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QSOs ASSOCIATED WITH M82

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ABSTRACT

The starburst/AGN galaxy M82 was studied by Dahlem, Weaver, and Heckman using X-ray data from *ROSAT* and *ASCA* as part of their X-ray survey of edge-on starburst galaxies. They found 17 unresolved hard X-ray sources around M82, in addition to its strong nuclear source, and other X-rays within the main body of M82. We have measured optical point sources at these positions and have obtained redshifts of six candidates at the Keck I 10 m telescope, using the low-resolution imaging spectrograph (LRIS). All six are highly compact optical and X-ray objects with redshifts ranging from 0.111 to 1.086. They all show emission lines. The three with the highest redshifts are clearly QSOs. The others with lower redshifts may be either QSOs or compact emission-line galaxies. In addition to these six, there are nine QSOs lying very close to M82 which were discovered many years ago. There is no difference between optical spectra of these latter QSOs, only two of which are known to be X-ray sources, and the X-ray–emitting QSOs. The redshifts of all 15 range between 0.111 and 2.05. The large number of QSOs and their apparent association with ejected matter from M82 suggest that they are physically associated with the galaxy and have large intrinsic redshift components. If this is correct, the absolute magnitudes lie in the range $-8 < M_v < -10$. Also, we speculate that the luminous variable X-ray source which has been detected by *Chandra* in the main body of M82 some 9″ from the center is another QSO in the process of ejection from the nucleus, and we propose some observational tests of this hypothesis.

Subject headings: galaxies: individual (M82) — galaxies: starburst — quasars: emission lines — X-rays: galaxies

1. INTRODUCTION

M82 is the nearest active (starburst) galaxy to the Milky Way. Early optical evidence for an outburst in its center was found by Lynds & Sandage (1963), who measured outward velocities in hydrogen, ionized nitrogen, and oxygen in the filamentary structures on both sides of this nearly edge-on galaxy. They deduced that the outward-flowing gas was the result of an explosive event in the nucleus some 1.5×10^6 yr ago. More recently, it has been shown that the outflow observed by Lynds & Sandage, and by later workers, is related to the tremendous star-forming activity in the central regions of the galaxy (Telesco & Harper 1980). As well as the optical evidence using Hα (e.g., Burbidge, Burbidge, & Rubin 1964; Devine & Bally 1999), a large number of compact radio sources identified as supernova remnants and compact H α regions have been seen (Strickland, Ponman, & Stevens 1997; Pedlar et al. 1999; Griffiths et al. 2000). It appears that large amounts of molecular gas are also present (Walter, Weiss, & Scoville 2002).

The first QSOs close to M82 were found serendipitously by Arthur Hoag, who detected three faint stellar objects with emission lines on an objective prism/grating plate taken of the field around M82. Spectra of these were obtained at Lick Observatory with the Wampler-Robinson image dissector scanner on the 3 m telescope and revealed all three as QSOs with very similar redshifts, $z = 2.048$, 2.054, and 2.040, respectively (Burbidge et al. 1980). The similarity of the redshifts first suggested that perhaps they were associated with a distant cluster of galaxies and QSOs which accidentally lies very close to the line of sight to the center of M82. However, doubt was immediately cast on this suggestion when one of us (Arp 1983) found a fourth QSO in the same small area with a very different redshift ($z = 0.85$; see Table 2).

Following these studies a detailed investigation of a field southeast of M82 close to the field in which the first four QSOs had been found was undertaken by Afanas'ev et al. (1990), Boller (1988), and Boller et al. (1989). In these studies the limit that was set was $m_b = 22.0$. Five more QSOs in this area were discovered from these observations with the Russian 6 m telescope. This gave a total of nine QSOs lying in a cone extending about 10′ southeast of M82. This was the situation prior to the publication of an important paper by Dahlem, Weaver, & Heckman (1998).

