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X-Ray Signatures of the Seyfert-Starburst Connection

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Abstract. We analyze X-ray spectra and images of a sample of Seyfert 2 galaxies that unambiguously contain starbursts, based on their optical and UV characteristics. Although all sample members contain active galactic nuclei (AGNs), supermassive black holes or other related processes at the galactic centers alone cannot account for the total X-ray emission in all instances.

Spectrally, a physically-motivated composite model of the X-ray emission that includes a heavily absorbed ($N_H > 10^{23}\,\mathrm{cm}^{-2}$) nuclear component (the AGN), power-law like scattered AGN flux, and a thermal starburst describes this sample well. We suggest that the interstellar medium of the nuclear starburst is a significant source of absorption. The observed far-infrared emission may be associated almost exclusively with star formation, rather than the active nucleus. The ratio of the hard and soft X-ray luminosity to the far-infrared luminosity distinguishes most of these composite galaxies from ordinary Seyfert 2 galaxies. The soft X-ray to far-infrared luminosity ratios are similar to those of starburst galaxies, while the total observed hard X-ray luminosities of the composites are significantly greater than those of the starbursts. The majority of the sample are located in groups or are interacting with other galaxies, which may trigger the starburst or allow rapid mass infall to the central black hole, or both. Thus, these composites are significant in understanding the starburst-AGN connection. We conclude that starbursts are energetically important in a significant fraction of active galaxies, and these two types of galaxies, starbursts and AGN, may be part of a common evolutionary sequence. See Levenson, Weaver, & Heckman 2000a,b for more complete results from this work.

1. Motivation

What powers Seyfert galaxies? While the central engines of many Seyfert galaxies have generally been successfully described by accretion onto supermassive black holes, starbursts are also important. Much of the optical and ultraviolet emission from type 2 Seyfert galaxies is a featureless continuum that *cannot* be light from a "hidden" Seyfert 1 nucleus that is scattered off dust or warm gas. Heckman and collaborators (Heckman et al. 1995, Heckman et al. 1997, González Delgado et al. 1998, González Delgado, Heckman, & Leitherer 2000) have found optical and UV evidence that starbursts are the source of this featureless continuum in many cases. Their sample consists of the brightest Seyfert 2 nuclei, based on [O III] $\lambda\lambda 4959, 5007$ flux or nonthermal flux density at 1.4 GHz. They detect spectroscopic signatures of a luminous population of young stars in approximately half of the Seyfert 2 galaxies they have examined.

We are studying this optical- and UV- selected sample of 14 known Seyfert/starburst composites using X-ray spectroscopy and imaging (Levenson, Weaver, & Heckman 2000a,b). Starbursts and accretion phenomena both contribute to observed soft (0.5–2 keV) X-ray flux, while harder ($E > 5\,\mathrm{keV}$) X-rays that the nuclear engine emits directly can penetrate column densities $N_H \lesssim 10^{24}\,\mathrm{cm}^{-2}$.

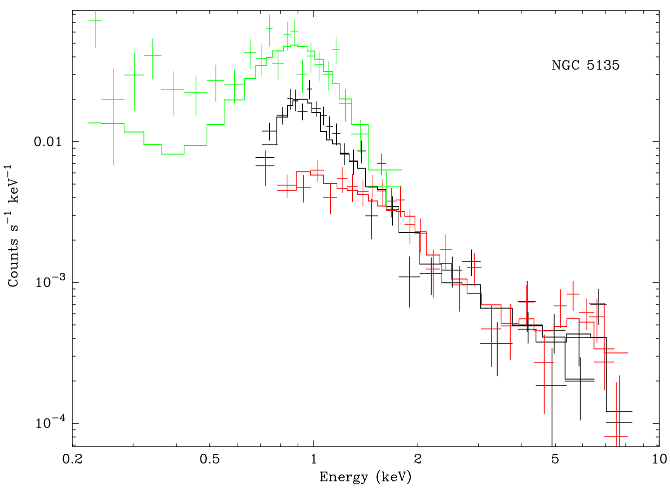

Fig. 1. The spectrum of NGC 5135 obtained with the PSPC (green) and the *ASCA* detectors (black and red, for SIS and GIS, respectively). The best-fitting model (solid lines) includes both the intrinsic and scattered AGN and the thermal starburst.

