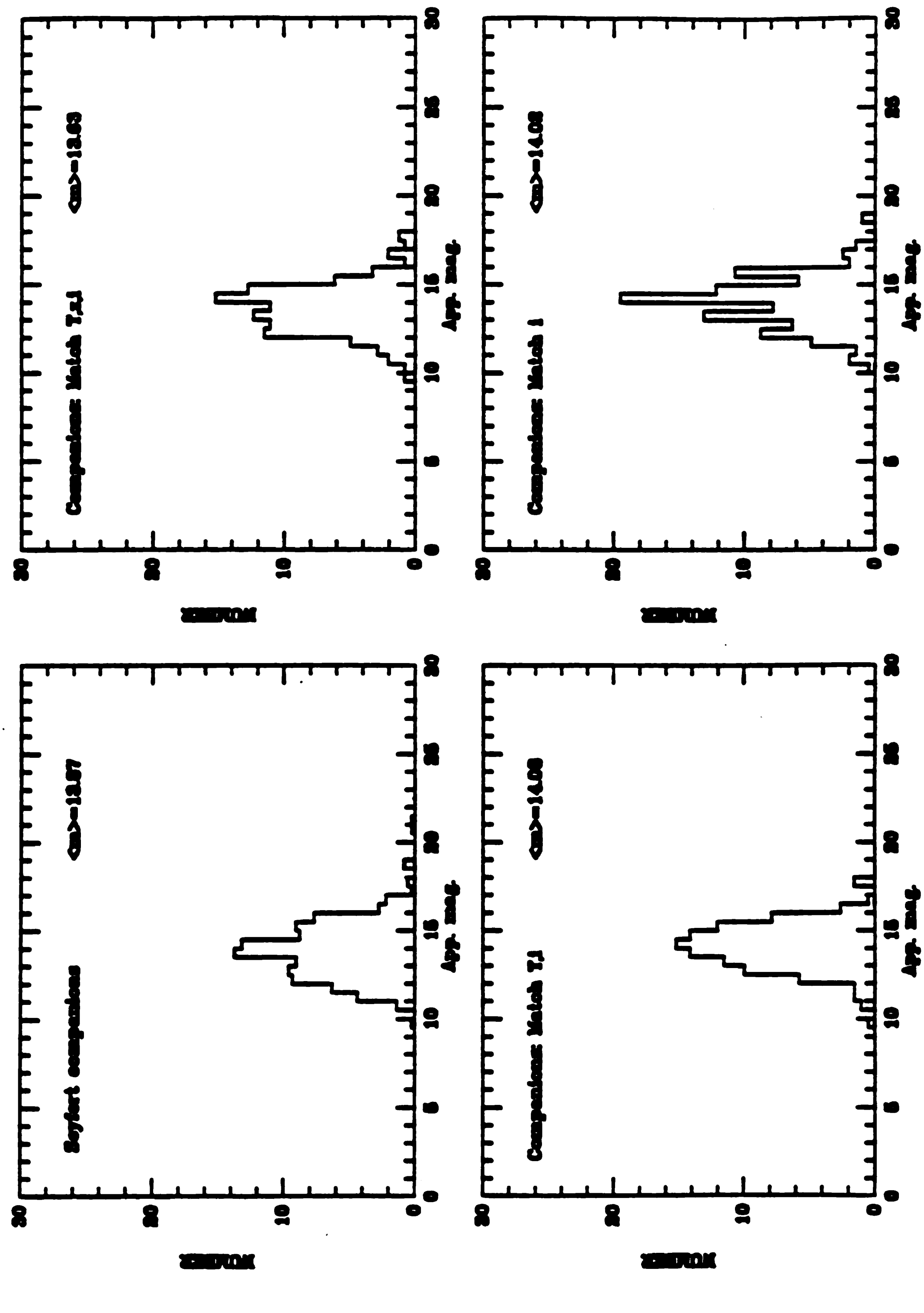


Figure 13

Figure 14: Histograms of the absolute magnitude of the companions for the given cases. The absolute magnitudes of the companions at larger velocities are brighter due to their greater distance.