2. UNRESOLVED X-RAY SOURCES AROUND M82

An X-ray survey of edge-on starburst galaxies was carried out by Dahlem et al. (1998), using data from *ROSAT* (both position-sensitive proportional counter and high-resolution imaging data) and *ASCA*. A map by Dahlem et al. of the X-ray data centered on M82, and covering a field 35′ × 35′, shows strong emission centered on the nucleus and extending over an elliptical area in the directions north-northwest to south-southeast where the optical filaments of Lynds and Sandage are located on both sides of M82, and where *ASCA* data has pinpointed many sources because of the star formation/supernova activity within M82 (see Griffiths et al. 2000). In addition, Dahlem et al. mapped 17 unresolved sources outside, but close to, M82 (see Fig. 13 of Dahlem et al.). They noted the similarities of the thermal temperatures of these sources to those of components within the body of M82 and pointed out that this suggests " that at least some

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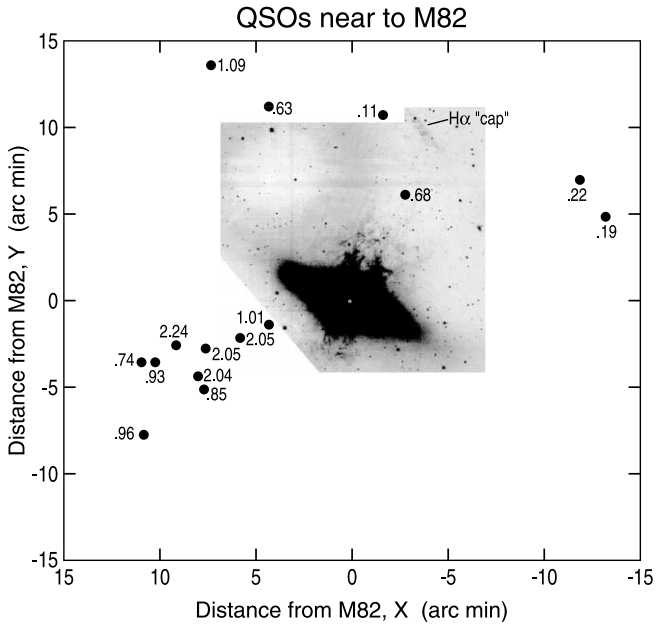

FIG. 1.—Plot shows all of the QSOs and QSO-like objects within an area of 0.25 deg^2 centered on M82 (from Tables 1 and 2). The inserted image is M82 in the light of Hα emission with the filament going northwest and ending on the Hα "cap." (Image from Devine & Bally 1999.)

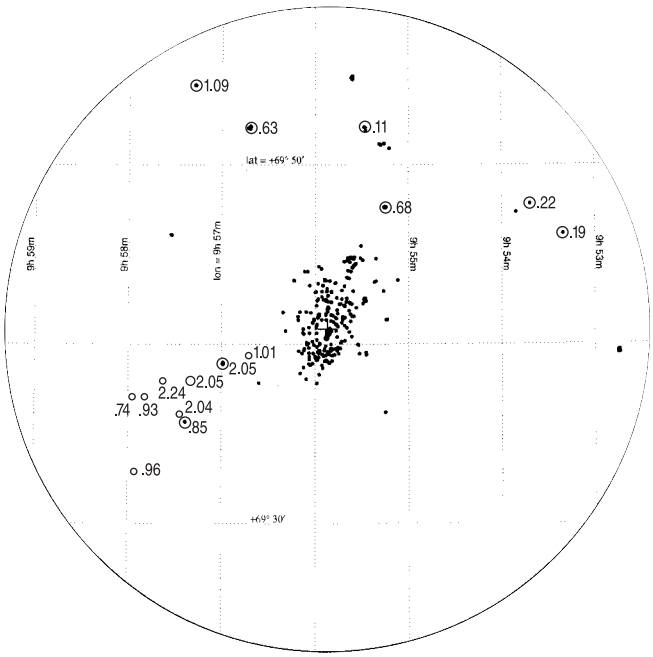

FIG. 2.—Points are cataloged X-ray sources from the *ROSAT* high-resolution imager (HRI). Circled objects have redshifts from Tables 1 and 2. The inner point sources appear to be part of the gas ejected from the nucleus of M82. A principal outflow of molecular gas has been mapped in just the direction of the east-southeast QSOs at P.A. = 110°. (Walter et al. 2002, Fig. 1.)

of the unresolved sources are associated with M82." They also pointed out that it was statistically very unlikely to have so many background point sources so close.

