MULTICOLOR OPTICAL IMAGING OF INFRARED-WARM SEYFERT GALAXIES. V. MORPHOLOGIES
AND INTERACTIONS: CHALLENGING THE ORIENTATION MODEL

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ABSTRACT

This paper is the last in a series investigating the optical properties of a sample of mid-IR warm Seyfert galaxies and of a control sample of mid-IR cold galaxies. In the present paper I parametrize the morphologies and interaction properties of the host galaxies and combine these with the major conclusions in my previous papers. My results confirm that nuclear activity is linked to galactic interactions. I suggest an alternative view to the simple orientation-obscuration model postulated for Seyfert types 1 and 2 that takes into account the time evolution of their environmental and morphological properties. Within this view, the distinction between warm Seyfert 1 and 2 galaxies is not one of simple orientation; the latter might instead represent an earlier evolutionary stage, with properties intermediate between the (starburst-dominated) cold galaxies and the (AGN-dominated) warm Seyfert 1 galaxies.

Subject headings: galaxies: active — galaxies: interactions — galaxies: Seyfert

1. INTRODUCTION

Two of the most fundamental outstanding questions regarding the nature of active galactic nuclei (AGNs) are as follows: (1) To what extent can the differences between various observed types of AGN be attributed to their orientation, evolutionary history, or intrinsic properties? (2) What are the processes responsible for triggering activity in galactic nuclei? I am exploring these questions on the basis of new observations and analysis of a sample of IR-luminous Seyfert galaxies that are sufficiently close so that their morphologies, environments, and kinematics can be studied in great detail. Let me first review briefly our current knowledge of the Seyfert phenomenon based on the most recent observational studies.

1.1. Overview

A generally accepted unification model for AGNs postulates that many of their observed characteristics depend on the orientation of the observer relative to the dusty torus that is surrounding the central black hole (see, e.g., Antonucci & Miller 1985; Antonucci 1993). Although it is certain that orientation must play a key role in the AGN phenomenology, recent studies of Seyfert samples draw a rather confused picture of a possible unification scenario. There is growing observational evidence that the optical depth and covering factors are different between type 1 and 2 (obsured and unobsured) Seyfert galaxies, which implies that the interstellar medium might play a definitive role in the optical nuclear classification of a Seyfert nucleus.

Turner et al. (1998) used ASCA observations of Seyfert 2 and narrow emission line galaxies to show that the absorbing material exists under significantly different conditions (dust composition and grain size, circumnuclear gas density) in type 1 and 2 Seyfert galaxies. Levenson, Weaver, & Heckman (2001b) obtained X-ray data for a sample of Seyfert 2 galaxies showing that the interstellar medium of nuclear starbursts significantly contributes to the absorption of the central AGN and to the 60 μm emission in these objects. Larger dust content in Seyfert 2 galaxies on scales of hundreds of parsecs was also found by Malkan, Gorjian, & Tam (1998), through a Hubble Space Telescope snapshot survey of more than 200 Seyfert galaxies, involving column densities of 10^{22}–10^{23} atoms cm^{-2} at most. Guainazzi et al. (2001) followed up this sample in X-ray wavelengths, suggesting a bimodality of the Seyfert 2 population: the Compton-thick Seyfert 2 galaxies contain the standard molecular torus, which furthermore might be causally related to the larger fraction of stellar bars found among these objects (Maiolino, Risaliti, & Salvati 1999); the Compton-thin Seyfert 2 galaxies do not contain such a compact nuclear torus but have instead a dust-rich environment on scales of hundreds of parsecs (see also Matt 2000). Other recent studies show a large discrepancy between optical/IR and X-ray extinction (the former being smaller by at least an order of magnitude), this discrepancy increasing for larger column densities up to N_H = 10^{24} (Maiolino et al. 1998; Risaliti, Maiolino, & Bassani 2000; Iwasawa et al. 2001; Guainazzi et al. 2001). The most direct implication of these results is that the X-ray and optical absorbing media may be totally decoupled in Seyfert galaxies, thus challenging the simple orientation scheme that was based on the optical classification of Seyfert nuclei. A similar suggestion comes also from theoretical studies (e.g., Courvoisier 2000), namely, that differing levels of starburst activity and obscuring material dictate the AGN classification rather than pure orientation effects.

Some recent studies of Seyfert galaxies show well-matched radio properties between the nuclear types 1 and 2 (e.g., Giuricin et al. 1990; Kukula et al. 1995; Rush, Malkan, & Edelson 1996; Nagar et al. 1999; Morganti et al. 1999; Thean et al. 2001), while others find differing compactness of the radio cores of the two types (e.g., Roy et al. 1994). Thean et al. (2001) found correlations between the radio core and 25 μm fluxes and between the extranuclear radio emission and total IRAS flux densities. Furthermore, the Seyfert 2 galaxies appear to have overall brighter 60 μm fluxes (presumably extended emission) compared to the Seyfert 1 galaxies. This is in agreement with recent findings of excess star formation and dust in the host galaxies of Seyfert
2 nuclei (Maiolino et al. 1995; Malkan et al. 1998; Hunt & Malkan 1999). Another interesting result of Thean et al. (2001) is that Seyfert 2 galaxies with a hidden broad-line region (BLR) show more powerful nuclear radio sources than either Seyfert 1 galaxies or Seyfert 2 galaxies without hidden BLRs.

Using polarimetric studies to detect hidden BLRs in Seyfert 2 galaxies, Tran (1993, 1995a, 1995b, 1995c) and Heisler, Lumsden, & Bailey (1997) are led to somewhat different conclusions: hidden BLRs are found predominantly in interacting galaxies with warm mid-IR colors (\(\alpha_{25,60} \lesssim -1.6\)) and smaller internal extinction. They originally interpreted these results within the orientation model, suggesting that the flat-spectrum (warm) Seyfert 2 galaxies are oriented at intermediate (between pole-on and edge-on) torus viewing angles. However, subsequent studies of this sample in optical and X-ray wavelengths (Tran et al. 1999; Alexander 2001) have shown that the presence or absence of significant star formation in the host galaxies, rather than the orientation of the central engine, is the dominant factor affecting the mid-IR colors. This was further confirmed with the spectropolarimetric survey of a complete sample of IR-selected Seyfert 2 galaxies by Lumsden et al. (2001). These authors concluded that the presence or absence of a hidden BLR in Seyfert 2 galaxies depends on the relative luminosities of the AGN and the host galaxy, powering the mid- and far-IR emission. The level of nuclear obscuration is also a factor, but it seems to correlate with the level of star formation activity rather than the orientation of an obscuring torus.

Other recent studies show a correlation between host morphologies (level of distortion, presence of bars, and other signs of a recent interaction) and gas column densities and/or the presence of nuclear starbursts in Seyfert 2 galaxies (Matt 2000; Maiolino 2001; Levenson et al. 2001b). This is not unexpected since galaxy interactions are thought to bring an effectively large amount of gas to the galaxy centers, but it could also mean that galaxies that have been recently involved in an interaction are more likely to have formed a torus and thus present type 2 characteristics, while those involved in an earlier or less disruptive interaction or that are isolated might instead present Seyfert 1 characteristics. Furthermore, Maiolino (2001) finds that about 10% of optically classified Seyfert 2 galaxies are “fossil” AGNs; that is, although they appear to be Compton thick, this is not due to obscuration but rather to the fact that their nucleus is in a quiescent state.

All these recent results seem to imply that reflection off the torus is not sufficient to explain the hidden BLR/AGN; instead, they suggest that radio power, BLR visibility, and the 25/60 \(\mu\)m ratio are all indicative of the relative strength of the nuclear versus disk emission (see also Alexander 2001). Alternatively, there might be two types of Seyfert 2 galaxies: the Compton-thick Seyfert galaxies with hidden BLRs and strong radio emission and Seyfert 2 galaxies with absent BLRs, dust extinction at larger scales, and weak radio emission. Whether this is indicative of an evolutionary connection between two phases or of two independent Seyfert 2 classes cannot be assessed yet on the basis of the present data.

1.2. The Present Study

In Chatzichristou (2000b, hereafter Paper II) I discussed the results from aperture photometry, showing a transition in the optical and IR properties between the cold and warm samples and between the warm Seyfert 1 and 2 galaxies, with a partial overlap between the cold and the warm Seyfert 2 properties. I interpreted these results as indicative of larger dust content and recent star formation in warm Seyfert 2 (and cold) galaxies compared to their Seyfert 1 counterparts, whose optical properties are mostly dominated by their nucleus. In Chatzichristou (2001a, 2001b, hereafter Papers III and IV) I parametrized the host light and color profiles and found intrinsic differences in their properties. The Seyfert 1 nuclei tend to lie in earlier-type hosts with more centrally concentrated light compared to their Seyfert 2 counterparts. They also show opposite color gradients, which I interpreted as indicative of larger dust extinction and recent star formation in the Seyfert 2 hosts and mostly older stellar populations in the Seyfert 1 hosts. The cold galaxies are disk-dominated systems with complex morphologies and colors that are largely overlapping with the warm Seyfert 2 colors.

In the present paper I will complete this study by investigating the host morphologies and close environments of our warm and cold samples. I will then discuss the major results from Papers II–IV in connection with these interaction characteristics. I will underline the evidence for a causal connection between galactic interactions and IR/nuclear activity and will suggest a possible evolutionary link between starburst-dominated and AGN-dominated IR emission. The paper is organized as follows: In § 2, I describe my parametrization of morphologies and environments. In §§3–5, I link my current results with the major conclusions of Papers II–IV. To navigate the reader through the multiplicity of results, the most important points in each section are emphasized. In § 6, I will combine all my results in a coherent picture and will discuss the implications for the Seyfert unification model. Section 7 summarizes the conclusions.

2. Parametrization

Most statistical studies of Seyfert environments concentrate on the galaxy density within a certain (more or less arbitrary) radius. This, together with the lack of, or inappropriate, control samples, can lead to biased conclusions. In the present work I chose instead an approach that emphasizes evidence for strong interactions between the Seyfert hosts and their neighbors. Since our samples are incomplete and their IR selection criteria might favor denser environments compared to optically selected samples, I will concentrate on the environmental differences and the host morphological differences among our samples, and I will investigate how these are related to their nuclear and IR activity types.
2.1. Environments and Morphologies

I classify the objects according to their interaction stage and morphologies. For the moment, this classification is phenomenological, but as I will show throughout this paper, there is a physical basis for this classification. My interaction classification (IC) comprises four classes: I: isolated; C: objects with companions but no signs of disruption; S: strongly interacting systems where at least one of the galaxies is obviously distorted with tidal extensions; and M: mergers that are either double-nucleus systems or evolved mergers, where the two nuclei cannot be disentangled but the system possesses typical characteristics of a recent merger (for example, tidal tails emanating from the main body in opposite directions). My morphological classification comprises also four classes: N: normal, that is, objects with apparently undisturbed morphologies, no obvious tidal features, or bar-/ringlike asymmetries; B/R: barred/ringed systems (for brevity, in some of the graphs, I use the label B for the B/R class); T: objects that show some tidal feature (an obviously deformed disk, an asymmetric spiral, a one-sided tail, etc.) but do not undergo a disruptive encounter with a close-by companion; and BT: simultaneous occurrence of the last two classes, which as we will see, is an interesting discriminator by itself. The mergers (Mg) are not part of this morphological classification, but they are included in the plots together with the morphological classes for comparison with the rest of the objects. Thus, in summary, I allow for four morphological types for the isolated galaxies or systems with companions and two morphological types for the strongly interacting systems.

