The Astronomical Journal, 129:2579–2584, 2005 June

MIXED-MORPHOLOGY PAIRS AS A BREEDING GROUND FOR ACTIVE NUCLEI

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Received 2004 November 18; accepted 2005 February 15

ABSTRACT

Mixed-morphology pairs offer a simplification of the interaction equation that involves a gas-rich fast rotator paired with a gas-poor slow rotator. In past low-resolution *IRAS* studies it was assumed that the bulk of the far-infrared (FIR) emission originated in the spiral component. However, our *Infrared Space Observatory* studies revealed a surprising number of early-type components with significant IR emission, some of which turned out to show active nuclei. This motivated us to look at the current statistics of active nuclei in mixed pairs using the radio-FIR continuum correlation as a diagnostic. We find a clear excess of early-type components with radio continuum emission and active nuclei. We suggest that they arise more often in mixed pairs via cross-fueling of gas from the spiral companion. This fuel is more efficiently channeled into the nucleus of the slow-rotating receptor. In a sample of 112 mixed-morphology pairs from the Karachentsev catalog, we find that about 25%–30% of detected mixed pairs show a displacement from the radio-FIR relation defined by normal star-forming galaxies. The latter objects show excess radio continuum emission, while others extend the relation to unusually high radio and FIR flux levels. Many of the outliers or extreme emitters involve an early-type component with an active nucleus. The paired E/S0 galaxies in the sample exhibit a significant excess detection fraction and a marginal excess luminosity distribution compared to those of isolated unpaired E/S0 galaxies.

Key words: galaxies: elliptical and lenticular, cD — galaxies: interactions — galaxies: spiral — radio continuum: galaxies

1. INTRODUCTION

Binary galaxies play an important role in the study of galaxy evolution because they represent the most common interaction scenario and comprise about 10% of the galaxies in the non-clustered universe (Xu & Sulentic 1991). Gravitational interactions in pairs affect galaxy evolution because these encounters can (1) redistribute gas within each galaxy, (2) enhance the level of star formation (Keel et al. 1985; Xu & Sulentic 1991), and possibly (3) stimulate active nuclei. Between 15% and 25% of a reasonably unbiased sample of binary galaxies involves systems with mixed (E/S0+S) morphology (e.g., Karachentsev 1972; Reduzzi & Rampazzo 1995). They are perhaps the most puzzling and, at the same time, useful simplification of the galaxy-galaxy interaction equation involving a gas-rich rapid rotator paired with a gas-poor companion with low specific angular momentum. Mixed pairs minimize the role of the relative orientation of pair component spin vectors in driving interaction-induced effects (e.g., Keel 1991). The late-type spiral component should be the primary source of gas in a mixed pair, and this is reflected in H I studies (see, e.g., Zasov & Sulentic 1994). It is therefore expected to be the site of all or most star formation and nuclear activity. The activity might be stimulated by gravitational perturbations from the early-type companion. Evidence of significant amounts of gas and/or star formation and active nuclei in early-type components has not been reported and is not expected.

Mid- and far-infrared (MIR and FIR) emission has proven to be one of the most sensitive diagnostics of interaction-induced enhancements in pairs (Kennicutt et al. 1987; Sulentic 1989; Xu & Sulentic 1991; Hernández-Toledo et al. 1999, 2001). It is especially useful for assessing the level of star formation enhancement in such pairs. Radio continuum observations also reveal excess detections and higher flux levels in binary galaxies (Sulentic 1976; Condon et al. 1982). Throughout the history of IR studies, largely exploiting the *IRAS* database, the working hypothesis was that MIR and FIR emission originated largely from late-type galaxies in unresolved pairs and groups. This gave mixed pairs a possible advantage over spiral-spiral pairs in which both components are expected to produce similar levels of radio and IR emission. In mixed pairs we can study interaction properties and infer which component is likely to be responsible for most of the long-wavelength emission. Higher resolution *Infrared Space Observatory* (*ISO*) observations for about a dozen mixed pairs revealed that the above working hypothesis was violated in many of the pairs. *ISO* maps, Hα images, and literature sources revealed pairs in which active galactic nuclei (AGNs), LINERs, and starburst nuclei were present in the early-type component. In fact, more Seyfert nuclei were found in the early-type components of our *ISO* mixed-pairs sample (Domingue et al. 2003) than in our *ISO* sample of $n = 8$ S+S pairs (Xu et al. 2000). The *ISO* E+S and S+S samples were similarly selected for study on the basis of FIR brightness and signs of interaction. Since spiral galaxies are thought to preferentially harbor Seyfert nuclei, we expected equal or greater numbers of active nuclei in our *ISO* S+S sample (16 and 12 spirals in the S+S and E+S samples, respectively). All galaxies in the S+S sample have good spectroscopic data available, while a number of the E+S pairs have only a pre-CCD redshift determination. While the numbers are small, the *ISO* data raise the possibility of a significant population of active early-type galaxies in mixed pairs.

