ON THE EXCESS OF PHYSICAL COMPANIONS AMONG SEYFERT GALAXIES

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ABSTRACT

The results of a search for close companions in two magnitude limited samples ($m_B \leq 15.5$) of 99 Seyfert 1 and 98 Seyfert 2 galaxies are presented. It is found that there is an excess of physical companions in both samples of galaxies, compared with two control samples of normal field spiral galaxies. The calculated lower limit percentages of physical companions are $(12 \pm 3)\%$ and $(12 \pm 4)\%$ for Seyfert 1 and Seyfert 2, respectively, while the upper limits on the percentage of galaxies with physical companions are in the range $(0\% - 5\%)$ in both control samples. The excess is confirmed by analysis of the redshifts for all pairs found in the complete, magnitude limited $[B(0) \leq 14.5]$ CfA sample of Seyfert galaxies.

1. INTRODUCTION

The suggestion that galaxy interactions or mergers might have something to do with the nuclear activity in Seyfert galaxies had its roots in the *Galactic Bridge and Tails* paper by Toomre & Toomre (1972) in a section titled “Stoking the furnace.” The clear empirical suggestion of that paper was that encounters could have strong effects, not only on the loosely bound outer parts of the galaxies, but also on processes occurring in their central regions.

The explicit connection to nuclear activity in the usual sense was made by Gunn (1979), who suggested interaction as one plausible means of channelling external gas into the nucleus of a galaxy.

Hernquist (1989) demonstrated that gas, distributed throughout a galaxy, responds strongly to the tidal field of a much less massive companion during a merger. In some cases dynamical instability will drive a large fraction of the gas into the inner regions of the primary galaxy, even if the companion is gas free. A strong burst of star formation will follow and subsequent evolution may lead to the formation of a black hole. Continued accretion of gas by the black hole may provide sufficient fuel to explain nuclear activity in otherwise normal galaxies.

More recently, Barnes & Hernquist (1991) modeled the dynamics of gas in a merger of two disk/halo galaxies of equal mass showing how violent tidal forces trigger the formation of central bars. As bars form, gas in the inner half of each disk loses most of its angular momentum through gravitational torques, falling into a compact cloud within the center of the galaxy and producing a violent burst of star formation. If some of the nuclear gas can continue to lose angular momentum it may be able to fuel or even form a *central black hole* resulting in a radio galaxy or possibly even an active nucleus.

Physical mechanisms, which are able to trigger a burst of massive star formation in the central regions of interacting spiral pairs have been investigated in the last years also by

Jog & Das (1992), Jog & Solomon (1992), and Mihos *et al.* (1992).

Many observations suggest that galactic encounters enhance star formation rates, as demonstrated by studies of the optical (e.g., Larson & Tinsley 1978; Kennicutt *et al.* 1987; Bushouse, 1987), infrared (e.g., Lonsdale *et al.* 1984; Xu & Sulentic 1991; Bernlöhr 1993; Telesco *et al.* 1993) and radio (e.g., Sulentic 1976; Hummel 1981; Smith & Kassim 1993) emission from interacting systems.

A study of the environment around 516 Starburst Markarian galaxies belonging to a redshift bounded sample (Keel and Van Soest 1992) shows that 33% are in pairs, which is an evident excess compared to the 7% found in a control sample of disk systems. The situation for Seyfert galaxies is unclear. Different statistical studies by Petrosian (1982), Dahari (1985), and MacKenty (1989, 1990), suggested that there was an excess of companions around Seyfert galaxies and an excess of Seyfert galaxies among galaxies that have nearby companions.

The contrary result was obtained by Bushouse (1986) and Fuentes-Williams and Stocke (1988). The conflicting results are probably due to differences in control sample definition, as pointed out by Heckman (1990) and Osterbrock (1993), or to the use of early catalogs quite poor in Seyfert 2 galaxies. This is no doubt at least part of the reason why both Petrosian (1982) and MacKenty (1989, 1990) found Seyfert 2 galaxies more likely to have companions than Seyfert 1 galaxies, whereas Dahari did not find any statistically significant difference.

Our present work has two goals: to test the claimed excess of physical companions near Seyfert galaxies and to determine whether Seyfert 2 (S2) galaxies are more often physically paired than Seyfert 1 (S1) systems.

Throughout this paper we define generically as *companion* a galaxy that can be either physically bound or optically aligned to another galaxy. Otherwise the label *physical companion* or *optical companion* will be used.

The first step in this project has been to select the possible

companions of all presently known Seyfert galaxies (287 S1, 195 S2), with $z \leq 0.11$ and $\delta \geq -23^\circ$ on the blue Palomar Observatory Sky Survey prints (hereafter referred to as POSS). The first restriction $z \leq 0.11$ was introduced to avoid too distant galaxies, which have a stellar shape on the POSS prints. The second restriction was due to the need to use the Shane & Wirtanen (1967) counts of galaxies to guess the projection effects on the search for physical companions around each Seyfert galaxy.

The method used to identify possible physical pairs on the POSS prints is described in Sec. 2. The samples of S1 and S2 galaxies and the results of the analysis of the environment of each galaxy are given in Sec. 3.1, where an estimate of optical pairs contamination is given. Two control samples of normal spiral galaxies, one for S1 and one for S2 galaxies, are defined in Sec. 3.2 and investigated using the same procedures applied to the Seyfert galaxies. The statistical significance of the different percentages of physical companions found in Seyfert and control samples are discussed in Sec. 4. Finally, available redshifts for suspected physical companions have been used to further test the significance of our statistics.