MacKenty (1990) classified his sample of Markarian Seyfert galaxies in a similar fashion, but his definitions are quite different from ours. His interaction classes 2 and 3 are contained in my interaction class (S), while my merger class (Mg) is not a distinct type for his classification but probably makes part of his interaction class 3 (bridge/tail/jet) or his morphological class 0 (amorphous); the latter does not correspond to any of my classes. Whittle (1992) adopted a similar two-fold classification (see also Dahari 1985; Dahari & De Robertis 1988), according to the strength of the interaction and the degree of distortion of the host galaxies, and combined the two to a “perturbation” class. Hutchings & Neff (1991) considered the interaction strength and age as the two major parameters in their interaction classification system, following a more or less subjective evolutionary “sequence.” In my approach, the interaction class represents the strength of the actual tidal perturbation between the two galaxies, while the morphological class represents the level of response of the target galaxy to a current or earlier interaction. Thus, we can recognize an early evolutionary phase (close encounter and large distortions) as well as a quiescent phase that presumably corresponds to the end of the merging sequence (isolated and symmetric hosts). Any other combination of observed characteristics is degenerate between interaction strength and interaction age, and thus its interpretation is subject to an a priori adopted evolutionary scheme. In order to disentangle these various factors as much as possible, I have chosen to also parametrize independently the strength of the gravitational perturbation as a function of the projected separation and the relative mass of the perturber galaxy (these factors are blended within the usual interaction classification schemes). This is explained in the following section.

2.2. Interaction Strength

The classification scheme described above allows for a qualification of the general environmental and interaction properties of our samples. One would also like to determine and quantify the factors that might affect the observed nuclear activity type and the development of IR excess in these objects. To decide whether the target galaxy is isolated, we have to estimate the strength of the tidal interaction with the candidate companion galaxy. This is proportional to \( \left( \frac{M_1}{M_2} / (R/D_p)^3 \right) \) (see, e.g., Byrd et al. 1986), where \( M \) and \( D \) denote the galaxy total mass (disk + halo) and the major-axis diameter, respectively, and the indices \( p \) and \( s \) are referring to the target (primary) and companion (secondary) galaxies; \( R \) is the perigalactic distance (at closer passage) of the perturber galaxy. Incorporating Dahari’s (1984) approximation for the galaxy mass \( M \sim D_1^{1.5} \), appropriate for early-type spiral galaxies, we are lead to the following definition of the interaction strength parameter:

\[
Q_D = \frac{(D_1 D_2)^{1.5}}{S^3},
\]

where \( S \) is the projected separation between the two galaxies. Dahari (1984) found a median separation \( S = 1.4 D_p \) for his (redshift-limited) Seyfert sample and defined as “strong” interactions for which \( Q_D \geq 1 \). Byrd et al. (1986) modeled the gravitational instability flows in interacting systems and found that the minimum interaction strength necessary to trigger nuclear activity is \( Q_D \approx 0.05 \) (for low halo systems). Assuming the minimum encounter separation to be \( S_{\text{min}} = D_p \), Byrd et al. concluded that the minimum dimensions for a companion galaxy to destabilize the primary’s disk are \( D_{(S_{\text{min}} = 0.05^{1/3} D_p} \approx 0.14 D_p \) (which according to them caused Dahari 1984 to miss 50% of companions for his sample because of the POSS limitations). Now if we assume an exponential light profile for the companion galaxies, it follows that the limiting magnitude for a companion is \( m_{s_{(S_{\text{min}} = 0.05^{1/3} D_p}} - m_p = 3 \text{ mag} \) (for most of our objects, I use the R-band magnitudes). For comparison, the interacting galaxies in the Vorontsov-Velyaminov Catalogue (Vorontsov-Velyaminov 1959) have a \( \Delta m_{s_{(max}} = m_s - m_p = 3 \text{ mag} \). I used the conventional limiting search radius of \( 3D_p \) for all our objects, which I justify in terms of homogeneity, given the limited image sizes. Such a choice is biased toward a particular stage of the interaction (close to perigalacticon) and possibly excludes hyperbolic encounters (the companion can move fast from perigalacticon to large distances). However, these will be common limitations for all our objects and should not affect the main purpose of this study, which is to probe the occurrence and stages of strong interactions in each of the samples, focusing in particular on their intercomparison. Since I am also interested in the properties of the companions that are most likely to have perturbed our target galaxies, I have chosen to parametrize both the brightest companion within my search radius and the closest companion to the target galaxy. In what follows, these will be referred to as the “brightest” and “closest” companions. Their magnitudes, dimensions, and separations are scaled to those of the primary galaxy.

Thus, the relevant parameters in what follows will be \( Q_D, \Delta m = m_s - m_p, D_p / D_{p_{\text{lim}}} \), and \( S / D_p \). For this study, I will use the totality of our imaged samples, that is, 21 Seyfert 1 galaxies, 33 Seyfert 2 galaxies, and 16 cold galaxies.
3. ENVIRONMENTS AND MORPHOLOGIES

Results are presented in Table 1 and Figure 1. In the left-hand panels of the latter I show the distribution of interaction classes for the three samples. The ordinate indicates the fraction of objects within each bin. In Figure 1 within each interaction class I also mark the morphological classification (the strongly interacting systems are split in two morphological groups; with or without bars/rings).

The main conclusions of my interaction classification are as follows:

1. Although there is a relative overlap in interaction properties between the three samples, the general trend is for warm Seyfert 1 galaxies to tend to be isolated, for warm Seyfert 2 galaxies to have a rather flat distribution of interaction classes, and for cold galaxies to tend to be strongly interacting systems.

2. Of the Seyfert 1 galaxies, 57% are isolated, and about half of these show tidal features. From the remaining, 29% have companions but do not obviously interact with them, and only 14% of the Seyfert 1 hosts appear in strongly interacting or merging systems. Moreover, within each interaction class, bars or rings are not common features.

### Table 1

| Interaction Class | Normal (%) | B/R (%) | Tidal (%) | Mergers (%) |
|-------------------|------------|---------|-----------|-------------|
| **Seyfert 1**     |            |         |           |             |
| Isolated          | 19         | 14      | 24        | ...         |
| Companions        | 19         | 5       | ...       | ...         |
| Interacting       | ...        | ...     | 9.5       | 5           |
| **Seyfert 2**     |            |         |           |             |
| Isolated          | 18         | 3       | 3         | ...         |
| Companions        | 15         | 6       | 6         | ...         |
| Interacting       | ...        | ...     | 12        | 18          | 9           |
| **Cold**          |            |         |           |             |
| Isolated          | 6          | ...     | ...       | ...         |
| Companions        | ...        | 12.5    | ...       | ...         |
| Interacting       | ...        | 19      | 44        | 12.5        |

Note. — Distribution of the warm Seyfert 1, Seyfert 2, and cold samples in morphological and interaction classes, as defined in the text.

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Fig. 1.—Interaction and morphological classes for our three samples. I define four interaction classes: isolated (I), companions (C), strongly interacting (S), and mergers (Mg), and four morphological classes: normal (N), barred/ringed (B), tidal (T), and barred/ringed plus tidal (BT) features (note that the mergers appear also along the morphological classes).
3. Seyfert 2 galaxies show a remarkable spread in their interaction properties: approximately 27% are isolated systems, 33% have companions, 30% are strongly interacting, and 9% are merger systems. Again, within each interaction class, bars or rings are not common.

4. Cold galaxies are clearly very different objects or in a different phase in their lifetimes compared to the warm galaxies: 63% lie in strongly interacting systems, 12% are mergers, and 18% have companions but not disruptive encounters (although all the objects in this class show bar/ ring or tidal instabilities that are likely to be triggered by their companion). Only one cold galaxy (∼7%), IRAS 02439–7455, appears to be isolated (a small companion lies at ∼8 kpc projected distance but is 5 mag fainter in R and thus was rejected by my selection criteria, described in the previous section).

To test the differences between these binned distributions, I used the χ²-test, with the null hypothesis of matching frequencies between any two samples. I find that the null hypothesis can be safely rejected in all cases, at a significance level better than 0.01.

The right-hand panels of Figure 1 show the following distribution of morphological classes for our samples:

1. Of the Seyfert 1 hosts, 38% show normal morphologies, while 19% are barred/ringed systems, and 38% have a prominent tidal feature (the majority of which are isolated systems). The combination of bar/ring+tidal features is not common (only one object), and the same holds for double-nucleus merging systems (one object). The Seyfert 1 galaxies with normal morphologies can have any type of environment, while galaxies showing some type of disk instability are preferentially isolated systems.

2. Of the Seyfert 2 hosts, 33% appear to have normal morphologies, 9% are barred/ringed systems, and 48% show at least one prominent tidal feature (the majority of which are in strongly interacting systems). The simultaneous occurrence of a bar/ring and some tidal feature is more common here (21% of the total sample). Finally, 9% of the Seyfert 2 sample (three objects) are double-nucleus mergers. Within each morphological class, objects with companions or strongly interacting systems tend to be more common, except for normal galaxies that again can reside in any type of environment.

3. Only one cold galaxy (6%) appears to have normal morphology; 69% of the sample shows tidal morphologies (among which one-third also show a bar or ring instability). Two objects (12% of the sample) are barred/ringed systems, and a similar fraction are double-nucleus mergers.

The large spread in morphological classes (causing statistically similar mean absolute and standard deviations) for our samples makes it difficult to test the statistical significance of the differences between them.