It is no longer surprising that interacting galaxies show evidence of enhanced nonthermal radio continuum emission, because a surprisingly strong correlation exists between IR and radio flux measurements in star-forming galaxies (de Jong et al. 1985; Helou et al. 1985). The correlation apparently reflects a close coupling between thermal and nonthermal processes related to star formation. Many radio continuum surveys of early-type galaxies now exist (Sadler et al. 1989; Wrobel & Heeschen 1991; Slee et al. 1994) and, as for IR results (e.g., Knapp et al. 1992), show low detection/flux levels. AGNs often display excess radio emission, which displaces them above the radio-FIR correlation (Condon & Broderick 1991). This makes the radio-FIR correlation a useful diagnostic tool for identifying AGN candidates in the absence of good-quality nuclear spectra and high-resolution IR data. Among early-type galaxies, a tendency has been shown for S0 galaxies to obey the star formation relation (Bally & Thronson 1989; Walsh et al. 1989; Wrobel & Heeschen 1991), while elliptical galaxies are less well defined and can show AGN characteristics (Wrobel & Heeschen 1991). Our previous *ISO* results suggest that mixed pairs may represent an environment in which active nuclei can be more easily generated via cross-fueling of gas from the S component onto the slow-rotating E component.

The results from the *ISO* studies motivated us to search for radio activity in a large sample of nearby mixed pairs by utilizing the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). The NVSS provides complete coverage for the Karachentsev (1972) Catalog of Isolated Pairs of Galaxies (KPG) and the Karachentseva (1973) Catalog of Isolated Galaxies (KIG). The NVSS resolves the radio emission in virtually all the pairs, while the matching *IRAS* survey does not resolve the IR emission. Both surveys provide a reasonably large fraction of detected galaxies, enabling us to construct useful radio-FIR correlation diagrams. This makes it possible for us to identify pair members that deviate from the star formation–driven correlation.