Comparing positions of point sources in the field (Strickland et al. 1997) and a few known optical positions, one of us (H. C. A.) was able to apply zero-point corrections of (−2 s, −18″) to the Dahlem positions and thereby make optical identifications of most of those point X-ray sources (see Figs. 1 and 2). Where more than one optical object was in the error circle, quick-look spectroscopic data enabled us to eliminate a few objects that are faint foreground stars. Following this procedure, we concluded that 10 objects are strong candidate X-ray sources, and they were observed by E. M. Burbidge with the low-resolution spectrograph (LRIS) on the Keck I telescope on 2002 March 20, through considerable and variable cirrus cloud. Of the 10 objects observed, three turned out to contain objects which had no features from which to determine redshifts. One was a blue galaxy, not measured, and the remaining six furnished emission-line redshifts. The average difference between the X-ray position and optical candidate for the six new emission-line objects was 19″. In the three cases where featureless continua were observed there was no evidence from absorption lines or colors that they were stars. Therefore they would remain as candidates for BL Lac–type spectra associated with M82.

3. RESULTS

The six Dahlem et al. emission-line sources that we observed turned out to be low- to medium-redshift QSOs or QSO-like objects (Table 1 and Fig. 3, which shows the spectra).

The three objects with the highest redshift show typical QSO spectra. For the lower redshift objects, only the red end of the spectra showed clearly measurable features. Details of the spectra are as follows.

Dahlem 7.—Mg II 2798, [O II] 3727, [Ne III] 3869, Hγ, [He II] 4686, Hβ, [O III] 4959, 5007.

Dahlem 12.—Mg II 2798, Hγ, Hβ, [O III] 4959, 5007.

Dahlem 17.—Si III] + C III] blend 1900, C II 2326, [Ne IV] + Fe III blend 2423, Mg II 2798.

Dahlem 3.—[O II] 3727, Hα, [S II] blend 6725.

Dahlem 4.—Hα, [S II] blend 6725.

Dahlem 9.—[N II] 6548, Hα, [N II] 6583, [S II] 6717, 6731.

We believe that the three low-redshift objects are QSOs, but we cannot exclude the possibility that they are compact emission-line galaxies.

All of the QSOs and QSO-like objects now known to lie within 30 arcmin of M82 are listed in Tables 1 and 2. There are 15, and they do not appear to be randomly distributed. In Figure 1 we plot all 15 around an image of M82 which was taken in its Hα emission line. We note the following:

1. The nine QSOs south-southeast of M82 have, on average, higher redshifts than the six north of M82.
2. There is a comparatively close pair, BOL75 and M82 No. 69, which has a separation of only 39″ (630 pc at the distance of M82), and a triple system Hoag 1, Hoag 2, and Hoag 3 with separations of 118″ (1–2), 62″ (2–3), and 195″ (3–1), and similar redshifts.
3. All 15 objects with redshifts, of which 12 are certainly QSOs and three are emission-line objects which may also be QSOs, lie within 15′ of the center of the galaxy. This gives conservatively a density of at least 61 QSOs per square degree. Of the 12 QSOs, six are brighter than 19.5 mag, eight are brighter than 20 mag, and 10 are brighter than 20.5 mag. These correspond to densities of 30, 41, and 51 per square

TABLE 1
QSOs and Other Objects Near M82

Object	α (J2000)	δ (J2000)	Mag. E	Color $O-E$	Redshift z	Angular Distance from M82 θ (arcmin)	X-Ray Counts ks^{-1} C	Δ Position Δr (arcsec)
Observed QSOs with Redshifts								
Dahlem 3	9 53 18.9	+69 45 44	18.7	1.1	0.190	14.2	6	6
Dahlem 4	9 53 35.3	+69 47 51	18.6	0.4	0.221	13.8	9	25
Dahlem 7	9 55 18.8	+69 47 00	19.8	~0.0	0.675	6.9	9.7	31
Dahlem 9	9 55 32.7	+69 51 34	18.9	0.4	0.111	10.9	18.4	27
Dahlem 12	9 56 41.0	+69 52 01	18.9	0.2	0.626	12.0	2.6	7.4
Dahlem 17	9 57 16.4	+69 54 25	17.2	0.1	1.086	5.4	2.5	17
Other Objects								
Dahlem 6	9 54 34.1	+69 48 37	>19.2	blue	Continuum		1.2	20
Dahlem 8	9 55 16.5	+69 51 15	18.2	0.9	Continuum		10	19
Dahlem 10	9 55 36.4	+69 55 07	17.3	−0.2	Blue galaxy		12	...
Dahlem 15	9 56 56.4	+69 34 05	18.9	0.4	Continuum		3.9	24
Dahlem 14					QSO Hoag 1			
Dahlem 1					No data			
Dahlem 2					No data			
Dahlem 5					No data			
Dahlem 11					No identification			
Dahlem 13					No identification			
Dahlem 16					QSO NGC 3031 U4			