In summary, I find a clear progression in environmental properties and interaction stage between the different samples: The fraction of isolated systems dramatically decreases from Seyfert 1 to Seyfert 2 and to cold galaxies. The fraction of disruptive encounters over simple neighboring is large in cold galaxies and small in warm Seyfert 1 hosts, while there is almost an equal fraction of them in warm Seyfert 2 hosts. Similarly, the merger rate increases from Seyfert 1 through Seyfert 2 to cold galaxies. Thus, it would appear that the distinction between Seyfert 1 and 2 galaxies is not only one of simple orientation but that the latter occur in different environments, “intermediate” between Seyfert 1 and cold galaxies. This conclusion is further reinforced by the comparison of host morphologies: There is a dramatic decrease in the fraction of normal host morphologies from warm to cold galaxies, although this fraction is not very different between the two Seyfert types. The fraction of hosts showing tidal disturbances increases from Seyfert 1 through Seyfert 2 to cold galaxies, and the environmental density also increases in this sense. Furthermore, this seems to be related to the type of tidal features that appear to also be systematically different between the three samples: one-sided tails or fans in Seyfert 1 tidal arms and bridges and tails in Seyfert 2 and cold galaxies. The most likely explanation for this would be that the shape of tidal features is primarily related to the strength and frequency of (or time since) the interactions rather than to the particular characteristics of the encounter (e.g., prograde vs. retrograde, direct vs. polar, etc.). Finally, if we consider the frequency of bars and rings, independently of the galaxy’s interaction stage, there is a progressively larger fraction of barred/ribbed systems as we go from Seyfert 1 through Seyfert 2 to cold hosts. However, if we exclude from these the strongly interacting systems, the fractions of barred/ribbed hosts become similar for Seyfert 1 and 2 galaxies. The latter observation and the fact that a similar fraction of normal hosts contains the Seyfert type 1 and 2 nuclei may indicate that the orientation unification scheme applies for some Seyfert galaxies, but at least a fraction of Seyfert 2 galaxies (the strongly interacting systems) are intrinsically different objects than Seyfert 1 galaxies.

4. INTERACTIONS VERSUS OTHER PROPERTIES

To further investigate the Seyfert type 1 versus 2 relation, I searched for connections between environments and host morphologies on one hand and optical and IR properties on the other. In Figure 2, I plot some of these correlations.

4.1. Optical Properties

The optical properties are as follows:

1. There is a definite correlation between Seyfert 2 optical (in particular, disk; top row, left-hand panel) luminosities and interaction class. Moreover, within each interaction class, bars/rings or tidal features further increase the disk luminosity (see also top row, right-hand panel). In Paper II, I had found that Seyfert 2 disks are larger and brighter than Seyfert 1 disks; this might be related to the largest fraction of interacting systems among the former.

2. Seyfert 1 galaxies, on the other hand, show no correlation of nuclear optical luminosities with interaction class, but their integrated V-band magnitudes (De Grijp et al. 1992) become fainter at more advanced interaction classes (second row from top, left-hand panel). This is most likely an effect of increased dust extinction in these systems. Furthermore, tidal and barred/ribbed morphologies seem to increase the Seyfert 1 disk brightness (top row, right-hand panel).

3. In Papers II and III, I have seen that the light in Seyfert 1 hosts is more centrally concentrated compared to the Seyfert 2 and cold galaxy hosts. In Figure 2 (second row from top, right-hand panel) I now find that the degree of light
Fig. 2.—Optical and IR properties vs. interaction and morphological classes. The filled circles are warm Seyfert 1 galaxies, open circles are warm Seyfert 2 galaxies, and crossed squares are cold galaxies. (The left-hand panel in the second row from the top shows integrated $V$-band luminosities from De Grijp et al. 1992 for the Seyfert 1 sample; see text.)
concentration is also a function of morphological class (the effect being stronger for Seyfert 1 galaxies).

4. The Seyfert 2 nuclear and disk colors are uniformly distributed among interaction/morphological classes (third row from top, left-hand panel). Interestingly, the Seyfert 1 nuclei lying in isolated hosts are significantly bluer than their Seyfert 2 counterparts. Seyfert 1 galaxies in other interaction classes seem to have similar colors to the Seyfert 2 galaxies. In Paper II, I have shown that Seyfert 1 nuclei tend to be overall bluer compared to Seyfert 2 nuclei, which I demonstrate here might be related to the larger occurrence of the former in isolated galaxies.

5. Seyfert 2 galaxies show a clear trend for their host color gradients to become bluer with interaction “strength” (third row from top, right-hand panel). There are too few Seyfert 1 hosts with measured color gradients to assess any such correlation. As I have pointed out in Paper IV, Seyfert 2 color gradients are indicative of strong starbursts, which I demonstrate here are related to the host interaction stage.

6. For the cold sample, there is no clear trend for optical luminosities to correlate with environment or morphology. They are on the average fainter than both the warm Seyfert types for similar interaction/morphological classes (top row).

7. I do not observe any bimodality in any of the above properties or correlations among the Seyfert 2 galaxies of our warm sample. I instead find rather continuous distributions for the three samples, the Seyfert 2 galaxies lying between the (generally) different loci of Seyfert 1 and cold galaxies.

4.2. IR Properties

The IR properties are as follows:

1. I find that the 25 μm emission is correlated with interaction class for the warm Seyfert 2 galaxies and possibly for the cold galaxies too (Fig. 2, bottom left-hand panel). A similar correlation of L_{25} with interaction class exists for the cold sample only (not plotted). Furthermore, within each interaction class systems with tidal features have larger L_{25} values compared to barred/ringed or normal morphologies.

2. Among Seyfert galaxies that are isolated and/or have normal morphologies L_{25} is comparable for types 1 and 2, but among strongly interacting or merging Seyfert galaxies L_{25} is larger for the type 2 objects. This behavior would be consistent with a bimodality of the Seyfert 2 population. In Paper II, I had found that Seyfert 2 galaxies show overall stronger IR emission compared to Seyfert 1 galaxies, and I had attributed this to warm dust in their disks. Here I show that this result is probably due to the larger fraction of strongly interacting systems within the warm Seyfert 2 sample.

3. The cold sample galaxies show in general lower L_{25} values and similar (or larger) L_{3.6} luminosities compared to the warm sample galaxies (of both nuclear types), within the same interaction or morphological class.

The most straightforward interpretation of points 1–3 is as follows: The 25 μm emission in Seyfert galaxies is mainly due to warm dust heated by the AGN, unless these are strongly interacting type 2 systems, in which case disk star formation causes excess emission. The far-IR emission, on the other hand, is mainly due to colder dust in the host disks and is similarly enhanced by strong interactions in warm and cold galaxies. This interpretation is also consistent with the absence of any observed correlation between the α(25, 60) color index and the interaction or morphological classes. Thus, although the frequency of disruptive encounters is an important discriminator between samples selected according to their mid-IR colors, the strength of these encounters is not the only factor determining the mid-IR excess α(25, 60).

4. There is a good correlation between IR loudness α(α, 25) and interaction class for Seyfert 1 galaxies (bottom right-hand panel), mainly due to their decreasing optical luminosity (see also point 2 in § 4.1). Seyfert 2 galaxies are in general IR louder than their Seyfert 1 counterparts, with a large scatter of values for advanced interaction classes. In Paper II, I had shown that in Seyfert 1 galaxies, the IR loudness α(α, 25) anticorrelates with optical luminosities and host sizes, and I had suggested that it is primarily a measure of dust extinction and host luminosity. Here I show that this is the effect of interacting members in this class, while the isolated Seyfert 1 galaxies have a large range of optical and IR luminosities.

5. ENCOUNTER CHARACTERISTICS

In the previous section I have shown that some of the important differences between Seyfert type 1 and 2 galaxies are related to their (different) environmental properties, providing clear evidence against the simple orientation model often postulated for Seyfert galaxies. Furthermore, I have found that the IR-cold galaxies have markedly different environmental properties compared to the IR-warm Seyfert sample, in particular the type 1 Seyfert galaxies. It is thus of great interest to determine (1) what environmental factors influence the observed nuclear Seyfert type and (2) will a cold galaxy develop nuclear activity and mid-IR excess in some later interaction stage? In this section I will address these questions by studying the close environments of the nonisolated objects in our samples. These include eight Seyfert 1 galaxies, 20 Seyfert 2 galaxies, and 12 cold galaxies.

The distributions for the quantities Q_{Dp}, M_{L} - M_{p}, D_{s}/D_{p}, and S/D_{p} (defined in § 2) are plotted in Figure 3 for the brightest and closest companions. The median values and standard deviations of these distributions are given in Table 2.

5.1. Brightest Companions

5.1.1. Separation

I first consider the brightest companions in all samples, selected as described in § 2. Their distributions are plotted on the four upper panels of Figure 3. The projected separations S normalized by the diameter of the primary D_{p} span a large range for the warm sample, with a median value of 1.2 (projected separation ~40 kpc) for the Seyfert 2 galaxies and 1.57 (projected separation ~29 kpc) for the Seyfert 1 galaxies. In fact, the distribution of Seyfert 1 bright companions is rather flat, showing a similar probability for a galaxy to have a companion at 1D_{p} or 4D_{p}, while the Seyfert 2 companion distance distribution is more segregated between 1 and 2D_{p}. This is expected, given the larger fraction of disruptive encounters found among the latter. The median relative separation in Dahari’s Seyfert sample was
$S/D_p = 1.4$ (Dahari 1984), comparable to the median for the whole warm sample. The cold galaxies show a very different distribution peaking at smaller values, with a median of 0.56 (projected separation $\sim 22$ kpc). This quantifies my earlier statement that the mid-IR cold sample contains almost exclusively strongly interacting systems. The $F$- (variance) and K-S tests show statistically significant difference in the warm and cold galaxy distributions of projected companion separations (according to the K-S test, the probability that any two samples are drawn from the same parent

### TABLE 2

**Median Values and Standard Deviations for Derived Quantities**

| Statistical Property | Brightest Companions | Closest Companions |
|----------------------|----------------------|---------------------|
|                      | $S/D_p$ | $\log [Q_d]$ | $D_s/D_p$ | $M_s - M_p$ | $S/D_p$ | $\log [Q_d]$ | $D_s/D_p$ | $M_s - M_p$ |
| **Seyfert 1**        |         |               |         |          |         |               |         |          |
| Median               | 1.57    | -0.91         | 0.8     | 1.74     | 1.41    | -0.82         | 0.70     | 1.56     |
| $\sigma$            | 1.55    | 1.25           | 0.50    | 1.51     | 1.19    | 1.11          | 0.50     | 1.47     |
| **Seyfert 2**        |         |               |         |          |         |               |         |          |
| Median               | 1.20    | -0.91         | 0.50    | 1.59     | 0.88    | -0.54         | 0.50     | 1.88     |
| $\sigma$            | 1.09    | 1.20           | 0.51    | 1.70     | 1.09    | 1.16          | 0.49     | 1.61     |
| **Cold**             |         |               |         |          |         |               |         |          |
| Median               | 0.56    | 0.16          | 0.60    | 1.79     | 0.78    | -0.07         | 0.70     | 1.61     |
| $\sigma$            | 0.81    | 1.02           | 0.50    | 1.21     | 0.98    | 1.19          | 0.32     | 1.24     |

**Note.** $S/D_p$: Separation of two galaxies normalized to the major-axis diameter of the primary. $Q_d$: Interaction strength (as defined in text). $D_s/D_p$: Ratio of major-axis diameters of companion and primary galaxies. $M_s - M_p$: Optical magnitude (mostly $R$) difference between companion and primary.
population is smaller than 5%). For both samples, the absolute projected separations were ≤120 kpc, which is approximately the typical search radius in most recent studies of the (optically selected) Seyfert environments.

