HUBBLE SPACE TELESCOPE OBSERVATIONS OF THE SERENDIPITOUS X-RAY COMPANION TO MARKARIAN 273: CLUSTER AT z = 0.46?

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ABSTRACT

We have used Hubble Space Telescope (HST) I-band images to identify Mrk 273X, the very unusual high-redshift X-ray–luminous Seyfert 2 galaxy found by ROSAT in the same field of view as Mrk 273. We have measured the photometric properties of Mrk 273X and have also analyzed the luminosity distribution of the faint galaxy population seen in the HST image. The luminosity of the galaxy and the properties of the surrounding environment suggest that Mrk 273X is the brightest galaxy in a relatively poor cluster at z ≈ 0.46. Its off-center location in the cluster and the presence of other galaxy groupings in the HST image may indicate that this is a dynamically young cluster on the verge of merging with its neighboring clusters. We find that Mrk 273X is a bright, featureless elliptical galaxy, with no evidence for a disk. It follows the de Vaucouleurs (r^1/4) surface brightness law very well over a range of 8 mag. Although the surface brightness profile does not appear to be dominated by the active galactic nucleus (AGN), the galaxy has very blue colors that do appear to be produced by the AGN. Mrk 273X is most similar to the IC 5063 class of active galaxies—a hybrid Seyfert 2/powerful radio galaxy.

Subject headings: galaxies: active — galaxies: clusters: general — galaxies: individual (Markarian 273) — galaxies: Seyfert — X-rays: galaxies

1. INTRODUCTION

Mrk 273 (IRAS 13428+5608) is one of the nearest members (at z = 0.0378) of a special class of galaxies, the ultraluminous infrared galaxies (ULIRGs), identified by IRAS (Sanders et al. 1988a, 1988b). It shows a long tidal tail and a disturbed morphology, thus indicating its presumed galaxy-galaxy collision + merger origin. The merger and its accompanying starburst and/or active galactic nucleus (AGN) activity leads to the high IR luminosity (> 10^{12} L_\odot) through dust absorption and reemission of the intense but obscured radiation field. Mrk 273 has a Seyfert 2 nuclear spectrum (Lutz, Veilleux, & Genzel 1999) and consequently is a soft X-ray source (Turner, Urry, & Muchotsky 1993). ROSAT PSPC X-ray observations of the field surrounding this galaxy and several other Seyfert 2 galaxies revealed the presence of serendipitous companion X-ray sources around each primary source (Turner et al. 1993; see also Laurikainen & Salo 1995; Radecke 1997; Arp 1997). The X-ray companion to Mrk 273 (hereafter, Mrk 273X) is 1.3° to the northeast (projected separation ≈ 57 kpc at the redshift of Mrk 273), with a soft X-ray count rate ~ 50% that of Mrk 273. (For this paper, we assume H_0 = 70 km s^{-1} Mpc^{-1} and q_0 = 1/2.)

Recent spectroscopic observations of Mrk 273X have revealed that it is itself a Seyfert 2 galaxy, although at a much higher redshift (z = 0.458) and with some very unusual properties (Xia et al. 1998a, 1998b, 1999). Xia et al. (1999) report a soft X-ray luminosity (6.1 × 10^{43} erg s^{-1}) that is extraordinarily high compared to most Seyfert 2 galaxies, even though the photon power-law index has a typical Seyfert 2 value (~ 1.98). The radio luminosity (L_{1.4 GHz} ≈ 1.0 × 10^{40} ergs s^{-1}) is also quite high for a Seyfert 2 galaxy (M. S. Yun & J. E. Hibbard 1999, in preparation). Furthermore, the derived column density of neutral hydrogen (from the X-ray spectrum) is very low for a Seyfert 2 galaxy: log (N_H) ≈ 20.6. Many Seyfert 2 galaxies have log (N_H) > 21 (Turner et al. 1997), although values similar to those of Mrk 273X are not uncommon (Turner et al. 1998). High X-ray and radio power along with low N_H are more indicative of an unobscured view of the AGN (i.e., as in a Seyfert 1 galaxy), and thus these observations challenge the conventional inclined dusty torus models for AGNs. Xia et al. (1999) thereby compare the possibilities that Mrk 273X may be either a Seyfert 2 or a narrow-line Seyfert 1 (NLS1) galaxy. They conclude that various optical emission line ratios and the X-ray spectral index weigh strongly against the NLS1 hypothesis and in favor of the Seyfert 2 interpretation. Xia et al. (1999) also discuss the evidence for X-ray variability in Mrk 273X, which is still not certain but nevertheless possible.