2. METHOD OF IDENTIFICATION

Two parameters that can be measured on the POSS prints and used in a comparative way are the separation S between pairs of galaxies, normalized to the major axis d of the main component and a rough estimate of the difference in magnitude Δm . In order to select pairs of galaxies that are likely to be physical binaries, it is necessary to know the upper limits of both these parameters derived analyzing a sample of pairs of galaxies that have been initially selected on the blue POSS prints, and are defined as physical companions. Such a sample is given in the *Atlas and Catalogue of Interacting Galaxies* by Vorontsov-Velyaminov (1959; hereafter referred to as V-V), which lists 355 interacting galaxies defined as *objects connected by bridges of matter*, selected on the blue POSS prints. The following data can be easily extracted from this atlas:

- (1) m_A = apparent magnitude of the main component of the system. The main component is defined either as the brighter galaxy or as the central one if the system is multiple.
- (2) $\Delta m = m_{\text{comp}} - m_A$, difference of magnitude between the companion and the main component.
- (3) S = separation between the components of the system.

All companions of the 355 V-V objects are found to fall in a circle of radius $3d$, centered on the main component. Hence, $S < 3d$ is the first condition to be imposed in our attempt to identify possible physical companions of Seyfert galaxies.

The number of interacting V-V galaxies as a function of the magnitude of their principal component, Fig. 1, increases up to $m_A \sim 15.5$, and shows a rapid decrease for $m_A > 15.5$, indicating that systems whose principal component is fainter than $\sim 15.5^m$ are likely to be lost, because either m_{comp} is fainter than the limit magnitude of the blue POSS prints or the bridges of matter are fainter than the level of the sky noise. This is confirmed by Fig. 2, which gives the number of

FIG. 1. Number of interacting V-V galaxies as a function of the magnitude m_A of their principal component.

V-V galaxies as a function of Δm for different intervals of magnitude of the principal component. The histogram increases almost proportionally up to $15 < m_A < 16$, as can be expected when looking in larger and deeper shells of sky, while their shape changes for $m_A > 16$. This is strong evidence that a direct search for pairs of galaxies connected by bridges of matter on the POSS prints is biased for galaxies fainter than $m \sim 15.5$.

The upper limit of Δm can then be easily derived from Fig. 3, which shows that $\sim 90\%$ of the companions of the V-V galaxies have $m_{\text{comp}} < m_A + 3$, from which it follows that $(\Delta m)_{\text{max}} = 3$. The same limit $\Delta m < 3$, but a less strict condi-

FIG. 2. Number of interacting V-V galaxies as a function of the difference in magnitude between the principal component and the companion $\Delta m = m_{\text{comp}} - m_A$ for different magnitude ranges of the principal component.

FIG. 3. Number of interacting V-V galaxies as a function of their difference in magnitude Δm .

tion on the separation $S < 4d$ would have been obtained analyzing the 528 systems listed in the *Catalogue of Isolated Pairs of Galaxies* by Karachentsev (1987, hereafter referred to as CPG), which represents a sample complete up to $m \sim 15.0$ of pairs, having a difference in radial velocity $|c \cdot \Delta z| \leq 1000 \text{ km s}^{-1}$. This result and the finding that only 12% of the CPG galaxies belong also to the V-V catalog strongly suggest that the condition of presence of bridges of matter for defining interaction is more stringent than the condition $|c \cdot \Delta z| \leq 1000 \text{ km s}^{-1}$ for physical coupling of pairs.

Extending then the results $S < 3d$, $\Delta m < 3$ to all galaxies detectable on the blue POSS prints and not fainter than $m_A = 15.5$ we can affirm that all galaxies that have a companion at a distance $S < 3d$ and not fainter than $m_A + 3$ are likely to be members of physical pairs.

3. RESULTS

3.1 Sample Selection

The method of search described in the previous section has been applied to all S1 ($N_{S1}=287$) and S2 ($N_{S2}=195$) galaxies with $z \leq 0.11$ and $\delta \geq -23^\circ$ listed by Veron-Cetty & Veron (1991, hereafter referred to as VCV).

Our definition of companion required the measurements of the angular diameter (major axis) of each galaxy involved and an estimate of the difference in magnitude between the components of each pair of galaxies. Both these parameters were measured on magnifications $5\times$ of the blue POSS prints. A rough eye evaluation of the difference in magnitude (larger or smaller than 3) was obtained independently by the authors. Similarly, the angular diameters were measured independently taking as the boundary of each galaxy the faintest envelope visible on the print.

The number of galaxies with companion N_C identified in this way is quoted in Table 1, where N is the total number of galaxies, and $F_C(\%)$ is the percentage of objects with a companion. It must be remarked that all Seyfert galaxies with

TABLE 1. Start-sample of Seyfert galaxies.

	Seyfert 1	Seyfert 2
$\delta \geq -23^\circ$ $z \leq 0.11$		
N	287	195
N_C	71	56
$F_C(\%)$	25%	29%

companion with $z \leq 0.03$ and $\delta \geq -23^\circ$ found by Dahari (1985) have been again identified using our procedure.

Since the Seyfert galaxies listed in the VCV were extracted from a complete survey of the literature, but are not complete in any sense, they are not well suited for statistical studies. Anyway, we do not necessarily need a complete sample of active galaxies for a meaningful statistical study, but rather a large enough sample of objects, identified as active in spectroscopic surveys or in surveys that were not based on a morphological type (e.g., surveys of disturbed or multiple systems).