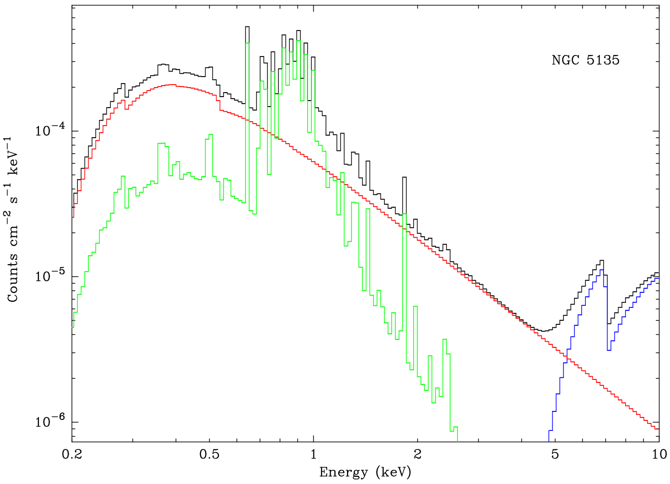

Fig. 2. The model spectrum of NGC 5135 includes three characteristic components: a heavily-absorbed intrinsic AGN (blue), the scattered AGN (red) and the thermal starburst (green).

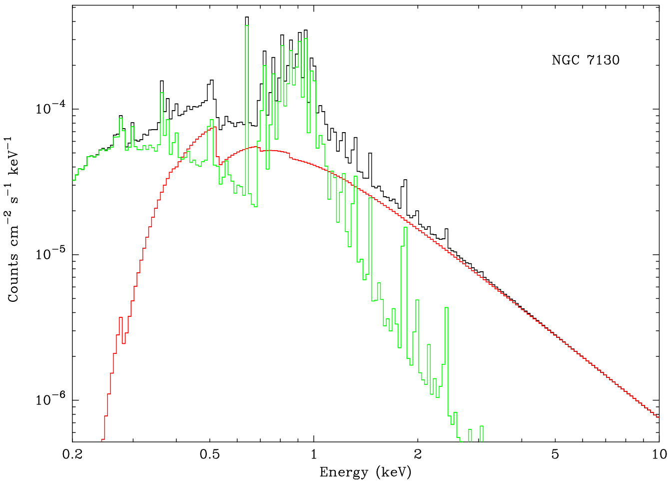

Fig. 3. The model spectrum of NGC 7130 includes only the scattered AGN (red) and thermal starburst (green). The intrinsic AGN is completely absorbed by $N_H > 10^{24}\,\mathrm{cm}^{-2}$.

2. Starbursts and AGN in X-rays

The spatial signature of a starburst in X-rays is emission that extends out of the galaxy on physical scales of several kpc (Dahlem, Weaver, & Heckman 1998). The energy of the starburst, deposited as stellar winds and supernovae, drives this superwind outflow. Spectrally, thermal emission dominating at energies less than about 1 keV characterizes the starburst. The AGN is unresolved in X-rays. In the unified model of Seyfert nuclei, the X-ray continuum in a type 2 nucleus consists of two components: 1) the heavily-absorbed power-law emission from the hidden Seyfert 1 that is transmitted through the obscuring torus; and 2) the lightly-absorbed reflected component that has the same characteristic power-law spectrum as the intrinsic emission. All of these components are combined in the composite galaxies. In addition to the bright central point source, they exhibit soft, diffuse emission. In the spectra, the starburst and scattered spectral components dominate the soft X-ray flux, while the buried intrinsic AGN contributes to the harder X-ray emission. NGC 5135 displays all these characteristics. The *ROSAT* HRI resolves the soft X-ray emission from this galaxy, which extends to at least 5 kpc, and the more sensitive PSPC detects emission on scales of 13 kpc. We fit the spectra obtained with the PSPC and *ASCA* (Figure 1) with a physically-motivated model that includes the three characteristic components. Both the scattered AGN and thermal starburst contribute at soft energies, while the heavily-absorbed intrinsic AGN appears at $E > 5$ keV (Figure 2).