5.1.2. Companion “Mass”

Galaxy separation is not the only factor that determines the strength of an interaction; the tidal force is also proportional to the relative mass of the companion (§ 2). Since we have no direct “mass” measure, we can instead use its relative size or luminosity. In Figure 3 I show the distribution of major-axis ratio and magnitude difference between the companion and primary galaxy. At first sight, the relative sizes of the Seyfert 1 and 2 companions are quite similar, whereas the cold galaxy companions have a tendency to be larger. The three distributions are statistically similar according to the F- (variance) and Student’s (mean) tests with medians in the range 0.5–0.8. However, the K-S test shows that the Seyfert 2 and cold galaxy companion relative sizes are likely to be drawn from the same population at a significance level of 99.6%, while the same test remains inconclusive (significance <95%) when comparing the Seyfert 1 to the Seyfert 2 or the Seyfert 1 to the cold samples. Fuentes-Williams & Stocke (1988) in their study imposed a lower limit on the companion diameters \(D_c \geq 0.25D_p\) (in order to disentangle stars from galaxies on the POSS plates). From Figure 3 we see that applying a similar limit to our samples would have caused us to miss ~30% of the Seyfert 2 and cold galaxy companions. The distributions of companion relative brightnesses are also shown. They appear to be similar for the two Seyfert types, with the cold companions shifted to somewhat fainter magnitudes (that is, larger \(\Delta m\)). However, statistical tests performed on the three distributions show the same results as above; that is, that the Seyfert 2 and cold samples do not differ at a statistically significant level (confidence at the 98.2% level), while it remains inconclusive in the other cases. The median values of companion relative brightnesses are in the range 1.55–1.8 mag for all three samples. Rafanelli, Violato, & Baruffolo (1995) have imposed a selection criterion more stringent than ours \([\Delta m/\text{max} = 3\text{ mag}]\) based on the distribution of relative companion magnitudes in the Vorontsov-Velyaminov Catalogue (Vorontsov-Velyaminov 1959). From Figure 3 we see that such a limit would cause us to miss ~20% of the companions in each sample.

5.1.3. \(Q_D\)

Let me now consider the interaction strength \(Q_D\) that includes both companion mass and separation. The warm Seyfert 1 and 2 galaxies have similar distributions (99.99% significance of the K-S test) and median \((0.12)\). The cold galaxies have significantly larger \(Q_D\) values (median 1.44) than the Seyfert samples (the K-S test lends <95% significance to the null hypothesis of similar distributions). Dahari (1984) has found that the fraction of Seyfert to normal galaxies in his sample is ~7 when \(Q_D \geq 1\) and drops to 2 when \(1 < Q_D < 0.05\), which suggests that Seyfert galaxies are more likely to have close and/or more massive companions to perturb them. The median \(Q_D\) value in his Seyfert sample was 1.18, and he suggested that \(Q_D \geq 1\) defines “strong” interactions. Byrd et al. (1986) showed that tidal triggering can be a physically sufficient mechanism to induce nuclear activity through the formation of bar or spiral instabilities and consequent mass inflow into the nuclear regions. They modeled the gravitational instability flows in terms of \(Q_D\) and \(Q_O\) = halo/disk mass and found such instabilities to set in for \(Q_D \geq 1\) independently of \(Q_O\) and for \(Q_D \geq 0.05\) only for low halo systems. In our warm Seyfert galaxies I find a similar fraction of types 1 and 2 (25%–30%) with \(Q_D \geq 1\), with this fraction increasing up to ≥50% for the cold sample.

I conclude that if the presence of bright companions within a radius of three galaxy diameters dominates the environmental effects in IR-luminous galaxies, my results indicate that the interaction strength (and in particular the companion proximity) is an important discriminator between mid-IR warm and cold galaxies.

5.2. Closest Companions

Let me now consider the properties of the closest companions (four lower panels of Fig. 3). As before, I find similar distributions for the companion relative “mass” (sizes or magnitude) but significantly different distributions of projected separation (smaller for Seyfert 2) and interaction strength \(Q_D\) (larger for Seyfert 2). It is intriguing, on the other hand, that both the Seyfert 2 and cold samples have similar \(Q_D\) and relative projected separations. I suggest that these differences are likely to reflect the denser environments of Seyfert 2 and cold galaxies compared to Seyfert 1 galaxies. Thus, among warm nonisolated Seyfert galaxies, the proximity of close companions seems to be a discriminator between nuclear activity types. However, in none of these cases does the K-S test lend significance larger than 95% to the null hypothesis of matching distributions; thus, any of the above results remains purely qualitative.

5.3. \(Q_D\) versus IR Properties

The main correlations found between interaction strength and mid-IR properties are shown in Figure 4. The open circles indicate Seyfert 2 galaxies (members of interaction class S are marked with a cross), the filled circles indicate Seyfert 1 galaxies, and crossed squares indicate the cold galaxies. The correlations are described as follows:

1. **Upper four panels.**—The strongly interacting Seyfert 2 galaxies (crossed circles) tend to show stronger mid- and far-IR luminosities compared to the rest of the warm sample (either Seyfert 1 or Seyfert 2 types). A similar correlation exists for the cold galaxies, for which the IR luminosities \(L_{25}\) and \(L_{125}\) correlate with interaction strength or projected separation (at significance level better than 0.03 according to the Spearman’s rank correlation test). Comparison between the warm and cold samples in all cases shows that warm Seyfert galaxies (of both nuclear types) have larger \(L_{25}\) than cold galaxies with similar interaction strength. These results support the conclusions that I reached earlier (§ 4) from different parameters: The excess \(L_{25}\) in warm Seyfert galaxies is mainly due to the AGN contribution, but it is further enhanced in strongly interacting Seyfert 2 hosts. In cold galaxies, we see mainly interaction-induced IR activity at all wavelengths.

2. **Lower four panels.**—The IR-loudness coefficients correlate with interaction strength and anticorrelate with relative separation for the warm Seyfert 1 sample (at significance level better than 0.005 according to the Spearman’s rank correlation). We have seen previously that the IR loudness in Seyfert 1 galaxies correlates with interaction
Fig. 4.—IR properties $\log L_{25}$ and $\log L_{\text{FIR}}$ (in solar units $L_\odot$) and IR loudness indices $\alpha_{(\text{F}, 25)}$, $\alpha_{(\text{F}, 60)}$ vs. projected separation $S$ (in kiloparsecs) or $S/D_p$ (scaled to the size of the target galaxy) and interaction strength $\log Q_D$, for our three samples. Symbols are as in Fig. 2 (crossed open circles indicate strongly interacting Seyfert 2). The labels "1" and "2" indicate the nuclear types of the cold sample Seyfert galaxies.
3. There are no significant correlations between any of the IR color indices $\alpha_{(25,60)}$, $\alpha_{(60,100)}$ and interaction strength for any of the samples. This is a significant result because it indicates that although the strength of tidal perturbations is a discriminator between warm and cold samples, the mid-IR excess (or lack of) is not a simple function of interaction strength, a conclusion reached earlier (§ 4.2) from different parameters.

5.4. Cold Seyfert Galaxies

At this point it is interesting to consider the properties of four galaxies in our cold sample that are known to harbor Seyfert nuclei: (1) type 2 IRAS 04265–4801 (interacting) and (2) type 1 IRAS 06506+5025 (barred galaxy with companion) have the lowest IR luminosities in the cold sample. In Paper II we have seen that they are also faint in optical wavelengths (among the faintest compared to the respective warm Seyfert samples) and have very red colors, at all spatial scales. Thus, it is likely that their cold mid-IR colors are due to large amounts of cool dust within their hosts and/or to an intrinsically faint AGN. The former is certainly the case for IRAS 04265–4801, which suffers large extinction so that even its nucleus cannot be unambiguously identified (see Paper IV). IRAS 06506+5025 has a rather complex color distribution (also Paper IV), and both the above factors are likely to be responsible for its cold mid-IR colors. It is interesting that both of these cold Seyfert galaxies show the smallest interaction strength $Q_p$ among all galaxies in the cold sample. The other two cold Seyfert galaxies, (3) IRAS 23128–5919 (merger) and (4) IRAS 19184–7404 (strongly interacting), both of nuclear type 2, are among the most IR-luminous objects in our cold sample. The latter object is shown in Figure 4 (labeled “2”) to have similar interaction strength and $L_{25}$ as the warm sample. Thus, the cold 25–60 $\mu$m colors of these two Seyfert galaxies are likely due to their excess far-IR luminosity. Although such a small number of cases is not enough to establish firm conclusions, the existence of these very different cases of cold Seyfert galaxies indicates that the occurrence of a mid-IR excess must be related to some intrinsic properties of the host galaxy rather than being merely a transition period in the evolution of strongly interacting systems. The evolutionary interpretation could account for the fact that the cold galaxies show statistically larger $Q_p$ than the warm sample (§ 5.1), and this might indeed be the case for the two powerful cold Seyfert 2 galaxies (cases 3 and 4). However, the existence of the other two IR-fainter cold Seyfert galaxies implies that other factors, maybe related to the properties of the progenitor galaxy, are contributing to the development (or lack) of the mid-IR excess.

5.5. Mergers

The objects classified as mergers in our IR-warm and IR-cold samples are either systems possessing double nuclei within a common envelope or advanced merger remnants possessing two tidal tails emanating from the same body in opposite directions. There are four mergers within our warm sample, one Seyfert 1 and three Seyfert 2 galaxies, and two mergers within our cold sample, one of which is a Seyfert 2 galaxy. In Table 3 I list some of their properties, and R-band images are shown in Figure 5.

The three warm Seyfert 2 mergers, independently of coalescence state, have larger IR and optical disk luminosities, fainter and redder nuclei, and warmer 60–100 $\mu$m and colder 25–60 $\mu$m colors compared to the (only) warm Seyfert 1 merger. This is consistent with the idea that the Seyfert 2 mergers contain a larger fraction of warm dust in their nuclear regions and enhanced star formation in their disks. This is also the case for the cold Seyfert 2 merger, which shows comparable large IR luminosities and warm 60–100 $\mu$m colors (no optical photometry available) as the warm Seyfert 2 mergers. In Paper IV, I had shown that all the double-nucleus mergers in our samples have remarkably similar color and line emission morphologies: one of the two nuclei is brighter and redder, and the line emission is centered on it with an extended morphology in direction perpendicular to the line connecting the two nuclei. The evidence for larger extinction in the Seyfert 2 mergers suggests that their optical spectral classification is most likely to be affected by obscuration. Indeed, the case of IRAS 13536+1836 was studied in great detail (see, e.g., Chatzichristou & Vanderriest 1995 and references therein) and was found to show Seyfert 1 characteristics in polarized light. It is thus likely that, given their common properties, the other three double-nucleus mergers...
are similar objects to IRAS 13536+1836. If there is an evolutionary sequence between the Seyfert 1 and 2 types, as I suggest later in this paper, the Seyfert 2 merger cases might be representing this rare phase of transition from nuclear type 2 to type 1. The small number of objects (six) examined here and their varied properties provide circumstantial evidence but do not allow us to further establish firm conclusions. A follow-up project to map the detailed morphologies, kinematics, and ionization of selected double-nucleus mergers is under way.