In order to obtain such a sample, we have extracted from the previous compilation of Seyfert galaxies only the objects whose classification in the literature was based on spectro-

FIG. 4. Cumulative number of spectroscopically selected Seyfert 1 ($N_{S1}=149$) and Seyfert 2 ($N_{S2}=112$) galaxies as a function of their magnitude. The straight line represents the function $\log N = 0.6 \cdot m + \text{const}$, which describes complete samples.

scopic surveys, namely 149 S1 and 112 S2 galaxies. The cumulative number of S1 and S2 galaxies, Fig. 4, as a function of the apparent magnitude, shows that almost all Seyfert galaxies with $m > 15.5$ are lost. We have then extracted from the Seyfert galaxies with $z < 0.11$ those with $m \leq 15.5$, obtaining $N_{S1}=129$ and $N_{S2}=90$. In order to further check the Seyfert type of these galaxies, we have used the *Catalogue of Seyfert Galaxies*, Lipovetski *et al.* (1987), which classifies Seyfert galaxies using the sequence suggested by Osterbrock (1984), namely S1, S1.5, S1.8, S1.9, and S2. We have adopted the convention that $S1=S1+S1.5$ and $S2=S1.8+S1.9+S2$. The objects, which were not classified as Seyfert in both catalogs, e.g., objects classified as Seyfert in one catalog and as Liner in the other one, were rejected. After this operation the final sample amounted to 99 S1 and 98 S2

galaxies, which are listed in Tables 2(a) and 2(b), respectively: the name of the object and its coordinates (1950.0) are given in columns (1), (2), and (3); the apparent visual magnitude and the redshift z , taken from VCV, are reported in columns (4) and (5); the diameters D_P and D_C of each Seyfert galaxy and of its eventual companion, measured by us, are given in columns (6) and (7), while the separation S between the centers of each pair is in column (8). Units of D_P , D_C , and S are mm, the scale is ~ 13.4 arcsec/mm, as measured on magnifications $5\times$ of the POSS blueprints. This sample has been used for our statistical study. The percentage F_C of companions found on the POSS prints is 29% and 33% for S1 and S2 galaxies, respectively; see Table 3.

In order to estimate the percentage of physical companions, the *upper limit* number of optical companions has been

TABLE 2 (a). Sample of 99 Seyfert 1 galaxies.