The remainder of the sample are similar. Variations in the absorption of the intrinsic AGN determine how strong the hard X-ray "bump" is, including some cases where it is absent because the AGN is completely absorbed by $N_H > 10^{24}\,\mathrm{cm}^{-2}$ (e.g., NGC 7130; Figure 3). The strength of the thermal component varies, although typically the thermal and power-law flux contribute equally in the soft (0.5–2.0 keV) X-ray band. Only in one case, Mrk 477, do we not significantly detect the thermal starburst emission directly.

Although we measure the extended and thermal emission separately, we associate both with the starburst-driven outflow and supernova processing of the interstellar medium. Within the Sy2/SB sample, the fractions of resolved and thermal soft X-rays are comparable. Furthermore, they are both similar to the dominant soft X-ray emission from ordinary starburst galaxies in terms of temperature and physical scale. Future observations with *Chandra*, for example, will provide spatially resolved spectroscopy to verify the common origin of the resolved and thermal components.

3. X-ray and FIR Flux Ratios

We use the ratios of luminosity in the soft X-ray (SX, 0.5–2 keV), hard X-ray (HX, 2–10 keV), and far-infrared (FIR) bands to illustrate an empirical relationship among Seyfert 1, Seyfert 2, starburst, and Sy2/SB composite galaxies. SX is corrected for Galactic extinction, but because the absorption corrections to recover the intrinsic hard X-ray luminosity are large and uncertain, we consider only the *observed* HX. The ratio of SX/FIR in the Sy2/SB galaxies is similar to that of ordinary starburst galaxies but distinct from those of a more general sample of Seyfert 2 galaxies (Figure 4). The composites that are most like other AGN have a high HX, either due to low absorption, high intrinsic AGN luminosity, or both. As a result, the thermal component, which is directly associated with the FIR emission, is relatively weak.

The hard X-ray luminosity distinguishes the starburst and composite galaxies (Figure 5). These two groups are

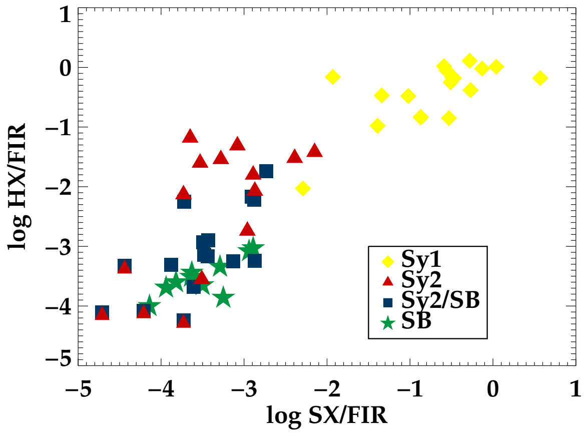

Fig. 4. Hard (2.0-10 keV) vs. soft (0.5-2.0 keV) X-ray luminosity, normalized by FIR luminosity for the Sy2/SB sample, other Sy 2 galaxies (Weaver et al. 2000), starburst galaxies (Dahlem et al. 1998, D. K. Strickland, K. A. Weaver, & T. M. Heckman, in preparation), and Sy 1 galaxies (Mas-Hesse et al. 1995). True composites in the Weaver et al. (2000) sample are plotted with both Sy 2 and Sy2/SB symbols. The composite sample members have SX/FIR ratios similar to starburst galaxies and HX/FIR in between ordinary Sy 2 and starburst galaxies.