2. SAMPLE SELECTION AND ANALYSIS PROCEDURE

The KPG is likely the most complete local sample of isolated binary galaxies and is estimated to be reasonably complete to 10^4 km s^{-1} and $m_{\rm Zw} = 15.0$ (Xu & Sulentic 1991). The catalog contains about 550 accordant redshift binaries with mixed pairs (E/S0+S) accounting for approximately 25%–30% of the sample. We restrict our study to mixed pairs with a radial velocity of $\leq 10^4$ km s^{-1} and a component velocity difference of $\Delta v \leq 10^3$ km s^{-1}. The final adopted sample includes 112 mixed pairs. The optical positions of KPG components have a positional uncertainty between 1″ and 10″, depending on the degree of central concentration in the galaxy. The NVSS catalog was searched for all 5 σ source detections within 30″ of each galaxy in a mixed pair, and radio-optical overlays assisted with identification. The NVSS is complete to $S_{1.4\ \rm GHz} = 2.5$ mJy, and the rms positional uncertainty ranges from less than 1″ for $S_{1.4\ \rm GHz} > 15$ mJy up to 7″ for $S_{1.4\ \rm GHz} < 15$ mJy. The angular resolution of the NVSS is ~45″ at FWHM. NVSS radio detections could immediately be assigned to one or both components in all but 20 of the pairs. Seventeen of the latter pairs with separation $D \leq 1'$ showed a radio position that was $\leq 0.2D$ closer to one component than the other, making these assignments reasonably secure in almost all sources. KPG 93 was confused because the NASA/IPAC Extragalactic Database (NED) has reversed the identifications of the early- and late-type components (data for the spiral component belong to the early type and vice versa). The NVSS radio detection belongs to the Seyfert spiral component. The NVSS radio position in KPG 116 lies slightly closer to the spiral and very close to a bright stellar object; it may be a radio-loud quasar (it is listed as a spiral detection here). In many cases radio detection assignments could be confirmed with higher resolution FIRST (Becker et al. 1995) survey data (positional accuracy at or below 1″ at the survey threshold with FWHM of 5″). Sixteen of our pairs were included in FIRST, and all our NVSS detection assignments were confirmed. FIRST resolved two of the most ambiguous pairs, involving KPG 155 and 167. FIRST maps reveal that both components of KPG 155 are weak radio emitters but that the early type is slightly stronger and the NVSS source is centered on it. It was therefore assigned the NVSS detection. All the emission from KPG 167 originates from the compact early-type component (NED has them reversed). Table 1 summarizes the radio detection statistics and is formatted as follows: Column (1): KPG designation; column (2): pair separation in arcminutes; column (3): pair components detected; column (4): NVSS flux for S detections; column (5): NVSS flux for early-type detections; column (6): adopted *IRAS* 60 μm flux in janskys (Moshir et al. 1992); and column (7): location of known spectroscopic "activity" listed as early-type (E), late-type (S), or both.

3. 1.4 GHz DETECTION STATISTICS

We define "AGNs" here to include LINERs, Seyferts, and radio galaxies. We find that 14% (detection fraction [DF] = 0.14) of the pairs show radio emission from both components, while the DFs for spirals and E/S0 components are 0.57 and 0.29, respectively. Radio continuum emission from 29% of the early types in pairs would have been a surprising result before the detection of MIR emission from many of them during the *ISO* survey (Domingue et al. 2003). Perhaps more surprising is that 24 of the 32 detected early-type components show a higher radio flux than their spiral companions. If the early-type components in mixed pairs are the same as isolated galaxies of similar types, then we expect similar radio DFs. We adopt the KIG as a control sample because it was compiled visually using an isolation criterion. In this sense it is a companion sample to the KPG, and both samples show similar low galactic density environments (typically, but not always, with a nearest neighbor crossing time of $T_c \sim 1$ Gyr). If the morphologies can be trusted, then the two samples differ only in the sense that the KPG early types are involved in interacting binaries with a spiral companion. We recently reclassified all galaxies in the KIG using POSS II and identified a sample of $n = 134$ E/S0 galaxies, of which $x = 25$ are detected by the NVSS, yielding DF = 0.18. A recent independent compilation of $n = 76$ early types from the KIG (Stocke et al. 2004) yields $x = 11$ detections for DF = 0.14, motivating us to adopt DF = 0.16 for the control sample, since both (overlapping) surveys have advantages and disadvantages. Adopting DF = 0.16 as the probability for NVSS radio detection yields an expected sample of $x = 18$ early-type KPG radio detections compared to $x = 32$ observed. The binomial probabilities for detecting 18 (expected) and 32 (observed) early types out of a sample of 112 mixed pairs are 0.10 and 3×10^{-4}, respectively. Thus, there is reasonable evidence of an excess of radio-emitting early-type KPG members.