Object	α (1950.0)	δ (1950.0)	V	z	D _P	D _C	S	Object	α (1950.0)	δ (1950.0)	V	z	D _P	D _C	S
	h m s	° ′ ″							h m s	° ′ ″					
Mkn 335	00 03 45.2	19 55 29	13.85	0.025	1.2			NGC 4258	12 16 29.4	47 34 53	11.30	0.002	37.0	3.0	12.0
Mkn 1146	00 44 42.2	14 25 50	15.28	0.039	2.6			NGC 4278	12 17 36.2	29 33 29	10.51	0.002	7.5	3.3	12.0
Mkn 352	00 57 09.1	31 33 28	14.66	0.015	1.4			Mkn 205	12 19 33.8	75 35 18	15.24	0.070	1.1	6.0	3.3
Mkn 975	01 11 12.4	13 00 26	14.50	0.050	2.0			Mkn 50	12 20 50.7	02 57 22	15.17	0.023	1.0		
Mkn 1152	01 11 21.8	-15 06 39	15.00	0.052	2.2	1.2	1.3	NGC 4593	12 37 04.6	-05 04 11	13.19	0.009	17.0	3.0	18.0
Mkn 358	01 23 45.0	31 21 25	15.23	0.042	2.8			NGC 4594	12 37 23.3	-11 20 55	09.64	0.002	33.0		
Mkn 359	01 24 50.3	18 55 12	14.21	0.017	2.6			NGC 4639	12 40 21.7	13 31 56	11.00	0.001	6.0		
Mkn 590	02 12 00.4	-00 59 57	13.55	0.027	4.1	0.8	4.8	IR1249-1308	12 49 35.2	-13 08 36	14.47	0.014	2.7		
Mkn 1400	02 17 34.6	07 58 36	15.28	0.029	2.5			Mkn 236	12 58 18.0	61 55 26	15.45	0.052	1.5		
Mkn 1040	02 25 16.5	31 05 18	14.74	0.016	9.8	1.8	1.7	Mkn 783	13 00 30.4	16 40 34	15.50	0.067	0.7		
Mkn 1044	02 27 38.2	-09 13 11	14.67	0.016	1.7			NGC 5033	13 11 09.2	36 51 30	12.37	0.003	41.0		
NGC 985	02 32 10.5	-09 00 21	14.95	0.043	3.2			NGC 5077	13 16 52.9	-12 23 38	12.58	0.008	6.0	5.4	14.5
Mkn 595	02 38 55.8	06 58 27	14.40	0.028	1.7	1.0	2.0	Mkn 1347	13 20 24.9	08 25 19	14.38	0.050	1.9		
Mkn 618	04 34 00.0	-10 28 36	14.65	0.035	2.6	0.7	4.3	NGC 5273	13 39 55.1	35 54 21	13.44	0.003	10.0	3.6	15.5
IR0521-1212	05 21 47.0	-12 12 41	14.46	0.049	0.5			Mkn 662	13 51 46.4	23 40 32	15.24	0.055	1.0		
Mkn 6	06 45 43.9	74 29 10	14.02	0.019	1.8			Mkn 279	13 51 53.6	69 33 13	14.45	0.031	2.7	1.3	3.6
Mkn 374	06 55 34.5	54 15 57	14.38	0.044	1.6			NGC 5548	14 15 43.5	25 22 01	13.46	0.017	5.0		
Mkn 9	07 32 42.2	58 52 56	14.68	0.039	1.7			Mkn 474	14 33 06.1	48 52 47	15.18	0.041	1.2		
Mkn 79	07 38 47.3	49 55 41	14.78	0.022	3.3			Mkn 817	14 34 57.9	59 00 39	13.79	0.033	2.1		
Mkn 10	07 43 07.4	61 03 25	14.70	0.030	5.2	2.1	10.0	Mkn 477	14 39 02.5	53 43 04	15.03	0.038	1.4	1.1	4.2
Mkn 382	07 52 03.6	39 19 07	15.50	0.034	2.1			Mkn 1494	14 59 13.8	10 37 01	15.50	0.031	2.3	0.65	7.1
NGC 2639	08 40 03.0	50 23 11	11.39	0.011	6.5			Mkn 841	15 01 36.3	10 37 56	14.92	0.036	1.2		
Mkn 391	08 51 32.3	39 43 46	14.14	0.013	3.7			Mkn 1392	15 03 26.0	03 54 00	14.14	0.036	3.1		
NGC 2782	09 10 53.8	40 19 16	13.45	0.008	8.5	1.5	12.5	Mkn 845	15 06 12.6	51 38 37	14.21	0.042	2.8		
Mkn 704	09 15 39.4	16 30 59	14.12	0.029	2.5	1.1	5.5	Mkn 1395	15 08 35.0	04 28 59	15.50	0.043	4.1		
Mkn 110	09 21 44.4	52 30 08	15.37	0.036	1.2			IR1509-2107	15 09 06.6	-21 07 48	14.04	0.044	0.7		
Mkn 705	09 23 20.0	12 57 04	14.55	0.028	2.1			Mkn 1098	15 27 37.9	30 39 23	14.08	0.035	1.2		
Mkn 124	09 45 24.3	50 43 29	15.33	0.056	1.0			NGC 5940	15 28 51.3	07 37 38	14.20	0.033	2.6		
Mkn 1239	09 49 46.3	-01 22 36	14.33	0.019	1.3			Mkn 290	15 34 44.8	58 04 00	14.62	0.029	1.5		
NGC 3031	09 51 27.3	69 18 08	11.72	0.000	6.9			Mkn 486	15 35 20.7	54 43 22	14.68	0.039	1.0		
NGC 3080	09 57 14.2	13 17 05	15.01	0.035	2.2			Mkn 291	15 52 54.1	19 20 16	15.50	0.035	1.4		
NGC 3185	10 14 54.0	21 56 18	12.73	0.004	0.7			Mkn 493	15 57 16.3	35 10 15	15.06	0.031	3.1		
Mkn 141	10 15 39.3	64 13 06	15.27	0.039	1.5	1.4	2.8	Mkn 871	16 06 15.5	12 27 44	14.42	0.034	2.9		
NGC 3227	10 20 46.8	20 07 08	11.29	0.003	12.5	8.0	11.0	NGC 6104	16 14 40.1	35 49 50	14.00	0.028	5.5	2.0	16.7
Mkn 142	10 22 23.0	51 55 50	15.50	0.045	1.0			Mkn 699	16 22 05.3	41 11 48	15.19	0.034	0.9		
Mkn 634	10 55 20.6	20 45 18	15.49	0.066	1.8			Mkn 885	16 29 42.9	67 29 06	14.17	0.026	2.6		
NGC 3516	11 03 22.8	72 50 20	12.23	0.009	7.0	1.7	21.0	NGC 6212	16 41 41.9	39 53 56	15.00	0.030	1.9		
Mkn 732	11 11 13.5	09 51 33	14.00	0.030	2.6			NGC 6240	16 50 27.8	02 28 55	13.37	0.024	5.0		
Mkn 734	11 19 10.9	12 00 46	14.71	0.049	1.1			Mkn 506	17 20 45.6	30 55 40	14.55	0.043	2.3	1.7	3.7
Mkn 40	11 22 47.8	54 39 26	15.39	0.020	1.3	0.7	1.5	NGC 6814	19 39 55.8	-10 26 33	14.37	0.005	7.8		
NGC 3718	11 29 50.0	53 20 42	11.00	0.003	22.0			Mkn 896	20 43 44.5	-02 59 46	14.28	0.027	2.3	0.7	6.0
Mkn 739A	11 33 52.7	21 52 22	14.02	0.030	1.8			Mkn 915	22 34 07.3	-12 48 17	14.03	0.025	3.4	2.1	9.8
NGC 3884	11 43 38.0	20 39 46	12.40	0.023	6.7			IR22374-0747	22 37 46.5	07 47 34	14.00	0.025	3.5		
Mkn 42	11 51 05.7	46 29 24	15.45	0.024	2.1			Mkn 1126	22 58 10.0	-13 11 15	14.11	0.010	2.5		
Mkn 1310	11 58 40.7	-03 23 58	15.08	0.019	1.2			NGC 7469	23 00 44.4	08 36 16	13.72	0.017	3.0	2.7	6.3
NGC 4051	12 00 36.4	44 48 35	12.12	0.002	19.0			Mkn 315	23 01 35.7	22 21 16	14.09	0.040	1.4	0.8	2.4
NGC 4151	12 08 01.0	39 41 02	11.26	0.003	12.5	3.6	23.5	NGC 7603	23 16 22.9	-00 01 47	14.21	0.029	4.2	0.8	4.8
Mkn 1469	12 13 38.7	51 06 10	14.29	0.031	1.9			Mkn 541	23 53 28.4	07 14 41	15.15	0.040	1.2		
NGC 4235	12 14 36.7	07 28 09	13.50	0.007	5.1			Mkn 543	23 59 52.5	03 04 27	14.09	0.026	2.0		
Mkn 766	12 15 55.8	30 05 26	13.00	0.012	3.0										

TABLE 2 (b). Sample of 98 Seyfert 2 galaxies.