6. DISCUSSION

6.1. Environments and Interactions

Observationally and theoretically, there are indications that transient encounters and accretion of small companions are responsible for triggering nuclear activity by funneling gas to the central black hole (through bar formation for instance). On the other hand, violent interactions would lead rather to complete destruction of the disks involved and trigger large-scale star formation events, such as the ones seen in ultraluminous infrared galaxies (ULIRGs; see, e.g., Combes 2001; Sanders & Mirabel 1996 and references therein). Indeed, several recent studies leave little doubt that mergers cause IR excess emission, especially in the most luminous IR galaxies (e.g., Sanders 1999 and references therein). Optically selected samples of AGNs show interactions in only a small fraction of objects; among IR-selected samples, however, this fraction is much larger, increasing systematically with IR power (Veilleux, Kim, & Sanders 1999; Gallimore & Keel 1993). All evidence so far considered indicates that interactions and mergers are an important triggering mechanism for powerful quasars and radio galaxies. However, this remains a controversial issue in the case of low-power AGNs and, despite the large number of related studies, nonconclusive.

Fig. 5.—R-band gray-scale images and overplotted contours for the six mergers in our warm and cold samples. The image sizes are IRAS 1958–1818: 19.8 $\times$ 19.8 kpc; IRAS 13536+1836: 130 $\times$ 130 kpc; IRAS 19254–7245: 270 $\times$ 270 kpc; IRAS 00198–7926: 72 $\times$ 72 kpc; IRAS 23128–5919: 83 $\times$ 83 kpc; and IRAS 03531–4507: 180.4 $\times$ 180.4 kpc.
There have been several recent reviews of the statistical properties of Seyfert galaxy environments (e.g., Laurikainen & Salo 1995; Dultzin-Hacyan et al. 1999). These involve mainly studies of the frequency of either AGN occurrence in morphologically disturbed galaxies or disturbed host morphologies and/or dense environments among Seyfert samples. In the first approach, no excess of Seyfert nuclei (and often even a lack of them) is found in disruptive systems, and only a marginal excess among systems at lower interaction levels is found (see, e.g., Keel et al. 1985; Dahari 1985; Bushouse 1986; Sekiguchi & Woltzencroft 1992). In the second approach, the results are more contradictory: an excess (compared to normal galaxies) of companions has been reported for Seyfert samples (see, e.g., Dahari 1984; MacKenty 1989; Monaco et al. 1994; Rafanelli et al. 1995). However, other studies suggest that Seyfert and control sample environments are comparable (e.g., Fuentes-Williams & Stocke 1988; Laurikainen & Salo 1995; De Robertis, Yee, & Hayhoe 1998). In fact, the situation seems even more complicated since sometimes excess of only faint companions or at earlier epochs, or (3) central elongations and even a lack of them) is found in disruptive systems. Indeed, most of the criteria used in the search for companions favor close environments (typically a few times the diameter of the target galaxy, as in the present study), relatively bright companions, and a particular interaction phase when the two systems are bound but not yet merged. Furthermore, environmental studies often are not coupled to morphological examination and thus might be missing (1) faint tidal features that indicate an evolved merger or tidal perturbations due to a faint companion (or a companion lying outside the maximum search radius), (2) bars and rings that suggest perturbation by smaller companions at or earlier epochs, or (3) central elongations and even faint secondary nuclei that indicate a recent merger.

When Seyfert 1 and 2 galaxies are considered separately a much clearer environmental connection appears. In general, the relative densities in Seyfert 2 environments are found to be 1.6–2.7 times larger than those of normal galaxies, while Seyfert 1 galaxies have identical or even smaller density of companions compared to normal galaxies (Laurikainen & Salo 1995). The larger density of Seyfert 2 companions was reported to depend strongly on morphological type (Petrosian 1982; MacKenty 1989; Dultzin-Hacyan et al. 1999 and references therein). However, Maiolino et al. (1995) found no significant differences in the Hubble types of Seyfert 1 and 2 galaxies and concluded that the enhanced star formation activity, often postulated for Seyfert 2 galaxies, does not seem to be related to the prevalence of late-type disks among them. However, these results are contradicted by other recent studies in which different host morphological types are often postulated, with type 1 nuclei residing in earlier type hosts than type 2 nuclei (see, e.g., Malkan et al. 1998). An important consequence of these studies is that they imply strong differences in host galaxy properties between the two Seyfert types, which is contradictory to the strong unification model postulating that the only difference between Seyfert nuclear types is the orientation of their central engine with respect to the observer.

How do my results compare to the above? The fraction of systems with companions is generally larger in our IR-warm Seyfert sample compared to the optical Seyfert samples: 43% and 63% of our warm Seyfert 1 and 2 galaxies, respectively, show signs of a current or previous interaction. Indeed, we already know that IR activity probes strong interactions, but more importantly, in our sample I find twice as many Seyfert 2 as Seyfert 1 galaxies in strongly interacting/merging systems (see § 2 for a definition). In Paper III, I found a tendency for Seyfert 1 nuclei to reside in earlier type hosts (peaking around SO-SO/a) compared to their Seyfert 2 counterparts (peaking at Sa types). These results are in general agreement with the studies of optical Seyfert samples (described above). Among our IR-warm Seyfert galaxies with companions, I find a smaller fraction, 25%–30%, than in Dahari’s sample to have $Q_D \geq 1$ (similar for types 1 and 2), this fraction increasing to 50% for the cold (mostly non-Seyfert) sample. Thus, the evidence for a causal connection between galactic interactions and type of nuclear activity is substantial. Considering the results presented in §§ 3–5, the development of nuclear activity and its observability appear to depend on the time elapsed since the interaction occurred and probably also on the host intrinsic properties.

I now address the question of whether important differences exist between isolated Seyfert 1 and 2 galaxies. In optical samples, the fraction of solitary Seyfert galaxies ranges between 10% and 25%. This is comparable to the fraction that I find (similar for type 1 and 2) among warm Seyfert galaxies if we consider undisturbed, nonbarred/ringed systems. However, when considering the totality of our warm sample, the fraction of isolated systems increases by factors of 3 and 1.5 for the Seyfert 1 and Seyfert 2 galaxies, respectively. In other words, the majority of Seyfert 1 nuclei lie in “isolated” hosts with disturbed morphologies, which suggests that these are in fact “pseudoisolated.” It is possible that they have experienced multiple tidal perturbations from faint companions, too faint to be considered as such. Alternatively, the apparent isolation of Seyfert 1 hosts could be a long-lasting effect of encounters: we might be seeing systems at their latest stages of merging, or on the contrary, dynamical friction in their vicinity might have gradually led to the removal of companions (see, e.g., Laurikainen & Salo 1995). Whichever of these two scenarios applies (different environments or evolutionary effect) our data show that there is a fundamental difference between the Seyfert 1 and 2 “isolated” galaxies in our sample. I favor the evolutionary effect because, as we saw in §§ 5.1 and 5.2, among the nonisolated Seyfert galaxies there is no significant difference in the companion relative sizes and luminosities of the two Seyfert types. Thus, there is no reason to postulate different, more disruptive environments for Seyfert 2 galaxies.
6.2. Morphologies

How common are disk instabilities and what do they imply for the recent interaction history of a galaxy? From a theoretical point of view, the modeling of interactions/mergers between two disk/halo systems of comparable mass commonly shows tidal triggering of central bars that perturb the orbits of gas and stars in the host galaxy causing infall and circumnuclear star formation, with subsequent AGN feeding/triggering (see, e.g., Byrd et al. 1986; Barnes & Hernquist 1996; Mihos & Hernquist 1996; Mihos 1999). Since the characteristic timescale for the starburst and nuclear activity phases is comparable ($\sim 10^8$ yr) and much shorter than the interaction timescale (but comparable to the late merger phase), it is more probable to observationally associate activity with morphological distortions or the presence of multiple nuclei than with the excess of nearby companions (see, e.g., Combes 2001). Although some observational work indicates a prevalence of kiloparsec-scale distortions (bars/rings) in Seyfert galaxies (Simkin, Su, & Schwarz 1980; Dahari 1984; Moles, Marquez, & Perez 1995; Peletier et al. 1999; Knapen, Shlosman, & Peletier 2000), according to other optical and IR studies, the frequency of occurrence of such features among Seyfert galaxies (25%–30%) is similar to that among normal spiral galaxies (e.g., MacKenty 1990; McLeod & Rieke 1995; Mulchaey & Regan 1997; Regan & Mulchaey 1999; Hunt & Malkan 1999). In fact, a few workers find that the presence of bars inhibits AGN segregation (e.g., Monaco et al. 1994). Thus, the observational evidence so far suggests that either bars are not a universal fueling mechanism, the bar formation inhibits gas infall (stabilizing the disk) and thus AGN triggering, or bars tend to be destroyed after the formation of a black hole (Hasan & Norman 1990; Pfenniger & Norman 1990). In fact, since nuclear activity requires that consumption of only 0.01 $M_\odot$ yr$^{-1}$ during $10^8$ yr, external triggering might not even be necessary to induce nuclear activity. However, external mechanisms are usually required to trigger large-scale starbursts. Recent observational evidence suggests a clear correlation between starburst activity versus bar frequency and a possible association between nuclear activity versus the presence of rings (LINERs have mostly inner rings, Seyfert galaxies mostly outer rings). In turn, this might be indicative of the differing timescales of the starburst and nuclear activity: bars can form within $10^8$ yr, triggering a starburst in the same timescale, whereas rings form in the dynamical timescales of the outer regions, i.e., within $10^9$ yr. Thus, we might consider these morphological clues as independent evidence for the evolutionary connection between starburst and nuclear activity in strongly interacting galaxies.

In our sample of warm Seyfert galaxies, after excluding the strongly interacting systems, I find a similar fraction of barred/ringed galaxies among Seyfert 1 and 2 hosts. However, the Seyfert 1 hosts tend to be purely barred/ringed and isolated, whereas the Seyfert 2 hosts often show additional tidal features, and most of them have at least one detectable companion. Interestingly, all the strongly interacting Seyfert galaxies in our sample that have bars/rings are of type 2. The fact that bar/ring and tidal features seem to be mutually exclusive in Seyfert 1 galaxies (only one possible candidate), whereas their simultaneous appearance is common in Seyfert 2 galaxies (especially when strongly interacting systems are considered), most likely reflects the differing evolutionary lifetimes of the bar and tidal features and/or the differing rates of bar versus tidal formation in different types of interactions (see also § 6.4). These results could thus be interpreted in the evolutionary context outlined above (Seyfert 2 galaxies are at an earlier interaction stage than Seyfert 1) or, alternatively, could be indicating that the two Seyfert populations represent different types of objects.