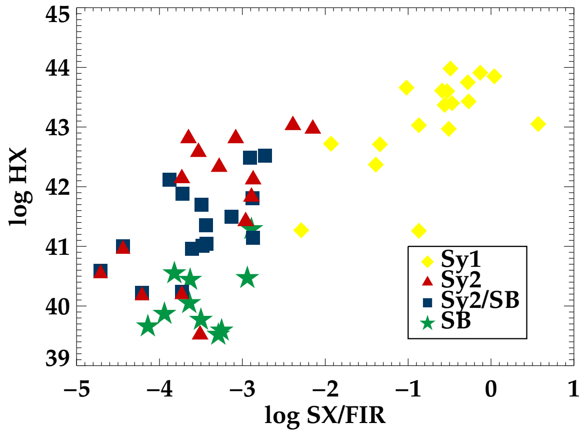

Fig. 5. The higher observed hard X-ray (2.0-10 keV) luminosities of the Sy2/SB sample distinguish them from starburst galaxies. The strong absorption of nearly all of the composites may account for their relatively low HX with respect to the other Sy 2 galaxies.

spectrally similar (e.g., Dahlem et al. 1998), with X-ray binaries, rather than an active nucleus, generating a power-law continuum in the former. The central concentration of the X-ray emission, higher luminosities, and the Fe Kα lines of the Sy2/SB examples imply that starburst phenomena alone are not the sole source of X-rays in these objects. Each genuinely contains an active nucleus, as well. Looking at HX alone, we find a maximum hard X-ray luminosity of about $10^{41}\,\mathrm{erg\,s^{-1}}$ for starburst galaxies, while the composites fall between starbursts and Seyfert 2s.

4. The Role of Galaxy Interactions

With the exceptions of Mrk 1066 and Mrk 78, all these Sy2/SB composites show evidence for galaxy interactions or mergers. They either contain multiple nuclei, show evidence for interaction with companion galaxies, or are members of groups or clusters. The high incidence of interactions implies that this phenomenon relates to the starburst, probably triggering the star formation, and is therefore important in efficiently providing material to the black hole, either directly—through dynamic instabilities—or indirectly—as a consequence of the starburst winds and supernovae. Starbursts may be important in the complete cycle of development of luminous active galaxies, possibly including the initial creation of the central black hole (Norman & Scoville 1988), through the clearing of obscuring material to allow lines of sight to the AGN directly in type 1 objects (Heckman et al. 1989).

5. Column Density and Starbursts

The distribution of absorbing column density in Sy2/SB composites is significantly different from that measured in "pure" Sy 2, such as that of Risaliti, Maiolino, & Salvati (1999). The column densities of the Sy 2s with no evidence of a starburst are distributed over a wide range, with 27% having $N_H < 10^{23}\,\mathrm{cm^{-2}}$. In contrast, the Sy2/SBs tend to have higher directly measured or inferred column densities, with $N_H < 10^{23}\,\mathrm{cm^{-2}}$ only in the unusual case of NGC 6221.

The nuclear column densities of molecular gas in ordinary starburst galaxies range from 10^{22} to $10^{25}\,\mathrm{cm^{-2}}$ (e.g., Dahlem et al. 1998, and Kennicutt 1998), and in ultraluminous galaxies, $N_H \sim 10^{23}$ to $10^{25}\,\mathrm{cm^{-2}}$ (Genzel et al. 1998). These column densities are comparable to those measured toward the central engines of Sy 2s. The presence of a dense ISM on circumnuclear scales may explain why the hard nuclear source is generally heavily obscured in the composite objects. Based on the new results from our Sy2/SB sample, we propose that the high inferred X-ray column densities are not solely due to the obscuring torus in these galaxies. *The circumnuclear starburst also obscures the AGN.*

Comparing the ratio of luminosity at 25 and 60μm ($L25/L60$) with HX/FIR illustrates the association of starburst activity and obscuration (Figure 6). The ratio $L25/L60$ indicates relative strength of AGN activity compared with star formation, while HX/FIR is a function of obscuration. As the Sy 1s show, relatively high values of both of these ratios indicate a relatively strong AGN *and* low obscuration. Including a starburst in an active galaxy not only changes the FIR color, but it also tends to obscure the AGN. Most significantly, few galaxies ex-