Object	α (1950.0)	δ (1950.0)	V	z	D _p	D _c	S	Object	α (1950.0)	δ (1950.0)	V	z	D _p	D _c	S
	h m s	° ′ ″							h m s	° ′ ″					
Mkn 334	00 00 35.6	21 40 54	14.62	0.022	3.7			Mkn744	11 37 04.9	32 11 11	13.74	0.010	4.8	7.5	6.8
Mkn 938	00 08 33.4	-12 23 08	13.52	0.019	2.7	1.8	9.5	NGC 3855	11 42 08.0	33 36 24	15.20	0.031	1.7		
Mkn 549	00 19 20.0	01 53 21	15.50	0.039	1.0			Mkn 1457	11 44 42.5	52 43 39	15.00	0.049	1.9		
IR0032-0018	00 32 10.6	-00 18 55	15.50	0.043	2.3			NGC 3982	11 53 52.3	55 24 12	11.70	0.003	6.9		
Mkn 955	00 35 02.0	00 00 21	14.09	0.035	2.7			NGC 4117	12 05 14.2	43 24 17	14.30	0.003	5.5	2.3	7.3
Mkn 348	00 46 04.9	31 41 04	14.59	0.014	1.6	0.5	5.0	Mkn 198	12 06 42.9	47 20 12	14.73	0.024	1.4		
IR0107-0348	01 07 13.5	-03 48 25	15.50	0.054	1.0			IR1246-1107	12 46 53.3	-11 07 42	12.71	0.048	3.5		
Mkn 1	01 13 19.6	32 09 33	14.96	0.016	2.3	2.6	8.5	NGC 4388	12 23 14.6	12 56 17	13.90	0.008	16.0	2.3	39.0
NGC 513	01 21 37.3	33 32 21	13.40	0.016	3.5			NGC 4922B	12 59 00.5	29 34 38	15.00	0.024	4.3		
Mkn 993	01 22 42.7	31 52 36	13.96	0.017	7.5			NGC 4941	13 01 37.6	-05 17 01	12.23	0.003	11.0		
Mkn 1157	01 30 38.8	35 24 43	13.90	0.015	4.2			NGC 5005	13 08 37.7	37 19 28	13.67	0.003	23.0		
IR0135-1307	01 35 37.6	-13 07 28	15.30	0.041	1.6			IR1319-1627	13 19 42.3	-16 27 53	13.90	0.017	3.0	2.1	8.4
Mkn 573	01 41 22.9	02 05 56	14.07	0.017	2.3			IR1329+0216	13 29 19.7	02 16 31	15.00	0.086	1.0		
IR0147-0740	01 47 33.7	-07 40 36	15.62	0.017	1.0			NGC 5252	13 35 44.4	04 47 47	14.21	0.022	4.2	0.7	8.9
NGC 788	01 58 36.8	-07 03 24	12.76	0.013	6.5			Mkn 266SW	13 36 15.0	48 31 54	13.42	0.028	2.5		
Mkn 1018	02 03 42.5	-00 31 46	14.65	0.043	2.6			Mkn 268	13 38 54.0	30 37 49	14.66	0.041	2.8	1.4	4.7
Mkn 1179	02 30 26.9	27 43 04	15.23	0.038	1.0			Mkn 270	13 39 41.4	67 55 27	14.05	0.009	2.2		
NGC 1068	02 40 07.0	-00 13 31	10.83	0.003	28.0			NGC 5427	14 00 48.6	-05 47 27	13.96	0.009	9.5	7.7	11.5
Mkn 372	02 46 31.4	19 05 50	14.81	0.031	1.7			IR1408+1347	14 08 16.6	13 47 33	15.20	0.017	2.3	0.5	2.1
Mkn 1058	02 46 46.9	34 46 53	14.54	0.018	2.1			NGC 5506	14 10 39.1	-02 58 26	14.38	0.007	8.9	3.5	12.5
NGC 1144	02 52 38.7	-00 23 08	14.41	0.029	3.2	1.5	2.4	Mkn 670	14 12 00.2	26 58 49	14.68	0.035	1.5		
IR0253-1641	02 53 42.7	-16 41 18	15.50	0.033	1.7			Mkn 673	14 15 06.1	27 05 15	15.00	0.036	4.5		
Mkn 1066	02 56 49.8	36 37 21	13.96	0.012	4.2			Mkn 471	14 20 46.7	33 04 39	14.42	0.034	3.6		
NGC 1241	03 08 49.0	-09 06 36	12.70	0.013	7.5	3.4	7.8	Mkn 684	14 28 53.1	28 30 29	14.68	0.046	4.0	2.0	9.0
Mkn 1073	03 11 42.8	41 51 03	14.18	0.023	3.1	1.5	5.0	NGC 5674	14 31 22.5	05 40 38	13.70	0.025	4.2		
Mkn 607	03 22 18.0	-03 13 03	14.00	0.009	2.2	6.0	8.5	Mkn 686	14 35 19.7	36 47 02	13.60	0.014	4.7		
Mkn 609	03 22 57.3	-06 19 09	14.12	0.032	1.1			NGC 5728	14 39 36.8	-17 02 26	13.40	0.009	1.8	0.8	1.6
Mkn 612	03 28 10.1	-03 18 28	14.25	0.020	2.4	1.8	7.8	IR1443+2714	14 43 25.9	27 14 38	14.50	0.029	1.3	0.5	2.7
NGC 1358	03 31 10.8	-05 15 24	13.05	0.013	2.6			Mkn 822	14 43 54.1	16 18 18	15.00	0.054	1.5		
IR0438-0828	04 38 28.8	-08 28 12	15.30	0.015	2.0			IR1506+0913	15 06 42.7	09 13 50	15.50	0.045	1.9		
NGC 1667	04 46 10.5	-06 24 24	12.86	0.015	5.8	0.6	5.0	IR1524+0046	15 24 04.5	00 46 04	15.50	0.051	1.0		
NGC 1685	04 50 03.9	-03 01 53	15.18	0.014	4.0			NGC 5929	15 24 18.9	41 50 41	14.00	0.008	5.2		
IR0450-0317	04 50 14.1	-03 17 54	15.00	0.016	2.0			NGC 5953	15 32 13.2	15 21 40	13.10	0.007	4.7	5.5	3.5
NGC 2110	05 49 46.4	-07 28 02	13.51	0.007	2.5			IR1541+2840	15 41 53.4	28 40 52	15.50	0.030	1.6		
Mkn 3	06 09 48.4	71 03 11	13.34	0.014	3.5			IR1548-0344	15 48 03.4	-03 44 20	15.10	0.030	1.0	0.5	1.4
Mkn 620	06 45 37.7	60 54 13	13.54	0.006	5.0			Mkn 883	16 27 47.1	24 33 07	14.43	0.038	1.2		
Mkn 78	07 37 56.8	65 17 42	14.58	0.038	1.6			NGC 6211	16 40 36.0	57 52 00	14.30	0.020	6.5	2.5	10.0
Mkn 1210	08 01 27.0	05 15 22	15.00	0.013	2.2			NGC 6393	17 29 41.7	59 40 33	15.40	0.028	3.1		
IR0827-0242	08 27 43.9	-02 42 47	15.50	0.041	1.2			IR1958-1818	19 58 02.7	-18 18 51	15.50	0.037	1.3		
Mkn 1218	08 35 13.2	25 04 18	14.12	0.028	2.6	1.3	5.1	Mkn 516	21 53 52.9	07 07 43	15.01	0.028	1.7	1.0	3.6
Mkn 403	09 37 55.7	21 27 43	14.53	0.024	1.7			NGC 7212	22 04 33.9	09 59 20	14.09	0.026	3.6	1.2	4.2
NGC 2992	09 43 17.7	-14 05 43	13.78	0.007	5.6	2.7	13.5	NGC 7319	22 33 46.0	33 42 59	13.53	0.022	3.5	4.8	6.2
NGC 3081	09 57 10.0	-22 35 10	13.55	0.007	6.1	1.3	8.8	Mkn 917	22 38 48.1	31 54 30	14.10	0.025	2.5		
Mkn 720	10 15 00.6	07 13 17	15.27	0.045	1.6			IR2302-0004	23 02 45.1	-00 04 48	15.40	0.030	4.8		
Mkn 34	10 30 51.5	60 17 22	14.65	0.051	1.4			NGC 7592	23 15 47.8	-04 41 23	13.56	0.024	3.5		
NGC 3362	10 42 15.4	06 51 35	15.00	0.028	4.5			NGC 7672	23 24 59.8	12 06 35	14.21	0.013	3.4		
NGC 3660	11 21 00.5	-08 23 16	14.45	0.011	6.5			NGC 7674	23 25 24.4	08 30 13	14.36	0.029	4.0	2.0	11.0
Mkn 423	11 24 07.6	35 31 34	14.29	0.032	2.5			NGC 7682	23 26 30.7	03 15 28	14.30	0.017	2.8		
Mkn 176	11 29 55.4	53 13 35	14.61	0.027	2.2	2.0	3.7	NGC 7743	23 41 48.6	09 39 18	13.28	0.007	8.0		