6.3. IR Activity and Star Formation

If interactions and Seyfert activity are linked by an evolutionary sequence, we can ask whether starburst and Seyfert activities are similarly linked. There is ample observational evidence in the recent literature suggesting that, while mainly old stellar populations are found in the Seyfert 1 hosts, circumnuclear and disk starbursts (1–100 Myr) occur in a large fraction of Seyfert 2 hosts (30%–50%) and contribute significantly to their overall energetics (Cid Fernandes & Terlevich 1995; Cid Fernandes, Storchi-Bergmann, & Schmitt 1998; Cid Fernandes et al. 2001; Heckman et al. 1995, 1997; Heckman 2000; Maiolino et al. 1995, 1997; Oliva et al. 1995, 1999; Hunt et al. 1997; González Delgado et al. 1998, 2001; Gonzalez Delgado & Heckman 1999; Storchi-Bergmann, Cid Fernandes, & Smitt 1998; Storchi-Bergmann et al. 2000; Schmitt, Storchi-Bergmann, & Cid Fernandes 1999; Aretxaga et al. 2001; Levenson et al. 2001a, 2001b). The ratio of Seyfert to starburst galaxies was found to be a function of IR power, and it was suggested that it is also a function of time since a merger occurred (Sanders 1999;Veilleux et al. 1999 and references therein). For those Seyfert galaxies with a composite starburst+AGN nature, usually it is the starburst that dominates the far-IR and radio properties up to the 90% level (Hill et al. 1999, 2001; Rigopoulou et al. 1999; Cid Fernandes et al. 2001).

In the latter study it was indeed shown that composite-type S2 galaxies are more powerful in the IR than “pure” S2 galaxies by a factor of 5 or than typical starburst galaxies, and almost all have $L_{\text{FIR}} \leq 10^{10} L_\odot$. Furthermore, more of the composite S2 galaxies (~50%) are strongly interacting systems, while this was not the case for “pure” S2 galaxies (only 20%). Similar results were presented by Storchi-Bergmann et al. (2001) and Mouri & Taniguchi (2002) from the analyses of optically and UV-selected Seyfert and starburst galaxies and by Levenson et al. (2001a, 2001b) on the basis of X-ray data for samples of pure and composite Seyfert 2 galaxies. The latter study shows that the starburst dominates the soft X-ray emission of composite S2 galaxies, while in pure S2 galaxies virtually all (soft and hard) X-ray emission is due to the AGN. The preferential association of composite S2 galaxies with strongly interacting systems suggests a causal relationship between interactions and circumnuclear star formation and an evolutionary relationship between composite and pure Seyfert 2 galaxies, thus, an evolutionary link between the starburst and AGN phases.

It has been proposed that AGNs and starburst galaxies can be linked according to the following evolutionary scenario (see, e.g., Sanders et al. 1988; Sanders & Mirabel 1996; Sanders 1999; Osterbrock 1993; Tran 1995c): The interaction of two gas-rich spiral galaxies funnels gas into the nuclear regions triggering intense star formation and, if there is already an AGN in the center, obscuring the BLR. The massive starburst produces the bulk of IR luminosity in
these initial stages of the merging process. When the gas becomes more concentrated (within the central <1 kpc) it feeds the central black hole, triggering the AGN that progressively dominates the luminosity output of the system; this corresponds to the peak IR phase. As time goes by, superwinds from the newly formed stars will clear away interstellar material from the central regions, so that most of the circumnuclear starburst eventually stops, while the AGN fueling continues for a while. During this phase, the AGN becomes visible, and warmer IR colors might develop, this primarily depending on the small-scale (torus) geometry. Sanders (1999) notes that most highly IR-luminous (L_{FIR} \sim 10^{13} L_{\odot}) galaxies were first characterized as "dusty Seyfert 2 galaxies" and later on shown to be obscured Seyfert 1 galaxies (or, at those luminosities, QSOs). A similar evolutionary scenario was suggested by Barthel (2001) on the basis of far-IR/radio indices. Hutchings & Neff (1991) studied a sample of IRAS galaxies with a range of IR and nuclear activity types. They found that the steep spectrum (\alpha \sim -1.3) galaxies (whether these are H II, LINERs, or Seyfert 2 galaxies) are the younger and stronger interactors and show larger dust obscuration, whereas the flat spectrum (warm) Seyfert 1 and 2 galaxies appear to be intermediate-age/strength interactors. The authors suggested that the level of IR warmness might represent different evolutionary paths of active galaxies: the steep-spectrum Seyfert 2 galaxies are at an earlier evolutionary stage than the flat spectrum Seyfert galaxies, and the type 2 nuclei are "hidden" type 1 nuclei at the flat-spectrum stage. Canalizo & Stockton (2001) have tested the evolutionary scenario between the AGN and ULIR phases and their relationship to the interaction stage of the host galaxies for a sample of galaxies supposed to be in the intermediate stage between ULIRGs and QSOs. They suggested that the galaxies' locations in the far-IR color-color diagram indicate an evolutionary sequence, with the younger objects occupying the ULIR region and the older the QSO region. All transition objects show strong star formation, on-going or up to 500 Myr old. The authors suggested that the ULIRGs evolve to QSOs with a short transition time (their evolutionary model resembles much the scenario described above). Although the lifetimes, spatial density, and bolometric emission of ULIRGs and QSOs seem to be comparable, recent studies suggest that QSOs and ULIRGs could coexist rather than being merely stages of a standard evolutionary path. Since both phenomena are relatively short-lived, multiple ultraluminous phases might be excited during the merger process (Murphy et al. 1996; Martini & Weinberg 2001; Farrah et al. 2001). Furthermore, the luminosity evolution of the system during the merger process might be such that the system alternates between luminous and ultraluminous IR phases (Barton, Geller, & Kenyon 2000). Farrah et al. (2001) find a remarkable diversity in the morphologies and merger stages of ULIRGs, whether these contain a QSO or not. Thus, it is unlikely that the ultraluminous phase is a simple transition stage toward the QSO formation. Instead, Farrah et al. suggest that the time evolution of the starburst and AGN activity during a merger is related to the diversity of progenitor morphologies and local environments. The evolutionary sequence proposed earlier might still hold for a subset of ULIRGs, associated with violent mergers of gas-rich galaxies.

My study of two IR-warm and IR-cold samples (selected according to the shape of their spectra between 25 and 60 \mu m) probes such an evolutionary link between starburst-dominated and AGN-dominated IR emission. Star formation is almost certainly the dominant source of far-IR emission in both starburst and Seyfert galaxies, whereas a combination of AGN and starburst thermal components is most likely the origin of the mid-IR emission in Seyfert galaxies (see, e.g., Bonato & Pastoriza 1997; Rodríguez-Espinosa & Pérez-García 1997; Sanders 1999). The relative contributions of these two components seem to be related to the type of Seyfert activity (higher dust temperatures for the type 1). Many of my results, presented in Papers II–IV and this paper, support these hypotheses: (1) The warm Seyfert 2 disks tend to be brighter than the warm Seyfert 1 disks at optical wavelengths, and their mid- and far-IR properties correlate with total optical luminosities and host galaxy size, indicating that the bulk of Seyfert 2 IR emission originates in their disks. Optical colors indicate that Seyfert 2 galaxies are overall more dusty than Seyfert 1 galaxies, their nuclei suffering the highest obscuration. (2) The Seyfert 2 color and emission-line distributions indicate starbursts of 1–0.5 Gyr or younger, superposed on the older galaxy population. Their color gradients (the starburst age) correlate with the host interaction strength and IR luminosity. The warm Seyfert 1 hosts show opposite color gradients and mostly older stellar populations. (3) The 25 \mu m emission in warm Seyfert galaxies seems to be primarily related to the AGN, but in strongly interacting systems (and thus, primarily in Seyfert 2 galaxies) it is further enhanced by disk star formation. On the other hand, the IR luminosity of 60 \mu m appears to be mainly excess emission at large scales and is similarly enhanced by strong interactions in the warm and cold samples. (4) In cold galaxies, the bulk of IR emission seems associated with dust in their disks, heated by strong star formation. In the large majority, these systems undergo disruptive encounters; their mid-/far-IR emission increases with interaction strength, and their 25–60 \mu m colors become colder at smaller projected separations. (5) I find a transition in most of the observed optical and IR properties between the cold and warm samples and between the warm Seyfert 2 and Seyfert 1 galaxies: (in this order) brighter nuclear magnitudes, bluer nuclear optical colors, bluer 12–100 \mu m colors, decreasing IR excess and IR loudness, increasing companion separations, and decreasing interaction strengths. This transition is further expanded to the structural (bulge, disk) parameters and host morphologies.

These results sustain an evolutionary scenario between the IR-warm and IR-cold galaxies that could explain their differing dust temperatures and dominant activity type. However, the occurrence of (at least) four Seyfert galaxies in the cold sample with a range of optical and IR properties indicates that factors other than evolution, such as the gas and dust content of the progenitor galaxies and the interaction geometry, might also be important for determining whether the merging galaxies will go through an IR-warm phase. Most of the warm Seyfert 2 properties are shared with the cold galaxies, while they are markedly different from the Seyfert 1 galaxies. It is possible that these differences indicate that the Seyfert 1 and 2 hosts are intrinsically different objects, but the correlation of many of these properties with interaction strength and the observed transition between cold and warm type 1 and warm type 2 galaxies, clearly favor an evolutionary connection between them. In summary, the plausibility of a scenario in which strong interactions are responsible for both enhanced star formation and
activation of the galactic nucleus suggests that Seyfert 1 and 2 galaxies might represent different phases in an evolutionary cycle.

6.4. An Interaction Sequence

The observational evidence put forward in the previous section does not sustain the simple orientation/obscuration picture for the unification of Seyfert types 1 and 2, although it might be true for some Seyfert 2 nuclei. An alternative view would be one that takes into account the time evolution of environmental and morphological properties of Seyfert galaxies. Failure to consider these factors in Seyfert environmental studies is likely to account for the discrepancies in the results of some previous studies.

6.4.1. Important Timescales

Numerical simulations have shown that the minimum interaction strength needed to trigger disk instabilities can be reached (1) during the perigalactic passage of very small companions, (2) by larger companions at greater distances (~30Dp or more), or (3) in massive hyperbolic encounters where shortly after perigalacticon, ~10^8 yr, the companion reaches large distances. Theoretical considerations suggest that in major mergers of two galaxies of comparable mass, it is the internal structure of the primary disk that is the main regulator of the gas accretion and thus of the starburst/nuclear activity triggering processes. A strong and centrally concentrated bulge would stabilize the disk against bar formation and thus prevent gas inflow until the final merging of the galaxies. Another important parameter that gives clues about the interaction geometry and age is the type and extent of the observable tidal perturbations. Tidal tails are formed in prograde collisions but not in retrograde ones; in the latter less violent case, a transient tidal arm might instead be developed. Thus, the generally less spectacular tidal tails in IR-selected interacting galaxies (compared to their optical counterparts) might be indicating a broad range of spin orientations (as opposed to the prograde-prograde encounters in most optical pairs). Long tidal tails at an earlier phase might give their place to shells and ripples at a later stage. Furthermore, prograde encounters are more likely to trigger gas inflow through a bar instability compared to retrograde encounters.