Given the unusual properties of this faint galaxy, we were pleased to find it within the field of view of our Hubble Space Telescope (HST) image of Mrk 273, part of our large HST survey of ULIRGs (Borne et al. 1997a, 1997b, 1999a, 1999b, 1999c). We report here on our analysis of the Mrk 273X image and its surrounding field (which includes many comparably faint galaxies). We describe the HST observations in § 2 and the results of our image analysis in § 3. The latter includes photometric and luminosity function derivations. We also summarize and discuss in § 3 the

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properties of this galaxy in relation to the properties of analogous active galaxies.

2. HST IMAGING OBSERVATIONS

We obtained two sets of HST imaging observations of the primary ULIRG target, Mrk 273, as part of our large ULIRG Snapshot Survey program. In each set of observations, we used the WFPC2 camera to obtain two 400 s images in the I band (F814W filter). Pairs of images were used to remove the effects of cosmic-radiation events in the CCDs (assuming the events are uncorrelated and have no persistence from one image to the next). In one set of observations, Mrk 273 was centered in the WF3 CCD (with 0.10 per pixel), and in a second set Mrk 273 was centered in the PC CCD (0.046 per pixel). In the latter observations, we found the X-ray companion Mrk 273X in the WF4 CCD frame (Fig. 1). The standard calibrated data products were rederived using the best calibration files and then combined into a single cosmic-ray-cleaned 800 s image. Our analysis was carried out using this final cleaned image.

3. RESULTS OF IMAGE ANALYSIS

3.1. Identification of Mrk 273X

From their ROSAT PSPC X-ray images, Turner et al. (1993) give a boresight-corrected J2000 position for Mrk 273X at 13\(^h\)44\(^m\)47.9\(^s\). Using this information...
and the images in Xia et al. (1998a, 1999), we have identified the optical counterpart in our WFPC2 image. We find the J2000 position (within the standard uncertainty of ±0.5 for HST positions) for Mrk 273X to be 13°44′47″.46, +55°54′11″.1. This is almost exactly the position given by Turner et al. (1993). We show in Figure 1 the 75′′ × 75′′ usable area of the WF4 CCD frame containing Mrk 273X. About 40 fainter galaxies are also seen in this frame. The darker grey shading of the background light distribution in the lower right quadrant (southwest) is real; this is the extended spray of emission from the tidal debris around Mrk 273, as indicated by Xia et al. (1998a, 1999). Mrk 273 is located in the PC frame just below the lower right quadrant of the WF4 frame shown here. Mrk 273X is well resolved, with measurable light out to a radius of ∼50 pixels (5″0 ≈ 25 kpc). It is an essentially featureless galaxy, probably an elliptical or S0, with a small degree of flattening. It has a bright nucleus, typical of an elliptical galaxy.

3.2. Photometric Properties of Mrk 273X

We used various photometric tasks within IRAF and STSDAS to analyze Mrk 273X and its surrounding galaxies. The ELLIPSE task was used to analyze the surface brightness profile and shape of Mrk 273X. We find that the half-light radius for Mrk 273X is 0′40 = 2.0 kpc, and the radially averaged ellipticity of the galaxy corresponds approximately to an E2 shape, at an average position angle of ∼115°. The derived intensity profile is shown in Figure 2. We find that the light follows the expected r1/4 profile for an elliptical galaxy very well—over a range of 8 mag in surface brightness. To determine how well the data are matched by the derived ELLIPSE model, we constructed a model galaxy using the derived parameters and subtracted that model from the data to produce a residual map. The different steps in this process are illustrated in Figure 3, including the original data (upper left), a 3 × 3 pixel boxcar-smoothed version of the data (upper right), the constructed model (lower left), and the residual (data minus model) image (lower right). From the near-zero residuals, we see that our “elliptical galaxy” model matches the data quite well.

According to Graham & Colless (1997), \( R_{\text{eff}} = 0.75 R_{\text{1/2}} \) for a wide range of luminosity profile shapes and galaxy models. Assuming that this applies to Mrk 273X, we find \( R_{\text{eff}} = 0.30 = 1.5 \) kpc, which is small compared to most ellipticals (Scoceddio, Giovanelli, & Haynes 1998).