Figure 1 shows the distribution of NVSS radio luminosities ($H_0 = 75$ km s^{-1} Mpc^{-1}) for our KIG and KPG samples, in which we obtain mean values of $\log L_{\rm NVSS} = 21.5$ ($n = 25$) and 21.9 ($n = 32$), respectively. The distributions are not very Gaussian, suggesting that a nonparametric rank sum test is the more appropriate vehicle for comparing them. We obtain a rank sum $R \sim 170$ and standard deviation $s \sim 60$, giving us an approximately 3 σ difference in the sense that early-type members of KPG pairs are more radio-luminous. We find almost twice the rate of radio detections and a factor of 3 times higher radio

TABLE 1
MIXED PAIRS WITH RADIO DETECTIONS

KPG Name (1)	Separation (arcminutes) (2)	NVSS Detection (3)	$S_{1.4\ GHz}$ (S) (mJy) (4)	$S_{1.4\ GHz}$ (E/S0) (mJy) (5)	*IRAS* S_{60} (Jy) (6)	AGN Location (7)	Reference (8)
078	3.50	Both	64.7	15.9	3.55	...	...
086	3.48	Both	26.4	4.6	4.32	E	1
127	6.32	Both	267.0	2.9	12.00	...	...
188	1.23	Both	3.0	3.9	1.09	...	...
202	1.29	Both	24.7	7.0	2.27	...	...
229	4.57	Both	6.7	31.1	0.59	...	...
234	2.35	Both	97.5	3.2	7.83	Both	1
353	2.57	Both	54.4	29.1	6.11	...	...
436	1.21	Both	7.4	4.0	0.83	...	...
468	0.77	Both	6.3	91.4	10.00	Both	2
476	1.98	Both	11.9	19.2	2.70	...	...
508	3.79	Both	4.7	145.1	0.34	E	3
530	9.27	Both	4.4	14.6	0.40	...	...
552	1.23	Both	5.5	16.9	2.80	E	4
553	1.42	Both	5.8	6.3	0.35	...	...
591	2.00	Both	16.9	24.9	4.80	...	...
062	2.39	E	...	11.9	0.22	...	...
093	0.21	E	...	15.2	0.87	Both	5
130	0.53	E	...	8.1	1.34	...	...
155	0.33	E	...	3.8	0.52	...	...
167	0.44	E	...	3.1	0.48	...	...
239	3.92	E	...	10.7	0.18	...	...
303	2.03	E	...	481.4	0.14	E	6
383	0.45	E	...	39.2	0.50	...	...
386	1.97	E	...	31.5	0.50	...	...
445	0.87	E	...	385.3	0.14	E	7
460	0.79	E	...	15.3	0.13	...	...
485	0.35	E	...	3.5	0.20	...	...
487	0.32	E	...	12.9	1.85	...	...
509	2.15	E	...	11.5	0.33	...	...
536	0.42	E	...	20.2	1.49	E	4
537	1.37	E	...	2.5	0.24	...	...
061	2.02	S	10.0	...	0.54	...	...
074	0.68	S	5.6	...	0.44	...	...
079	1.02	S	3.8	...	1.11	...	...
081	4.58	S	7.7	...	0.42	...	...
083	0.71	S	154.6	...	5.06	S	4
089	1.51	S	2.4	...	0.38	...	...
101	0.67	S	4.4	...	0.49	...	...
116	1.57	S	213.1	...	0.84	...	...
121	2.08	S	8.2	...	0.57	...	...
122	1.34	S	7.2	...	0.66	...	...
128	3.30	S	23.2	...	1.99	...	...
134	0.60	S	7.4	...	0.41	...	...
144	0.54	S	10.2	...	1.38	...	...
153	0.54	S	2.8	...	0.40	...	...
182	0.92	S	4.8	...	0.79	...	...
198	1.31	S	8.4	...	0.66	...	...
209	0.45	S	22.7	...	0.68	...	...
243	1.08	S	9.1	...	0.93	...	...
248	0.77	S	19.8	...	1.52	...	...
269	1.07	S	21.5	...	1.37	...	...
275	1.57	S	17.0	...	0.50	...	...
284	2.68	S	15.3	...	1.02	...	...
304	1.68	S	9.4	...	0.69	E	8
317	2.25	S	2.8	...	0.28	...	...
363	0.37	S	38.8	...	5.73	S	4
380	0.91	S	4.0	...	0.19	...	...
393	2.38	S	13.6	...	1.03	...	...
394	1.57	S	23	...	1.81	...	...
407	0.32	S	5.8	...	0.76	...	...
412	6.15	S	2.2	...	0.28	...	...