Notes.—The upper part of Table 1 lists the six Dahlem objects that we observed, the 2000 coordinates from Dahlem et al., the magnitudes and colors of our identified optical objects, our measured redshifts, their angular distances from the center of M82 in arcminutes, their X-ray counts per kilosecond, and the angular distance in arcseconds of the optical object from the X-ray position. The lower part gives the same data for four more Dahlem objects which we observed but for which we did not obtain redshifts, Dahlem 14 and 16, which were already known to be QSOs with known redshifts, three candidate identifications for which we obtained no data, and two sources with no optical candidate identification.

degree, respectively. Such densities are to be compared with those obtained in QSO surveys by Kilkenny et al. (1997) and Boyle et al. (2000), which give, respectively, 10 per square degree to 20 mag, and 25 per square degree for $18.25 < b_j < 20.85$ from the Two Degree Field survey with the Anglo-Australian Telescope. While there are small uncertainties associated with the magnitude calibrations, and the total numbers are small, they do mean that there is a significant overdensity of QSOs in the magnitude range down to 20–20.5 mag near to M82 compared with those in the general field.

4. The distribution of these QSOs is far from uniform. No QSOs have been detected southwest of M82 down to the magnitudes of the QSOs southeast of M82. There are candidates among the X-ray sources listed by Dahlem et al. immediately southeast of M82, but the distribution of unresolved X-ray sources as shown in their Figure 13 and our Figure 1 quite definitely shows the concentrations northwest to north and south to southeast.

5. As can be seen in Figure 1, there is a long Hα filament, apparently ejected along the minor axis north-northwest from M82 (Devine & Bally 1999). Just in the vicinity of the "cap" at about $\theta = 11'$ we find the strong X-ray–emitting object with $z = 0.111$. This suggests that the X-ray point sources have been entrained, moving along the path followed by the $z = 0.68$ QSO through the $z = 0.11$ object and on to the $z = 0.63$ QSO and the $z = 1.09$ QSO. There are many X-ray point sources found from the high-resolution *ROSAT* (HRI) map which are apparently emerging from the body of M82.

6. The reddening and absorption in active galaxies like M82 is known to be large. In this connection it is noticeable that in Table 1 the sources on the north-northwest side of M82 appear generally bluer and brighter than the sources on the southwest side. This might imply that these QSOs are on the near side of M82. If this is correct, it would imply that the 11 "background" QSOs suffer absorption and hence their density would be expected to be lower than it is in the central region. This means that the density of M82 quasars should be compared to a background density QSOs which are about a magnitude brighter, and thus less frequent.

Finally we turn briefly to the numerical values of the redshifts in Tables 1 and 2.

In a number of investigations of QSOs and active galaxies it has been shown that QSO redshifts tend to peak about certain values: $z = 0.061$, 0.30, 0.60, 0.96, 1.41, 1.96, etc., and that these peaks are periodic with $\Delta \log(1 + z) = 0.089$ (Burbidge & Napier 2001 and earlier references given there). In the most general case the observed redshift z_0 is given by $z_0 = [(1 + z_c)(1 + z_d)(1 + z_i)] - 1$, where z_c, z_d, and z_i are the cosmological, Doppler, and intrinsic redshift components. Where the sample is made up of QSOs associated with bright low-redshift galaxies, we know that z_c in each case is very small. Also, z_d is a measure of the projected speed with which the QSOs are ejected from the galaxies. It turns out that for the X-ray–emitting QSOs, $z_d \approx |0.04|$ (Burbidge & Napier 2001). Thus, for the QSOs associated with M82, $z_0 \simeq z_i$. We might expect, therefore, that many of the values of z_0 in Table 1 might lie close to the peak intrinsic values given above. This is clearly the case. There are two close to 0.60 (0.626, 0.675), three very close to 0.96 (0.93, 0.96, 1.01), and three very close to 1.96 (2.040, 2.048, 2.054). We conclude that the high surface density of these QSOs