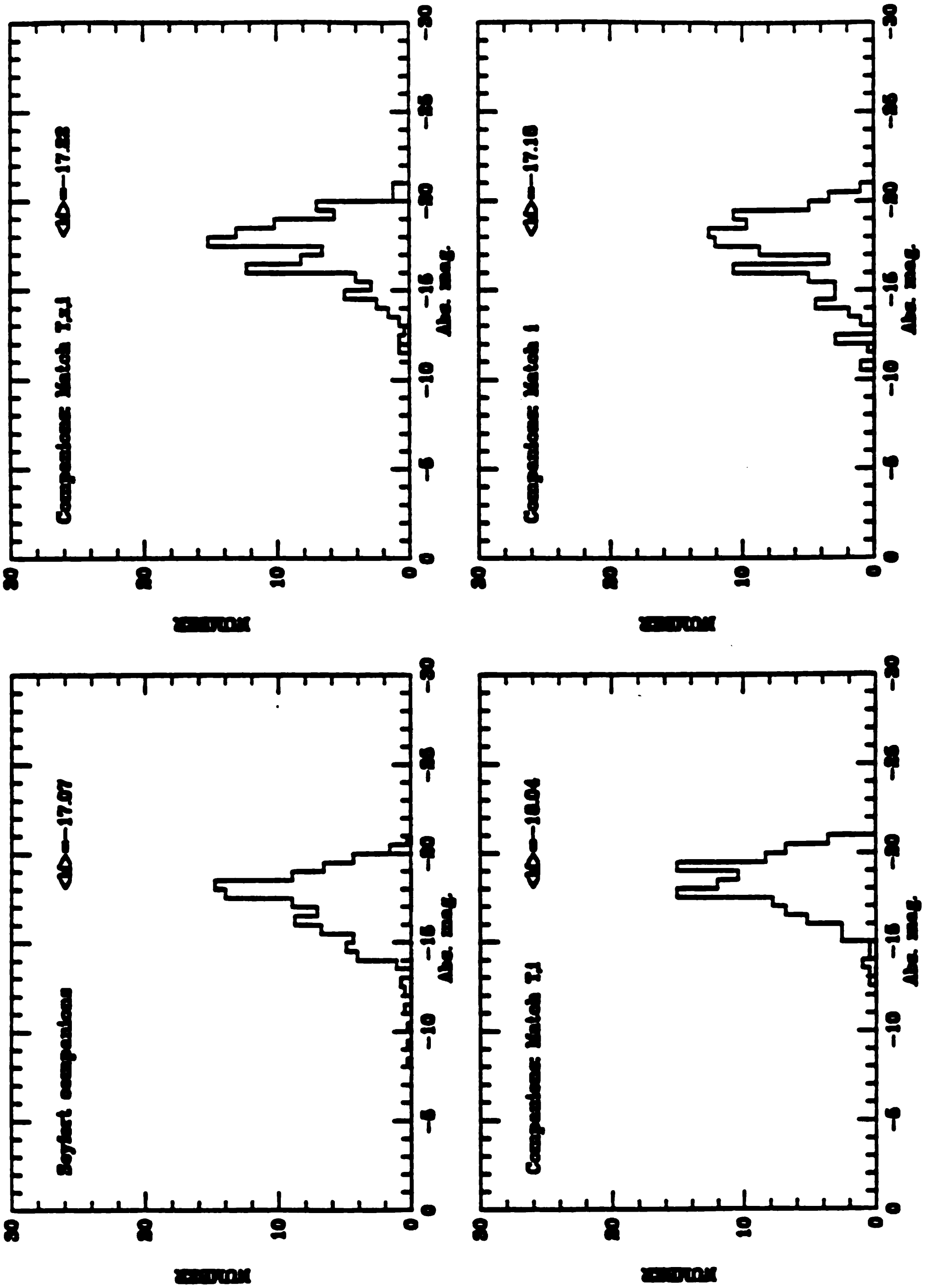


Figure 14

average velocity of the companions being greater in this case. The greater frequency of zero companions for the unconstrained velocity sample is postulated to be due to a selection effect in that dimmer companions are not observed around the more distant galaxies.

To obtain more significant results, the following test has been constructed. A program was written to select 20 ensembles of control galaxies for each Seyfert. The controls were selected at random from the lists constructed in each of the above cases. These ensembles were then searched for companions as before. A match for T, z and i was expected to yield the same results as in Case 1 above since there were very few controls possible for each Seyfert. For this reason, the above test was not done for this case.

The above test was run for Cases 2 and 3 above. The results are listed in Table 6 below.

Table 6: Companion Number Breakdown (20 runs)

Match z,i

Number with 1 Companion	11.5 (14)
Number with $\geq$ 1 Companion	50 (60)
Number with 0 Companions	21.5 (26)

Match T,i

Number with 1 Companion	14.2 (18)
Number with $\geq$ 1 Companion	38.2 (48)
Number with 0 Companions	26.7 (34)

Comparing the above results with those in Table 7, it is observed that there is good agreement between the results. The discrepancy between the numbers for the case of multiple companions is due to the presence of the Virgo cluster in Table 6. If Virgo is removed as was the case in Table 7, the data would agree very closely. This suggests that no bias exists in selecting the best control match for each Seyfert and examining them for companions. Similar results are hypothesized for Case 4.