TABLE 1—*Continued*

KPG Name (1)	Separation (arcminutes) (2)	NVSS Detection (3)	$S_{1.4\ \mathrm{GHz}}$ (S) (mJy) (4)	$S_{1.4\ \mathrm{GHz}}$ (E/S0) (mJy) (5)	*IRAS* S_{60} (Jy) (6)	AGN Location (7)	Reference (8)
416	3.21	S	29.0	...	3.36	...	...
419	3.82	S	338.8	...	8.41	S	4
429	4.31	S	4.8	...	0.61	...	...
432	3.35	S	3.6	...	0.70	...	...
439	0.86	S	35.3	...	3.69	...	...
451	5.61	S	29.4	...	5.11	...	...
465	4.00	S	9.1	...	1.08	...	...
519	3.03	S	2.9	...	0.53	...	...
526	2.31	S	182.2	...	0.64	S	4
542	0.68	S	29.2	...	2.47	...	...
547	0.67	S	17.7	...	1.73	...	...
570	5.20	S	45.7	...	0.21	...	...
572	0.92	S	13.1	...	0.50	...	...
576	1.55	S	2.6.0	...	0.38	...	...
583	1.00	S	3.0	...	0.62	...	...
596	0.67	S	10.0	...	1.82	...	...

References.—(1) Ho et al. 1995; (2) González-Delgado & Pérez 1996; (3) Corbett et al. 1998; (4) Keel 1996; (5) Keel 2004; (6) Puschell 1981; (7) Liu & Zhang 2002; (8) Magliocchetti et al. 2002.

luminosity for KPG early-type members compared to those for our KIG control sample. This result raises two questions: (1) Where did the gas giving rise to this effect come from? and (2) Is the excess radio emission a manifestation of star formation or AGNs?

4. FIR-RADIO CONTINUUM CORRELATIONS

The substantial number of both radio and FIR detections may provide an answer to the second of the two questions posed above. We can resolve the radio emission in essentially all the pairs, while very few are resolved by *IRAS*. We expect that most of the FIR emission is due to star formation in the spiral components. We can make a first attempt at calibrating the star formation contribution in the pairs by deriving a radio-FIR correlation relation for pairs in which only the spiral component shows an NVSS radio detection. It is safe to assume that any FIR contribution from an early-type galaxy is small if it is not detected by the NVSS. The converse is not true. Figure 2*a* shows the radio-FIR relation for spiral-only pair NVSS detections. The strong correlation (de Jong et al. 1985; Helou et al. 1985; Reddy & Yun 2004) is thought to be driven by the relationship between thermal emission from dust heated by massive young stars and nonthermal emission related to the supernova demise of the same stars. Star formation is thought to be enhanced in KPG spirals because the FIR properties of both S+S and E/S0+S pairs are enhanced (Xu & Sulentic 1991; Hernández-Toledo et al. 1999). Note that enhanced star formation will extend the correlation, but little or no blurring is expected. The best-fit regression line shown in Figure 2*a* gives a slope $\alpha = 0.84$ with a correlation coefficient $(\mathrm{CC}) = 0.82$ and $\sigma = 0.22$. Four outlier spiral-only detections were not included in the fit shown in Figure 2*a*. They show excess radio emission. (We know that the radio emission does not come from the early type.) Three of these galaxies (KPG 83, 419, and 526) show nuclear AGN/LINER spectra, while KPG 116 involves the aforementioned radio quasar candidate. Our derived slope for the correlation is very similar to other estimates (e.g., $\alpha = 0.76$ in Reddy & Yun 2004) and is consistent with the plotted star formation band in Figure 2 defined within the 3 σ deviations of the flux-flux relation for the 2 Jy *IRAS* sample of Yun et al. (2001). We next consider pairs with an early-type radio detection. Figure 2*b* presents the radio-FIR correlation diagram for early-type detections in both the KIG (*squares*) and KPG (*circles*) samples. Pairs included in Figure 2*a* are therefore not shown here. Circles indicate NVSS flux for the early-type galaxy only. The vertical lines indicate the contribution of the spiral component in pairs in which both galaxies were detected. It is interesting that the KIG sample follows the star formation band rather well, with a slope for that sample of $\alpha = 0.64$, $\mathrm{CC} = 0.71$, and $\sigma = 0.26$. The simplest interpretation of the KIG correlation is that the S0 part of the sample shows low-level star formation, as suggested for other samples (e.g., Wrobel & Heeschen 1991). The origin of the emission from elliptical galaxies is less clear. The KIG sample is taken as indicative of the typical radio-FIR properties for field early-type galaxies. Figure 2*b* shows the population of KPG early-type galaxies with higher than average radio