Let me now outline a possible sequence of events during the interaction and eventual merging of two disk galaxies of comparable mass (some of the most relevant references that we used for this section are Byrd et al. 1986, 1987; Noguchi 1988; Hernquist 1989; Turner 1991; Bernloehr 1993; Osterbrock 1993; Maiolino et al. 1995; Hibbard & Yun 1996, 1999; Mihos & Hernquist 1996; Mihos & Bothun 1998; Mihos 1999; Barnes 1998; Genzel et al. 1998; Gierlinski et al. 1999; Dultzin-Hacyan et al. 1999; Barton et al. 2000; Combes 2001; Thorley et al. 2000; Farrah et al. 2001). At perigalacticon, tidal distortions are triggered that are quickly amplified by disk self-gravity into bar or spiral instabilities. Rapid gas inflow (~rotation timescale at each radius) could lead to an early episode of starburst or AGN activity well before the galaxies merge, within a few rotation periods. It is estimated that normal galaxies (M ~ 10^10 M⊙) can have 10%–20% of their mass driven down to a few hundred parsecs from the center, within ~10^8 yr. Star formation can be induced by close passes after a few 10^7 yr, and its lifetime ranges within ~10^6–10^8 yr. At this stage the galaxies have already moved farther apart, and one might observe disk tidal distortions and perhaps an inner bar. Once tidal distortions have occurred and circumnuclear star formation is triggered, material loses angular momentum and falls farther inward. This has the effect of both feeding (or triggering) the AGN and obscuring the BLR. The galaxy appears as a Seyfert 2 type, and at this time, the contribution of the circumnuclear starburst to the luminosity output of the system could still be comparable to that of the hidden AGN. This might be the stage of several Seyfert 2 galaxies in our sample for which strong tidal features and central bars are simultaneously observed. While the tidal triggering of disk instabilities with subsequent gas inflow is a short process, the bar formation leads to a continuous low-level nuclear feeding for much longer periods. The timescale for the formation of a tidally induced bar or spiral galaxy is ~10^9 yr, assuming gas inflow rates of ~0.5 M⊙ yr^{-1}. A latency period (before material enters the nuclear regions) of ~2 × 10^8 yr (depending on the galaxy mass) precedes the bar phase. As time passes, the dusty material is consumed in forming stars or blown away by stellar winds; we start seeing the BLR, and thus we will classify the galaxy as a Seyfert 1 unless it is (unfavorably) seen along the edge of a remaining nuclear dusty torus. The time needed to progress from a (observed) Seyfert 2 to Seyfert 1 type according to the above scenario is comparable to the time needed for a small companion to merge via a double-nuclear phase into a remnant with tidal appendages. The merger process takes (5-15) × 10^8 yr to complete. The estimated time for the two nuclei to coalesce into a single remnant is relatively short (a few rotational periods), and their inner regions will be relaxed in only ~10^8 yr, which is comparable to (or shorter than) the Seyfert activity lifetime. The galaxies at these later stages might appear to reside in normal environments or be “isolated.”

Given the tendency of the majority of Seyfert 1 nuclei in our sample to reside in early-type and/or isolated hosts showing tidal appendages emanating from a single nucleus, I suggest that these might indeed be recent merger products.

The early phase, corresponding to strong circumnuclear star formation triggered by the initial pass, should be characterized by warm 60–100 μm and colder 25–60 μm colors. At later interaction stages when the AGN becomes visible and increasingly contributes to the energy output of the system, the mid-IR 25–60 μm color becomes progressively warmer. I should point out that this is not a well-determined transition phase. Star formation physics plays an important role in the strength and duration of the starburst phase, and in fact, star formation and feedback seem to be two of the outstanding problems when trying to model the dynamical evolution of interacting/merging systems. It was recently shown through case studies of ULIRGs that these can be found in very different dynamical stages, although they all seem to be associated with late-stage mergers. This indicates that there is no unique trigger for ULIRG activity since it could be excited both early in the interaction process and/or later at the final merger stage. The IR (ultra-)luminous phase should last approximately as long as the AGN lifetime, ~10^8–10^9 yr (Murphy et al. 1996, 2001; Martini & Weinberg 2001; Farrah et al. 2001) or slightly less since there exist IR-weak AGNs (Hutchings & Neff 1991).

In this section, it has become clear that not only the gas content of the progenitor galaxies but also their internal structure, the orbital geometry of the encounter, and the starburst physics are all important factors that determine the timing.
duration, type, and level of the activity induced (in one or both galaxies) by the interaction.

6.4.2. Putting It All Together

Based on the ideas described above, I can now combine my earlier classification in terms of morphologies and interaction strength (§ 2.1) in a common sequence and plot the distribution of our samples along this sequence (Fig. 6). This is by no means a unique description of the interaction process; nevertheless, comparing the distributions of Seyfert 1 versus Seyfert 2 samples and of IR-warm versus IR-cold samples through such a sequence can be instructive and lead to a better understanding of the nature of nuclear and IR activities. The logic I followed is simple:

1. Objects with normal morphologies, either isolated (NI) or with companion galaxies (NC) but no morphological indication of interactions, can be put together either in the beginning or at the end of the sequence. These might be objects that suffered a past encounter, either too weak or too long ago to affect significantly their morphologies, but enough to trigger nuclear activity.
2. Then the purely barred/ringed systems in isolated (BI) or systems with companions (BC) are grouped together. It is not clear where in the time evolution of the encounter these cases belong. They might be representing low-level interactions with distant companions and/or phases subsequent of perigalacticon passage, after bar formation and nuclear activation.
3. Then I put together the strongly interacting systems, with or without bars/rings (SB or S). These must be representing the impact or shortly after perigalacticon phases, when starburst and subsequent nuclear activation occur.
4. As these systems evolve in time, the companion separation increases, and the hosts often show bars/rings and/or strong tidal features (TC or BTC).
5. The final stage that I try to depict is the coalescence stage, where either the two nuclei are still visible within a common body (Mg) or only a tidal appendage emanates from a single-nucleus isolated galaxy (TI). There is one case (a Seyfert 2 galaxy) denoted (BTI), an isolated object with simultaneously bar and tidal features. It is not clear whether it belongs here or to some other phase, perhaps the BTC with a companion galaxy that is too faint or farther than my search radius.

In Figure 6 I plot the distributions of our warm and cold samples along this sequence. As expected from the earlier discussion of my results, the three samples show markedly different distributions:

1. The Seyfert 1 galaxies (upper panel) have a bimodal distribution peaking at normal morphologies and advanced mergers, that is, at the late stages of the interaction process according to my definition. There is a remarkable avoidance of the peak interaction phases at or right after perigalacticon, with only a few observed cases of strongly interacting Seyfert 1 galaxies. As I pointed out earlier, any evolutionary sequence should not be onefold (time) but must also depend on the physical properties (gas/dust content) of the host galaxy and on the interaction parameters (how much material and how fast is driven inward). These factors could explain the existence of the latter cases.
2. The strong interaction phase represents the peak of the Seyfert 2 distribution (middle panel). It is followed by a slow falloff toward the double-nucleus mergers. The least probable occurrence of Seyfert 2 type nuclei is in the isolated/tidal/bar phases (BI/TI). At those stages the galaxy is most probably seen as Seyfert 1 (upper panel).
3. Of the Seyfert 2 hosts, 33% have normal morphologies (NI+NC), similar to the equivalent Seyfert 1 fraction (38%). Galaxies in these classes are found in a wide range of environments and share similar properties: both Seyfert types have comparable $L_{25}$ and a similar (large) range in optical and IR luminosities. I suggest that the Seyfert galaxies belonging in these classes might indeed be “unified” within the context of the orientation/obscuration model.
4. The cold galaxies (lower panel) show a narrow distribution, confined within the disruptive phases of the encounter. It is remarkable that, if we exclude the Seyfert 2 galaxies with normal morphologies from the middle panel (which I “united” with Seyfert 1), the cold and warm Seyfert 2 distributions appear very similar.

The K-S test for matching distributions shows that the Seyfert 1 and cold samples differ at the 99.3% significance level. The Seyfert 2 and cold distributions differ at the 87% level, but excluding the NI and NC classes, the two samples match at a significance better than 85%.

I thus suggest that Figure 6 represents primarily an evolutionary sequence from bottom to top.

In order to better demonstrate this, I will assign to each phase a (relative) timescale using the available morphological evidence. Inspired from recent simulation results and age dating of the ULIRG mergers (see, e.g., Mihos 1999; Murphy et al. 2001 and references therein), I will consider three main states for an interacting system, early, intermediate, and late, and within each a range of timescales. At the early stage the two galaxies are seen shortly after perigalacticon and are characterized by strong tidal distortions. Warped disks and short bright tidal extensions develop right after impact [((5–1) × 10^8 yr) and they gradually develop to well-defined tidal arms or tails (shorter than the projected galaxy separation). At this time [(1–2) × 10^9 yr] gas in the disk might respond to the tidal perturbations, forming a bar or a strong spiral pattern. At the intermediate stage [(5–6) × 10^8 yr] the galaxies have moved farther apart, hanging for a while close to apogalacticon before they start approaching each other again for a second (final?) encounter. The tidal extensions have grown to sizes similar or larger than the actual separation of the two galaxies. Objects with strong bar/ring formations could also be included in this stage. At the late stages (≈8 × 10^8 yr) we mainly see systems (1) in the process of merging, typically possessing double nuclei and large symmetric tidal tails or (2) somewhat later (≈1 × 10^9 yr) after coalescence, when the inner regions of the merger remnant are in the process of relaxation, but we still see large diffuse tidal features in the outer regions. At the end of this age sequence we could place the NC/NI classes, assuming that these systems had the time to also relax their outer regions and to reorganize themselves to “normal” morphologies, the only evidence for the past interaction being their on-going nuclear activity. However, we have no reliable observational evidence about this, at least with the present data. This age classification is described in Table 4, together with the interaction sequence that I defined earlier.