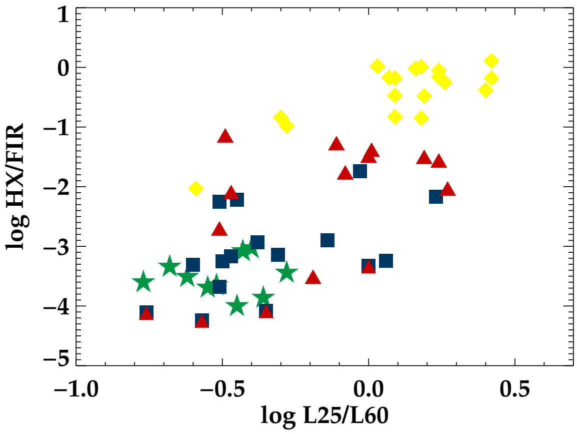

Fig. 6. Hard X-ray to far-infrared luminosity vs. 25 to 60μm luminosity for Sy2/SBs and comparison samples. The far-infrared luminosity ratio indicates the relative strength of the AGN and starburst components, with higher values observed when the AGN dominates. The ratio HX/FIR decreases with obscuration. The strong correlation between these two ratios and the absence of many objects from the high-$L25/L60$, low-HX/FIR regime (lower right corner) supports the suggestion that the starburst itself both alters $L25/L60$ and obscures the AGN in composite objects. (Symbols as in Figure 4.)

hibit high values of $L25/L60$ and low HX/FIR simultaneously. Thus, obscuration of the central engine seems to correlate with the presence of energetically significant star formation. While the comparison samples were not rigorously selected, this correlation is not due to selection effects; heavily obscured and AGN-strong candidates are not preferentially excluded from the comparison groups.

Luminous infrared galaxies ($FIR > 10^{11} L_\odot$) exhibit a similar distribution of these flux ratios. To explain these observations, Risaliti et al. (2000) propose that the infrared and X-ray emission suffer different absorption in these galaxies because of a particular viewing geometry. Our results support the suggestion that the X-ray source is more obscured, but it is not a function of viewing angle with respect to the circumnuclear torus. Rather, we specifically identify the starburst, the source of strong 60μm emission, as some of the additional medium that blocks the AGN. A compact torus may still be present, and its orientation may fundamentally account for the classification of these galaxies as Sy 2s rather than Sy 1s, but the torus is not the only absorber.

The presence of a circumnuclear starburst is a good indicator of large column density. This is true not only in our sample but also in larger samples with different selection criteria, such as Risaliti et al. (1999), in which we find that many of the heavily obscured active galaxies also contain significant star formation. Because we attribute some of the obscuration to the starburst directly, we suggest that the converse may also hold, that large column density may be a starburst indicator. Indeed, all the Compton thick galaxies of this sample in which the circumnuclear stellar populations have been studied in detail do contain starbursts.

6. Significance

Understanding the relationship between active galaxies and starbursts is important in the contexts of the unified model and galaxy evolution. Starbursts are common in Seyfert 2 galaxies, and Seyfert/starburst composites may have physical properties that are distinct from pure Seyfert galaxies. The observed relationship between infrared and X-ray luminosities, for example, in the present sample suggests that the buried engines of these composites are genuinely different from typical type 1 Seyferts.

More generally, the apparent ubiquity of supermassive black holes in the nuclei of present-day galaxies and the rough proportionality between the mass of the black hole and the mass of its "host" stellar spheroid (Ferrarese & Merritt 2000, Gebhardt et al. 2000) implies that the creation of supermassive black holes (presumably corresponding to a luminous QSO phase) was an integral part of the formation of ellipticals and galactic bulges. Thus, understanding the "starburst-AGN connection" is a crucial component of modern cosmogony. Exhibiting both starburst and AGN phases simultaneously, the Sy2/SB galaxies provide an excellent laboratory in which to examine these issues.

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