A very small companion galaxy is seen in the optical halo of the galaxy, approximately 16 pixels (1′′6 ≈ 8 kpc) east of Mrk 273X’s center (see Fig. 3, upper panels). In addition, three brighter companions are seen within 10″ (≈ 50 kpc) of Mrk 273X, and possibly two additional fainter companions are also seen within that distance (south-southwest) of Mrk 273X, as shown in Figure 3. Note that the brightness of the companion galaxies have asymmetric and disklike morphologies that are clearly evident at this spatial resolution (0′′2 = 1 kpc) and low signal-to-noise ratio (S/N). Such features are not seen at all in Mrk 273X, which therefore clearly possesses an ellipsoidal early-type galaxy morphology.

The ELLIPSE model does show significant isophote twisting (ΔP.A. ∼ 30°) within the central 2″ (∼10 kpc). This may be induced in Mrk 273X through interactions with the close companions. If the companions have that degree of influence on Mrk 273X, then their interaction may also be responsible for tidally triggering the AGN activity.

We used the IRAF APHOT task to measure the I-band magnitude of Mrk 273X and of the surrounding galaxies (see § 3.4). The NASA Extragalactic Database (NED) gives a magnitude of 19.6 (no passband specified, but probably R band) for Mrk 273X. We find \( m_r = 19.10 \) (Cousins I) for the total light. For \( z = 0.458, m - M = 41.66 \) and therefore \( M_I = -22.56 \), which corresponds to the rest-wavelength V band.

Xia et al. (1998a, 1999) report \( B = 20.8 \) and \( R = 19.6 \). Therefore, the colors of Mrk 273X are \( B - R = 1.2 \) and \( B - I = 1.7 \). We compare these colors in Table 1 with those measured for the galaxies in the z = 0.41 cluster Cl 0939 + 472 studied by Belloni & Roser (1996). The distance of that cluster is similar to that of Mrk 273X, and so the K-correction can be ignored in the comparison of colors. We find that the \( B - R \) and \( B - I \) colors of Mrk 273X are consistent with the colors of the late-type Im and Scd cluster galaxies, both in the mean value and in the observed ranges of these colors.

3.3. The Effect of an AGN

Based on the color information (Table 1), we conclude that either Mrk 273X is a very late type galaxy (i.e., with recent star formation) or else its colors are seriously affected

| Table 1 Colors of Mrk 273X vs. Cluster Galaxies at z = 0.41 (Belloni & Roser 1996) |
|-----------------|-----------------|------------------|------------------|
| Galaxy Type    | Number | \( \langle B - R \rangle \) | Range of \( B - R \) | Range of \( B - I \) |
|-----------------|--------|----------------|-----------------|----------------|
| E               | 139    | 2.4            | 1.6–3.0         | 3.5–4.4        |
| E + A           | 42     | 2.0            | 1.4–2.5         | 3.0–3.7        |
| Sbc             | 32     | 1.7            | 1.3–2.1         | 2.6–3.2        |
| Scd             | 16     | 1.4            | 0.8–2.4         | 2.2–3.4        |
| Im              | 17     | 1.1            | 0.9–1.4         | 1.7–2.0        |
| Mrk 273X        | ...    | \( B - R = 1.2 \) | \( B - I = 1.7 \) |
by the AGN (Seyfert 2 nucleus), or both. Ongoing star formation in Mrk 273X would suggest the presence of gas, which would provide a source of fuel for the AGN, and the nearby companions (Fig. 3) could provide a possible trigger for the activity.

As we see in Figure 2, the surface brightness of the galaxy follows the standard elliptical galaxy radial variation, providing no photometric evidence for an AGN point source contaminating the core brightness profile. However, the small measured value for the effective radius (1.5 kpc) may be an effect of the AGN contributing some fraction of the light in the core.

Mrk 273X has the optical spectral properties of a Seyfert 2 galaxy, but the radio flux, soft X-ray flux, optical morphology, and cluster dominance (§ 3.4) of a powerful radio galaxy (PRG). We compare various of these properties with the properties of analogous galaxies in Table 2. We see there that the properties of Mrk 273X span the range of the different types of active galaxies, and yet do not correspond to any one AGN type. Its properties are atypical for Seyfert 2 galaxies in that Mrk 273X has very high $L_{\text{opt}}$, $L_{\text{radio}}$, $L_{\text{SX}}$, and $L_{\text{H\alpha}}$, but very low $N_{\text{H}}$ (see § 1). Its properties are most similar to IC 5063; only $L_{\text{SX}}$ differs significantly between the two sources. We know that IC 5063 has a very high column...
of the diagonally opposite WF2 frame), at distances those other groupings are relatively far from the WF4 frame brightness, number count, and spatial extent. However, couple of other small groupings of galaxies of similar the WF2 and WF3 frames), and we note that there are a are fainter than Mrk 273X, but they are all comparably density and a high hard X-ray luminosity (log $L_{\text{HX}} = 43.04$), as measured by Koyama et al. (1992). Thus, the total (soft + hard) X-ray luminosity of the two sources is nearly the same (as are the optical, radio, and H\textalpha luminosities). Mrk 273X is therefore a galaxy of the IC 5063 type, except that its low allows a high $\text{flux}$ of soft X-rays to escape. Inglis et al. (1993) found that IC 5063 shows broad lines in polarized light and thus likely contains an obscured PRG or Seyfert 1 nucleus (Morganti, Oosterloo, & Tsvetanov 1998). Based on these comparisons, we believe that Mrk 273X is also a PRG.