derived, starting from the original counts of galaxies, made by Shane and Wirtanen (1967), and assuming that the probability of finding an optical companion is a Poisson probability,

$$P = 1 - \exp[-\pi \rho_* (S^2 - 0.25D^2)],$$

where D is the major axis of the Seyfert galaxy, in degrees; $S = 3D$ is the upper limit value of the separation between the pair components, in degrees; ρ_* is the density of galaxies around each Seyfert over 1 square degree, derived from Shane and Wirtanen galaxy counts ρ_{SW} in cells of ($5' \times 5'$), Seldner *et al.* (1977), and modified applying the restriction $\Delta m \leq 3$. Assuming that $dN_m/dm = 10^{0.6m}$, where N_m is the number of galaxies of magnitude m or brighter per unit solid angle, so that the value of ρ_* is given by the following integral:

$$\rho_* = \rho_*(m_*, \rho_{\text{SW}}) = \frac{0.6 \cdot \ln 10 \cdot \rho_{\text{SW}}}{1.9 \cdot 10^{11}} \int_{m_*}^{m_*+3} 10^{0.6m} dm.$$

The histograms of the probabilities of finding a companion in a sample of 99 S1 and 98 S2 galaxies are shown in Figs. 5(a) and 5(b), respectively, while the density functions $F_n(K)$ describing the probability of finding K optical companions in each sample of n Seyfert galaxies are given in Figs. 6(a) and 6(b). The results of this search for physical companions are also quoted in Table 3, where $\langle P \rangle$ is the mean probability of finding one *optical companion* in one trial according to a Poisson statistics and σ is its *standard deviation*. N_{PC} and $F_{\text{PC}}(\%)$ are the estimated number of physical companions and their percentage, respectively.