It should be clear that the timescales that I use are indicative and should not be taken literally. I assumed that at the earliest (impact) phase a starburst event can be triggered within ≈5 × 10^7 yr and that the merger needs ≈(5–15) × 10^8 yr to be completed (coalescence of the two nuclei, relaxation and/or mixing within the remnant). Then I compared representative morphologies of our systems to the results of recent simulations of major disk mergers (see, e.g., Mihos 1999) and was thus able to associate a timescale to each interaction phase. I could use another independent estimator of the encounter timescale, based on the projected galaxy separation. Assuming S_{max} = 90 kpc (the maximum separation observed among our sample objects), t_{max} ≈ 110^9 yr, and a quadratic time separation relation (see also Murphy et al. 2001, who applied this method to the age dating of ULIRGs), I list the results also in Table 4. Although here too the age estimation is subject to assumptions and thus should not be taken at face value, the two methods generally agree (within a few × 10^8 yr), which is reassuring given that they are completely independent. The larger scatter occurs for types that I classified earlier as “intermediate,” which is not unexpected given the uncertainty as to where in the interaction sequence these objects belong (see discussion earlier). It is probably more appropriate to assign a timescale relative to the total merger time t_{rel} = t/t_{merg} and this is what I depicted in Figure 7 (with the same anno-

Fig. 7.—Distribution of the three samples along a merger age sequence. The upper panel shows the three main stages, early, intermediate, and late, the middle panel shows the corresponding codes as defined in Table 4, and the lower panel the corresponding relative timescales t_{rel} = t/t_{merg} (see text for details).
### TABLE 4
**Interaction Sequence**

| Identification | IS | Stage | $t_{\text{age}}$ (× 10^8 yr) | $t_{\text{sep}}$ (× 10^8 yr) | Morphology |
|----------------|----|-------|-----------------------------|-----------------------------|------------|
| **Warm Seyfert 1** | | | | | |
| IRAS 14557−2830 | S | Ear(Y2) | 0.1−0.2 | 0.1 | Warped disk |
| IRAS 09453+5043 | BTC | Ear(Y2) | 0.1−0.2 | 0.06 | Bar, tidal arm>separation |
| IRAS 02553−1642 | S | Int(I1) | 0.5 | 1.0 | Warped disk, tidal arm>separation |
| IRAS 04339−1028 | BC | Int(I2) | 0.4−0.6 | 0.1 | Bar |
| IRAS 18401−6225 | BI | Int(I2) | 0.4−0.6 | ... | Bar |
| IRAS 11365−3727 | BI | Int(I2) | 0.4−0.6 | ... | Bar, ring |
| IRAS 21299+0954 | BI | Int(I2) | 0.4−0.6 | ... | Ring |
| IRAS 19580−1818 | Mg | Lat(L2) | 1.0 | ... | Distorted inner morphology |
| IRAS 23016+2221 | TI | Lat(L2) | 1.0 | ... | Isolated, distorted inner morphology |
| IRAS 01378−2230 | TI | Lat(L2) | 1.0 | ... | Isolated, Long tidal arm |
| IRAS 02566−3101 | TI | Lat(L2) | 1.0 | ... | Isolated, asymmetrical rippled disk/tidal loops |
| IRAS 05136−0012 | TI | Lat(L2) | 1.0 | ... | Diffuse tidal feature/faint spiral? |
| IRAS 04124−0803 | NC | Lat | 1.2−1.5 | 0.8 | Companion, normal morphology |
| IRAS 05218−1212 | NC | Lat | 1.2−1.5 | 0.9 | Companion, normal morphology |
| IRAS 09497−0122 | NC | Lat | 1.2−1.5 | 0.9 | Companion, normal morphology |
| IRAS 13512−3731 | NC | Lat | 1.2−1.5 | 0.9 | Companion, normal morphology |
| IRAS 04493−6441 | NI | Lat | 1.2−1.5 | ... | Isolated, twisted isophotes |
| IRAS 05059+1225 | NI | Lat | 1.2−1.5 | ... | Isolated, normal morphology |
| IRAS 06563−6529 | NI | Lat | 1.2−1.5 | ... | Isolated, normal morphology |
| IRAS 11215−2806 | NI | Lat | 1.2−1.5 | ... | Isolated, normal morphology |
| IRAS 15015+1037 | NI | Lat | 1.2−1.5 | ... | Isolated, normal morphology |
| **Warm Seyfert 2** | | | | | |
| IRAS 03335−5625 | S | Ear(Y1) | 0.05 | 0.02 | Distorted close system |
| IRAS 06317−6403 | BC | Ear(Y2) | 0.1−0.2 | 0.2 | Bar, distorted companion |
| IRAS 09453−7054 | S | Ear(Y2) | 0.1−0.2 | 0.06 | Warped disk, no BLR |
| IRAS 00598−1956 | S | Ear(Y2) | 0.1−0.2 | 0.04 | Warped disk |
| IRAS 09435−1307 | S | Ear(Y2) | 0.1−0.2 | 0.1 | Tidal tail (bridge)?<separation |
| IRAS 13144−4508 | S | Ear(Y2) | 0.1−0.2 | 0.07 | Tidal arm<separation |
| IRAS 09182−0750 | SB | Ear(Y2) | 0.1−0.2 | 0.1 | Bar, ring, multiple, tidal arm<separation |
| IRAS 03059−2309 | SB | Ear(Y2) | 0.1−0.2 | 0.04 | Bar, multiple system, tidal arms<separation |
| IRAS 01346−0924 | BTC | Ear(Y2) | 0.1−0.2 | 0.2 | Bar, warped disk |
| IRAS 05228−4602 | TC | Int(I1) | 0.5 | 0.6 | Bright, tidal arm<separation |
| IRAS 22017−0319 | TC | Int(I1) | 0.5 | 0.9 | Tidal extension>separation, hidden BLR |
| IRAS 23254+0830 | SB | Int(I1) | 0.5 | 0.9 | Bar, ring, tidal tails>separation, hidden BLR |
| IRAS 02580−1136 | BTC | Int(I2) | 0.4−0.6 | 0.8 | Bar, tidal spiral? |
| IRAS 03362−1641 | BC | Int(I2) | 0.4−0.6 | 0.2 | Bar |
| IRAS 08277−0242 | BI | Int(I2) | 0.4−0.6 | ... | Bar, hidden BLR |
| IRAS 11298+5313 | S | Int(I2) | 0.4−0.6 | 0.9 | Multiple, distorted system (hidden BLR) |
| IRAS 03202−5150 | SB | Int(I2) | 0.4−0.6 | 0.9 | Bar, ring |
| IRAS 11249−2859 | BTI | Int(I2) | 0.4−0.6 | ... | Asymmetric ring, warped disk |
| IRAS 00198−7926 | Mg | Lat(L1) | 0.8 | ... | Two nuclei, tidal tail (no BLR) |
| IRAS 19254−7245 | Mg | Lat(L1) | 0.8 | ... | Two nuclei, tidal tails, no BLR |
| IRAS 13536−1836 | Mg | Lat(L1) | 0.8 | ... | Two nuclei, tidal tails, hidden BLR |
| IRAS 03905−8408 | TI | (Lat(L2) | 1.0 | ... | Distorted inner morphology, warped disk |
| IRAS 20208−5655 | NC | Lat | 1.2−1.5 | 0.8 | Distorted companion, normal morphology? |
| IRAS 00321−0018 | NC | Lat | 1.2−1.5 | 0.9 | Companion, normal morphology |
| IRAS 03230−5800 | NC | Lat | 1.2−1.5 | 1.0 | Companion, normal morphology |
| IRAS 03278−4329 | NC | Lat | 1.2−1.5 | 0.7 | Companion, normal morphology |
| IRAS 20481−5715 | NC | Lat | 1.2−1.5 | 0.9 | Companion, normal morphology |
| IRAS 03355+0104 | NI | Lat | 1.2−1.5 | ... | Isolated, normal morphology |
| IRAS 04229−2528 | NI | Lat | 1.2−1.5 | ... | Isolated, normal morphology, no BLR |
| IRAS 04507+0358 | NI | Lat | 1.2−1.5 | ... | Isolated, normal morphology, no BLR |
| IRAS 15304+3017 | NI | Lat | 1.2−1.5 | ... | Isolated, normal morphology, no BLR |
| IRAS 15599+0206 | NI | Lat | 1.2−1.5 | ... | Isolated, normal morphology, hidden BLR |
| IRAS 16382−0613 | NI | Lat | 1.2−1.5 | ... | Isolated, normal morphology |

**Cold Galaxies**

| Identification | IS | Stage | $t_{\text{age}}$ (× 10^8 yr) | $t_{\text{sep}}$ (× 10^8 yr) | Morphology |
|----------------|----|-------|-----------------------------|-----------------------------|------------|
| IRAS 04530−3850 | S | Ear(Y1) | 0.05 | 0.01 | Warped disks, starburst |
| IRAS 04015−1118 | S | Ear(Y1) | 0.05 | 0.1 | Tidal arm<separation |
| IRAS 05217−4245 | S | Ear(Y2) | 0.1−0.2 | 0.07 | Asymmetric warped disk, starburst |
TABLE 4—Continued

| Identification  | IS   | Stage   | $T_{\text{age}}$ ($\times 10^8$ yr) | $T_{\text{top}}$ ($\times 10^8$ yr) | Morphology                      |
|-----------------|------|---------|------------------------------------|------------------------------------|---------------------------------|
| IRAS 04545–4838 | S    | Ear(Y2) | 0.1–0.2                           | 0.07                               | Bar, warped disks, tidal arm    |
| IRAS 23179–6929 | SB   | Ear(Y2) | 0.1–0.2                           | 0.07                               | Tidal arm (bridge) < separation, S2 |
| IRAS 05207–2727 | BC   | Int(L2) | 0.4–0.6                           | 0.09                               | Bar, warped disks, tidal tail   |
| IRAS 04265–4801 | SB   | Int(L2) | 0.4–0.6                           | 0.08                               | Bar, ring, warped disks         |
| IRAS 07514+5327 | BTC  | Int(L2) | 0.4–0.6                           | 0.09                               | Bar, tidal distortion < separation |
| IRAS 04304–5323 | SB   | Int(L2) | 0.4–0.6                           | 0.09                               | Bar, tidal tail < separation     |
| IRAS 23128–5919 | Mg   | Lat(L1) | 0.8                               | ...                                | Two nuclei, tidal tails          |
| IRAS 03531–4507 | Mg   | Lat(L2) | 1.0                               | ...                                | Distorted morphology, tidal tails |
| IRAS 02439–7455 | NI   | Lat     | 1.2–1.5                           | ...                                | Normal morphology                |

Note.—Col. (1): IRAS identifications. Col. (2): Interaction sequence (see § 6.4.2 and Fig. 6). Cols. (3) and (4): Interaction stage and corresponding timescales (see § 6.4.2 and Fig. 7; when within parentheses the classification is uncertain). Col. (5): Timescales calculated from the projected separations (see § 6.4.2). Col. (6): Short description of the interaction morphology.

7. CONCLUSIONS

A multiplicity of results presented throughout Papers II–IV and this paper confirm the link between nuclear/IR activity and galactic interactions. Furthermore, I find substantial evidence for an evolutionary sequence between the mid-IR warm and cold samples and between the two Seyfert types:

1. The mid-IR warm Seyfert 1 and 2 galaxies differ in two fundamental ways: time evolution and nuclear obscuration. Strongly interacting Seyfert 2 galaxies generally are at an earlier interaction stage compared to Seyfert 1 galaxies. On the other hand, Seyfert 2 galaxies with normal morphologies can be unified with their type 1 counterparts in the context of nuclear orientation/obscuration models.

2. The mid-IR cold galaxies are predominantly disrupted systems and bear significant similarities with the (weaker) warm Seyfert 2 interactors.

3. The development or absence of a mid-IR excess is a threefold effect: (a) evolution (b) dust/gas content in the progenitors, and (c) interaction parameters.

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