The similarity in the pairing rates between the Seyferts and controls matched to the Seyferts in every respect except nuclear activity seems to suggest that tidal interaction with companion galaxies is not sufficient on its own to sustain the fuelling of AGNs. In fact, a large-scale nonaxisymmetric disturbance of a galaxy, such as a stellar bar, appears capable of inducing global shocks, which drives the inflow of gas towards the center. Shlosman et al. (1989) have proposed that the gas which accumulates in the central kpc or so as a result of the inflow in the stellar bar forms a disk which under certain conditions goes dynamically unstable and forms a *gaseous* bar. A condition for this instability was derived using a simple model, and argue that the resulting inflow can extend all the way in to the center (the inner $\sim$ 10 pc.). It may be that companions could induce a stellar bar, at which time the above process occurs, but it is not necessary.

Table 7: Companion Number Breakdown

Match T,z,i

Galaxy Type	Seyferts (%)	Controls (%)
Number with 1 Companion	12 (19)	11 (18)
Number with $\geq$ 1 Companions	34 (55)	39 (63)
Number with 0 Companions	16 (26)	12 (19)

Match z,i

Galaxy Type	Seyferts (%)	Controls (%)
Number with 1 Companion	14 (20)	11 (16)
Number with $\geq$ 1 Companions	40 (57)	39 (56)
Number with 0 Companions	16 (23)	20 (28)

Match T,i

Galaxy Type	Seyferts (%)	Controls (%)
Number with 1 Companion	14 (20)	11 (16)
Number with $\geq$ 1 Companions	40 (56)	32 (45)
Number with 0 Companions	17 (24)	28 (39)

Match i

Galaxy Type	Seyferts (%)	Controls (%)
Number with 1 Companion	13 (19)	9 (13)
Number with $\geq$ 1 Companions	40 (59)	28 (41)
Number with 0 Companions	15 (22)	31 (46)

CHAPTER 5: CONCLUSIONS

A sample of 79 Seyfert galaxies with $cz \leq 4000 kms^{-1}$ and excluding the Virgo cluster was constructed from the "Catalog of Seyfert Galaxies and Related Objects" by N. Kaneko. A search for companions to these Seyferts was then performed using the CfA Redshift Catalog.

The statistical tests which have been run suggest that approximately 60% of the nearby Seyfert galaxies have bright physical companions. This is similar to the number of bright IRAS galaxies with companions (Lawrence, 1987). This study shows none of the kinematic orbital differences found in the published studies of Seyfert companions. It does, however, find a substantial excess of companions for both Seyfert 1 and Seyfert 2 galaxies and supports the conclusion of Kollatschny and Fricke that these objects frequently reside in physical groups.

Number distributions were plotted for the various cases studied in Chapter 2, and it was concluded that a match for T and z is the correct control sample to use when modelling Seyfert pairing rates. There is also evidence that the distribution of single pairs is the same for the Seyferts and controls, BUT there may be a deficiency of multiple pairs for the Seyfert 2's and an excess for the Seyfert 1's.

The "projected angular momentum", J, for the Seyfert and control companions was plotted and an excess of low J values was observed for the Seyfert pairs as opposed to the control pairs. This would imply that the companions to the Seyferts are different in some respect to those for the controls. One possiblity is that there are more bound companions for the Seyferts than the controls.

Seyfert galaxies appear to have pairing rates similar to that for a sample of nearby normal spiral galaxies. This seems to suggest that companion galaxies alone are not sufficient to serve as a mechanism for prolonged refuelling of an AGN. Indeed, large-scale nonaxisymmetric disturbances of galaxies, such as a stellar bar, appear capable of inducing global shocks which drive the inflow of gas towards the central regions. The passage of close companions may induce such stellar bars, but as noted by Shlosman et al. (1989), this is not necessary.

Finally, the morphologies of the companions for the Seyfert and control samples were compared in an attempt to reproduce the results of Fuentes-Williams and Stocke. They observed a significant population of elliptical companions around Seyfert galaxies as compared to their control sample. An examination of the companions of Seyfert and normal spirals yielded no evidence for Seyferts having a nonnegligible population of ellipticals compared to the normal spiral galaxies, which implies that the similarity of pairing rates for the control sample matching T, z and i and the Seyferts is real.

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