The following should be pointed out.

TABLE 3. Magnitude limited sample of Seyfert galaxies.

$\delta \geq -23^\circ$	$z \leq 0.11 \ m \leq 15.5$		
	Seyfert1	Seyfert 2	Seyfert 1+2
N_{TOT}	99	98	197
N_C	29	32	61
$F_C(\%)$	29	33	31
$\langle P \rangle$	0.11	0.13	0.12
σ	0.03	0.04	0.02
N_{PC}	12	12	28
$F_{PC}(\%)$	12	12	14

$\langle P \rangle$ =mean probability of finding 1 optical companion in 1 trial.

(I) The assumption that the probability of finding an optical companion is a Poisson probability is justified by the small search radii used in this investigation, $d \leq 120$ kpc ($H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$), all in the range of the *spatial pair correlation function*, where no clustering effects can be considered (Fall 1979).

(II) The mean probabilities of finding one optical companion, $(11 \pm 3)\%$ for S1 and $(13 \pm 4)\%$ for S2, are significantly smaller than the percentages of companions found on the POSS, namely $\sim 29\%$ (S1), $\sim 33\%$ (S2). This suggests that there is an excess of physical companions relative to a Poisson distribution. A comparison between the expected percentages of companions and the percentages found on the POSS prints, using a χ^2 test, gives a 99.99% confidence that the excess is real.

(III) The number of optical companions used in this investigation has been taken at a probability level ~ 0.01 on the decreasing branch of the density functions, Figs. 6(a) and 6(b). This means that we have taken an *upper limit* value of the number of optical companions (17 for S1 galaxies and 20 for S2 galaxies) to subtract from the total number of companions found directly on the POSS. The remaining pairs of objects are considered as physical companions and their number, 12 (S1) and 12 (S2), is then a *lower limit* value. Since the number of galaxies of our samples is close to 100, σ can be taken as the standard deviation of the derived percentages of physical companions, namely $F_{PC}(S1) = (12 \pm 3)\%$, $F_{PC}(S2) = (12 \pm 4)\%$.

The same statistical approach has been applied to the whole sample of S1+S2 galaxies, namely to a sample of 197 Seyfert galaxies in which the distinction in classes has not been taken into account, in order to evaluate the number of physical companions. The results are also quoted in Table 3.

FIG. 5. (a) Histogram of the probabilities of finding an optical companion for 99 Seyfert 1 galaxies. (b) Histogram of the probabilities of finding an optical companion for 98 Seyfert 2 galaxies.

3.2 Control Sample

The main concern in the selection of the control sample was to ensure that the percentage of optical pairs in the two samples were similar, as pointed out by Dahari (1984). Since this probability depends on the density of background galaxies and on the search area around the primary galaxy, we have looked around each Seyfert galaxy for the closest non-active spiral galaxy having major axis D_N in the range $0.5D_S \leq D_N \leq 1.25D_S$. This has been done using the *Merged Catalogue of Galaxies*, Kogoshvili (1986), distributed by the *Centre des Données Stellaires*. No attempt has been made to match the Hubble type of each Seyfert galaxy, because the morphological classification is not available for all Seyferts and the structure of the unclassified objects is often too faint and fuzzy on the POSS prints to allow any reliable classification. However, since Seyferts are known to be primarily early type spiral galaxies (Simkin *et al.* 1980), we have restricted our search to spiral galaxies in order to avoid effects introduced by the well-known morphology-density relation, such that galaxies of an earlier Hubble type live preferen-

FIG. 6. (a) Density function describing the probability $F_n(K)$ of finding K optical companions in a sample of $n=99$ Seyfert 1 galaxies. (b) Density function describing the probability $F_n(K)$ of finding K optical companions in a sample of $n=98$ Seyfert 2 galaxies.

tially in regions of higher galaxy densities than late type galaxies (Dressler 1980; Postman & Geller 1984).

In this way we have identified 99 objects for the S1 sample (control 1) and 98 objects for the S2 sample (control 2). The distributions of diameters for S1 and S2 galaxies and for their control samples are shown in Figs. 7(a) and 7(b), respectively.

The same procedures used for the Seyfert galaxies have been applied to these samples in order to find the pairs on the POSS prints, to evaluate the number of optical companions and then the corresponding number of physical companions. In this case, the number of optical companions has been taken at a probability level ~ 0.01 on the increasing branch of the density functions. It follows that we are estimating the lowest number of possible optical companions and then deriving an *upper limit* estimate of the number of physical companions.