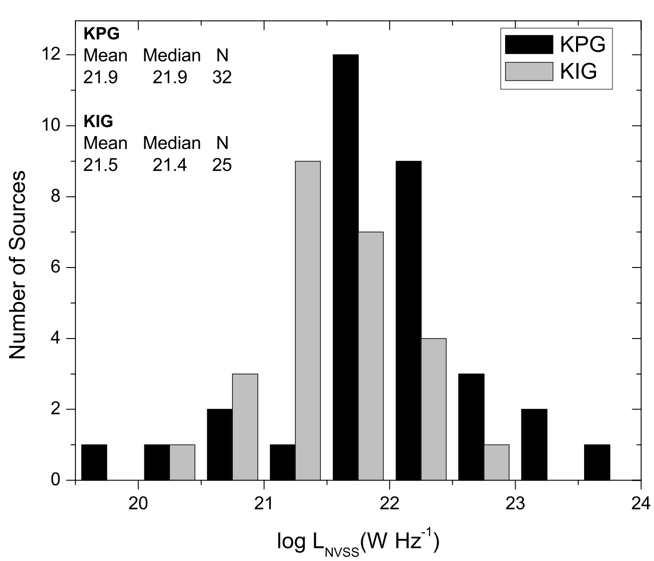

Fig. 1.—Histogram of radio luminosity for the 32 early-type KPG sources and the 25 early-type KIG sources detected by the NVSS.