### 3.4. Luminosity Function of Surrounding Galaxies

The brightest of the other galaxies seen in the WF4 frame are fainter than Mrk 273X, but they are all comparably bright. We have examined the full WFPC2 image (including the WF2 and WF3 frames), and we note that there are a couple of other small groupings of galaxies of similar brightness, number count, and spatial extent. However, those other groupings are relatively far from the WF4 frame (e.g., at the far edge of the adjacent WF3 frame and on the far half of the diagonally opposite WF2 frame), at distances of $75^\circ$, $110^\circ$, and $130^\circ$ (where 100$^\circ$ = 490 kpc). Even though they are not spatially close to the galaxies seen in WF4, these other groups could be associated with Mrk 273X nevertheless, given that all these galaxies have similar sizes and apparent magnitudes (i.e., at a similar redshift). To first order, given the observed spatial segregation of these groupings, we believe that the galaxies seen in WF4 comprise a small isolated group, of which Mrk 273X is the brightest member (at least, it is the brightest member that we have available within our WF4 image). Its rest-wavelength $V$ absolute magnitude ($\Delta 3.2$) is consistent with this being a brightest cluster galaxy (BCG; Postman & Lauer 1995). The BCG status is further supported by the $R$ magnitude ($\Delta 19.6$), which makes Mrk 273X comparable in brightness to the brightest galaxies (ellipticals) in the $z = 0.41$ cluster CL 0939 + 4713 that was studied with $HST$ by Dressler et al. (1994a, 1994b).

We used the IRAF APPHOT task to measure a metric $I$-band magnitude for the 34 circled galaxies in Figure 1. We measured the flux within a radius of 8 pixels ($0.8 = 4$ kpc) and included only those galaxies with $I$-band metric magnitude brighter than 24.0. (Fainter galaxies could not be measured reliably in this short-exposure image.) Within our fixed metric aperture, Mrk 273X has $I = 19.5$ (compared with $I = 19.1$ for its total light). The spatial distribution of the marked galaxies in Figure 1 shows that Mrk 273X is far ($\sim 200$ kpc) from the center of the group. In fact, a bright dumbbell pair of galaxies is seen near the center, but the pair’s combined total light has $I = 19.5$. We show in Figure 4 the luminosity function for the 34 galaxies in our WF4 frame along with the $I$-band luminosity function for two clusters of galaxies at nearly the same redshift: cluster CL 0939 + 472 (z = 0.41) from Belloni & Roser (1996) and cluster CL 2158 + 0351 (z = 0.45) from Molinari, Buzzoni, & Chincarini (1990).

A comparison of the histograms in Figure 4 reveals that the luminosity distribution of galaxies in the field surrounding Mrk 273X is similar to the bright end of a typical cluster luminosity function at that redshift. This further supports the notion that Mrk 273X is the brightest member of a poor cluster of galaxies at $z = 0.458$. Given this galaxy’s non-central location within the group, this is probably a dynamically young still-evolving cluster, perhaps still collapsing. In fact, this group may be on the verge of merging with the other small groups of galaxies seen in our wider WFPC2 field of view (see above). We note that there was no evidence in the X-ray images for an extended cluster-like hot ICM within this group.