For the 99 and 98 control 1 and control 2 galaxies, 13 and 11 companions were found, respectively (Table 4). These

FIG. 7. (a) Diameter distributions of S1 (solid line) and control 1 (dashed line) galaxies. (b) Diameter distributions of S2 (solid line) and control 2 (dashed line) galaxies. Diameters have been measured in mm on magnifications $5\times$ of the blue POSS prints.

numbers are statistically lower than the expected number of optical pairs ~ 25 for both samples, but not statistically different from the numbers of optical pairs at 0.01 level on the increasing branch of the density function. This would suggest that the number of optical companions is larger or, at most, equal to the number of companions found by us on the POSS prints. However, it is reasonable to assume that a few companions are physical. Then, since the uncertainty of the density function is $\sigma=5\%$ for control 1 and control 2 (Table 4), we can conclude that the *upper limit* percentage of physical companions is in the range (0–5)% in both samples. This

TABLE 4. Control samples.

$\delta \geq -23^\circ$	$z \leq 0.11 \quad m \leq 15.5$		
	control 1	control 2	control 1+2
N_{TOT}	99	98	197
N_C	13	11	24
$F_C(\%)$	13	11	12
$\langle P \rangle$	0.25	0.26	0.25
σ	0.05	0.05	0.04
N_{PC}	0	0	0
$F_{PC}(\%)$	0	0	0

$\langle P \rangle$ = mean probability of finding 1 optical companion in 1 trial.

range of percentages fits quite well the results of Turner (1976), who found on the basis of spectroscopic observations, that 137 out of 4400 galaxies of the UGC catalog, Nilsen (1973), namely $\sim 3.2\%$, are physical companions. The χ^2 test demonstrates that the observed percentage of companions found on the POSS prints fits a Poisson distribution in both control samples.

4. DISCUSSION AND CONCLUSIONS

The procedure used in this work has allowed us to derive a *lower limit* value for the percentage of physical companions to S1 and S2 galaxies. These values $(12 \pm 3)\%$ (S1) and $(12 \pm 4)\%$ (S2) are larger than the expected percentage $\sim 0\% - 5\%$ of physical companions in the control sample, which is an *upper limit* value, indicating the presence of an excess of physical pairs among Seyfert galaxies. This result is confirmed by the χ^2 test, which gives, in this case, a 99.99% confidence that both samples of S1 and S2 galaxies have more physical companions than their control samples.

In order to check further the results of our statistics, we have applied our method of identification of companions on the POSS to the complete, magnitude limited [$B(0) \leq 14.5$] CfA samples of Seyfert galaxies published by Huchra & Burg (1990), reclassified using the types of Osterbrock (1984) as given by Lipovetski *et al.* (1987) and by Osterbrock & Martel (1993). The results of such search for companions, 38% (S1) 27% (S2), are reported in Tables 5 and 6. Since the redshifts of all pairs identified in this list are available in literature, we have isolated the pairs with $|c \cdot \Delta z| \leq 1000 \text{ km s}^{-1}$ and considered them as physical pairs. In this way we find the percentages 19% (S1) and 18% (S2), which are both larger than the lower limit values found in our statistical work and comparable for both classes of objects.

TABLE 5. Seyfert 1: $\Delta m \leq 3$, $\Delta S \leq 3$ Dp.

Total number of objects	26
Number of objects with companion without limits in $ c\Delta z $	10
Percentage (%)	38%
Number of objects with companion with $ c\Delta z \leq 1000 \text{ km/s}$	5
Percentage (%)	19%

The final answer to the question on how much larger is the percentage of physical pairs among Seyfert galaxies can be obtained only by measuring the redshifts of all components of the identified pairs. This would allow us to check whether the percentage of physical companions is closer to the *lower limit* values, 12% (S1), 12% (S2), or to the values found using our method of identification on the POSS prints, 29% (S1), 33% (S2). An indication in this sense is given by the results of the analysis performed on the CfA complete sample of Seyfert galaxies. A bibliographical research has allowed us to find the redshift values for the components of 19 pairs of S1 galaxies out of 29 and of 20 pairs of S2 galaxies out of 32, identified with our method. It is evident that only a lower limit of the percentage of physical companions, namely pairs with $|c \cdot \Delta z| \leq 1000 \text{ km s}^{-1}$, can be evaluated for both S1 and S2 galaxies. In the case of S1 galaxies, we find 15%, lower than the value 19% found in the CfA complete sample and within the range $(12 \pm 3)\%$, found with our statistical procedure. Similarly, for S2 galaxies we find a lower limit value 18%, which is larger than the lower limit percentage of physical companions, $(12 \pm 4)\%$, found statisti-

TABLE 6. Seyfert 2: $\Delta m \leq 3$, $\Delta S \leq 3$ Dp.

Total number of objects	22
Number of objects with companion without limits in $ c\Delta z $	6
Percentage (%)	27%
Number of objects with companion with $ c\Delta z \leq 1000 \text{ km/s}$	4
Percentage (%)	18%

cally, and very close to the percentage found in the CfA complete sample. A careful and final discussion on the subject needs spectroscopic observations of the remaining 10 pairs of S1 and 12 pairs of S2 for which redshift values are not available for both components. The knowledge of these redshifts will also allow to indicate whether the percentage of S2 galaxies with a physical companion is larger than that of S1, as found by some authors (e.g., Petrosian 1982; Dahari & DeRobertis 1988; Mackenty 1989).

As a final remark, it must be pointed out that in our search we avoided to consider faint companions ($\Delta m > 3$), while objects showing a disturbed morphology, which could have hidden a merging process, or very close pairs, which are not resolved on the POSS prints, were regarded as isolated. This further strengthens the result that the excess of physical com-

panions among S1 and S2 galaxies, found statistically in this work, is a lower limit estimate of the real excess.

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