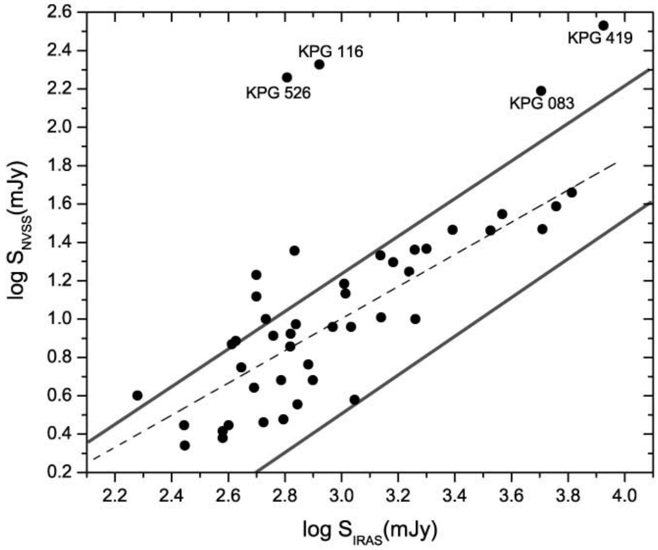

FIG. 2*a*

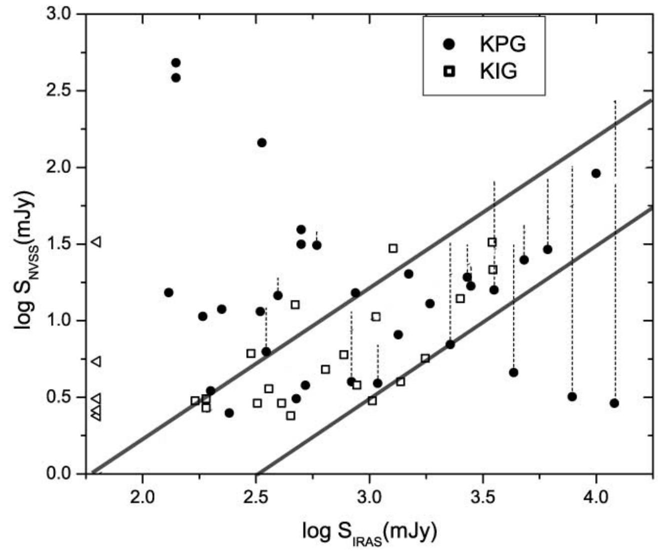

FIG. 2*b*

FIG. 2.—(*a*) NVSS flux vs. 60 μm *IRAS* flux in log-log scale for the 46 pairs with only a spiral detection. We use these pairs to determine a radio-FIR correlation for star-forming galaxies of this sample. The four labeled pairs are excluded from the fit. The solid lines indicate the region of star-forming galaxies defined by a 3 σ deviation from the correlation of Yun et al. (2001). (*b*) Same as (*a*) but for pairs with detected early types from the KPG sample (*circles*) and the early-type galaxies from the KIG control sample (*squares*). Dashed vertical lines indicate the pairs before and after removing the spiral contribution from the total NVSS flux.

fluxes. Only a few of the pairs in which both components are detected by the NVSS (KPG 86, 127, 234, and 476) show radio emission dominated by the spiral component. These pairs involve KPG spirals with very strong star formation. The residual radio emission from the early-type components in these pairs tends to be weaker than average. It is reasonable to assume that the spirals dominate the FIR flux even more and that correction for it would move the early-type components toward the left and into the principal KIG occupation domain ($\log S_{IRAS} < 3.0$).

We adopt $\log S_{\rm NVSS} > 1.0$ as the zone of interest, since only five KIG detections fall slightly above this level. KIG sources also follow the radio-FIR correlation more closely than the KPG early types; therefore, we exclude sources with $\log S_{IRAS} > 3.0$ as likely to involve early-type components (S0) with FIR emission dominated by star formation. This zone boundary marks a conservative intersection of the outliers and the star formation band.

This leaves one KIG detection in the zone of interest, compared to 11 early-type pair components (in eight cases, only the early type was detected by the NVSS). An additional six of the latter class may move into the zone of interest after correction for *IRAS* flux from the spiral components (KPG sources with $\log S_{IRAS} > 3.25$ other than KPG 86, 127, 234, and 476). It is therefore possible that about 17 early-type pair components show unusually strong radio emission relative to the KIG-defined radio-FIR relation. Ten known AGNs (radio galaxies, Seyfert galaxies, and LINERs) are already known among this early-type population, with many of the others lacking any modern spectroscopic data. Note that the radio-FIR correlation only helps find AGNs that show above-average radio emission. Some of the known AGNs in our sample fall at or below the lower edge of the zone of interest. A spectroscopic survey, especially of the remaining candidate pairs in the zone of interest, will likely reveal additional active nuclei among the early-type detections. Comparison of NVSS and FIRST radio data supports this expectation. While NVSS resolution is too low to resolve the emission within a pair component, it is likely to detect all the radio flux. FIRST, on the contrary, is insensitive to extended emission because of its spatial frequency attenuation. Typically, we find a large difference between peak and integrated flux for FIRST detections of spiral components, indicating resolution of the source. The resolved emission is likely related to star formation, in many cases leaving little unresolved flux that could be assigned to a nuclear AGN. Most of the FIRST detections of early-type components show near-equality between NVSS, peak FIRST, and integrated FIRST radio fluxes. This indicates that most of the radio emission from early types is unresolved, which is consistent with an AGN-related radio signature.