### 4. SUMMARY

We have analyzed $HST$ images of Mrk 273X, the serendipitously discovered X-ray companion to Mrk 273. Mrk

### Table 2

**Properties of Mrk 273X and Comparison Active Galaxies**

| Galaxy       | Type      | $z$  | Distance (Mpc) | $I$ (mag) | $M_I$ (mag) | $\log (L_{\text{UX}}^\text{soft})$ (erg s$^{-1}$) | $\log (L_{\text{radio}}^\text{1.4 GHz})$ (erg s$^{-1}$) | $\log (L_{\text{H\alpha}})$ (erg s$^{-1}$) |
|--------------|-----------|-----|---------------|---------|------------|--------------------------------|--------------------------------|----------------|
| NGC 5506     | Seyfert 2 | 0.0618 | 26.5          | 13.12$^a$ | -18.9      | 41.98$^b$                                | 38.57$^b$                        | 40.51$^d$       |
| NGC 2992     | Seyfert 2 | 0.0771 | 33.0          | 12.42$^a$ | -20.1      | 42.33$^b$                                | 38.52$^b$                        | 40.90$^f$       |
| IC 5063      | Seyfert 2 / RG | 0.01135 | 48.7          | 10.64$^a$ | -22.8      | $<41.40$\textsuperscript{$ab$}          | 39.60$^a$                        | 41.23$^i$       |
| Fairall 9    | Seyfert 1 | 0.0470 | 204           | 13.16$^a$ | -23.3      | 44.10$^a$                                | ?                               | 43.48$^g$       |
| 3C 273       | QSO       | 0.15834 | 703           | 12.17$^a$ | -27.1      | 45.8$^e$                                 | 43.62$^e$                        | 44.81$^i$       |
| Mrk 273X     | Seyfert 2 | 0.458  | 2150          | 19.10$^a$ | -22.6      | 43.8$^e$                                 | 40.0                             | 41.58$^e$       |

\textsuperscript{a} Kotilainen, Ward, & Williger 1993. \textsuperscript{b} Fabbiano, Kim, & Trinchieri 1992. \textsuperscript{c} White & Becker 1992. \textsuperscript{d} Storchi-Bergman, Kinney, & Challis 1995. \textsuperscript{e} Ulvestad & Wilson 1984. \textsuperscript{f} Forbes & Ward 1993. \textsuperscript{g} Estimated from $V - I = 1.23$ (Buta & Williams 1995) and $V = 11.87$ (de Vaucouleurs et al. 1991). \textsuperscript{h} Koyama et al. 1992 measured $N_H = 23.3$ and the hard X-ray flux, yielding $\log L_{\text{HX}} = 43.04$. \textsuperscript{i} Morganti et al. 1998. \textsuperscript{j} Colina, Sparks, & Macchetto 1991. \textsuperscript{k} Ceballos & Barcons 1996. \textsuperscript{l} Steiner 1981. \textsuperscript{m} Brinkmann, Siebert, & Boller 1994. \textsuperscript{n} This paper. \textsuperscript{o} Turner et al. 1993. \textsuperscript{p} Xia et al. 1999.
273X is at a much higher redshift and therefore not physically associated with Mrk 273 (Xia et al. 1999). Mrk 273X is a featureless early-type galaxy and appears to be the brightest member of a small cluster of galaxies. The optical morphology of Mrk 273X (including its radial surface brightness profile) and its role as the dominant member of a cluster resemble the properties of a PRG, an elliptical or other early-type galaxy. However, its colors and Seyfert 2 spectrum are typical of much later galaxy types. This suggests that the galaxy’s colors are strongly contaminated by the AGN (through both its blue continuum and its emission lines). We believe that Mrk 273X is an active galaxy of the IC 5063 type, except that the soft X-ray source in Mrk 273X is not obscured as it is in IC 5063. Mrk 273X therefore appears to be a selectively obscured PRG in that the radio core and X-ray-emitting region are exposed (as in a typical PRG or Seyfert 1), but the broad-line-emitting region is obscured (as in a typical Seyfert 2). This may indicate that the obscuring torus has an intermediate line-of-sight inclination. Follow-up observations (particularly redshift determinations) of the galaxies surrounding Mrk 273X would validate the cluster hypothesis and thus shed some light on the dynamical state of this system, possibly leading to an identification of the trigger (tidal companion) for the AGN activity.

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### FIG. 4.—Luminosity function for three regions. Each histogram shows the number distribution of galaxies as a function of $I$ magnitude (Gunn $i$ for the bottom plot). Top: field around Mrk 273X ($z = 0.458$; this paper). Middle: cluster CL 0939+472 ($z = 0.41$; Belloni & Roser 1996). Bottom: cluster CL 2158+0351 ($z = 0.45$; Molinari et al. 1990). The galaxies measured for the Mrk 273X distribution (top) are those that are indicated in Fig. 1. Both Belloni & Roser (1996) and Molinari et al. (1990) had magnitude cutoffs in their samples, of $R = 22.5$ and Gunn $i = 23.5$, respectively.
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