The excess of early-type radio detections in pairs motivates serious consideration of an interaction-related explanation. Gas transfer from the gas-rich spiral to the early-type component (i.e., cross-fueling) has been discussed for many years (Haynes et al. 1984; Demin 1984; Sotnikova 1988a, 1988b; Sulentic 1992; Andersen et al. 1994; de Mello et al. 1996). Some of the pairs have been discussed in this context, including KPG 468, one of the most FIR-luminous pairs in our sample. In this case correction for radio-FIR emission from the spiral does not significantly change the position of the source in Figure 2*b*. The early-type companion involves both starburst and AGN signatures, while the underlying morphology suggests that it is an early type and the known kinematic data allow for the possibility of cross-fueling (Jenkins 1984; González-Delgado & Pérez 1996; Hernández-Toledo et al. 2003). The activity in the early-type component of KPG 234 is not yet extreme but shows evidence consistent with mass transfer (González-Delgado & Pérez 1997). In the case of KPG 591 kinematic data and modeling suggest that mass transfer has taken place (Marcelin et al. 1987; Salo & Laurikainen 1993). In some of these cases the early-type companion is likely S0 rather than elliptical. Examples of cross-fueling might be more difficult to identify in such cases because the KIG control sample suggests that they are more likely to show radio and FIR emission from low-level star formation activity.

The most surprising result involves the number of pairs in which *only* the early-type component is detected in the NVSS. At least nine of the pairs in our zone of interest fall into this class, including two radio galaxies (KPG 303 and 445). How can one cross-fuel if the donor spiral galaxy shows no significant interstellar medium signature? In at least one case (KPG 93), recent *Hubble Space Telescope* images appear to show in flagrante delicto cross-fueling from, in this case, an active Seyfert spiral galaxy onto an S0 manifesting low-level LINER activity (Keel 2004). In this case the pair separation challenges the resolving power of the NVSS. However, the accuracy of the NVSS radio position for a 15 mJy detection is very high and suggests that most of the radio emission originates in the early-type component (Condon et al. 2002; note that one cannot rule out a contribution from the spiral). The same can be said for very close pairs KPG 460 and 487. In the other cases the separation allows no ambiguity in the detection assignment. Is the spiral galaxy misclassified in these cases (e.g., an "early-type" pair; Rampazzo & Sulentic 1992)? Our unpublished CCD images for all these pairs show evidence of spiral structure and allow only KPG 383 to be questioned as a true mixed pair. The more likely explanation is that the spiral galaxies in early-type-only NVSS-detected pairs are experiencing low levels of star formation. Perhaps donor spiral galaxies become anemic by cross-fueling with their companions and nuclear fueling of their own AGNs in response to tidal effects of the galaxy being fueled (e.g., KPG 93). Both radio galaxies in our sample (KPG 303 and 445) show companions with well-defined disks but little evidence of H II regions or dust lanes. They are the most anemic "spiral galaxies" in our sample. We are not suggesting that all our early-type detections are examples of cross-fueling. Some may simply involve slow rotators with a small amount of gas that is more rapidly channeled into their nuclei through the dynamical effect of the spiral galaxy.

5. SUMMARY AND DISCUSSION

We find a significant excess of mixed pairs with early-type NVSS detections that also show a factor of 3 enhancement in average radio luminosity. The detections involve both E and S0 companions of spiral galaxies. We suggest that this excess can be interpreted as a population of early types cross-fueled by their gas-rich neighbors. A surprising number already show evidence of nuclear activity, including AGN/LINER/starburst activity, while modern spectroscopic data exist for only about half of them. We suggest that cross-fueling onto slow rotators is more efficient at triggering nuclear AGN activity than similar cross-fueling onto spirals. We may be observing a sequence of activity beginning with cross-fueling that leads to enhanced star formation activity followed by ignition of an AGN. At least two of our early-type detections involve hybrid starburst-AGN activity. The two most extreme cases involving radio galaxies show disky companions that might be interpreted as anemic spirals or lenticulars. These may represent the end cycle of the process in which AGN activity leads to the development of radio loudness in the last stages of the AGN process. KPG 445 shows a double-jet radio morphology consistent with the early stages in the development of double-lobed (Fanaroff-Riley II) structure.

This research has made use of NED, which is operated by JPL, Caltech, under contract with NASA.

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