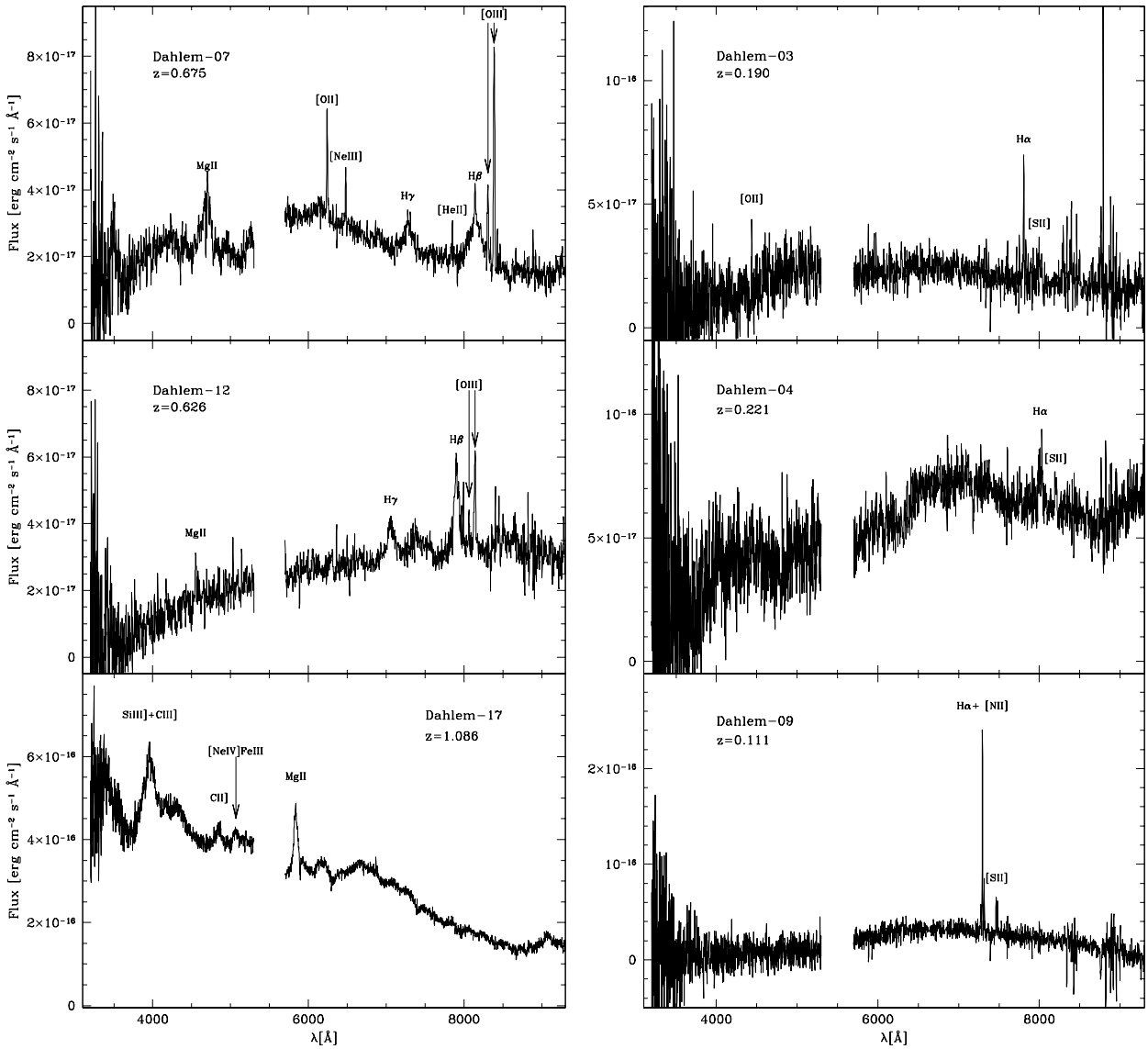

FIG. 3.—Point-source X-ray objects with emission-line redshifts northwest of M82 observed with the Low-Resolution Imaging Spectrometer (LRIS) on the Keck I 10 m telescope. Our setups used the 400/8500 grating, 1.86 Å pixel^{-1}, on the red side and the 400/3400 grism, 1.09 Å pixel^{-1}, on the blue side. *From top left*: Dahlem 7, $z = 0.675$; Dahlem 12, $z = 0.626$; Dahlem 17, $z = 1.086$. *From top right*: Dahlem 3, $z = 0.190$; Dahlem 4, $z = 0.221$; Dahlem 9, $z = 0.111$.

TABLE 2
QSOs IDENTIFIED EARLIER NEAR M82

Object	α (J2000)	δ (J2000)	Mag. V	Color $B-V$	Redshift z	Angular Distance from M82 θ (arcmin)	X-Ray Counts ks^{-1} C	Δ Position Δr (arcsec)
M82 No. 95	9 56 41.9	+69 39 24	19.44	0.36	1.01	4.55	...	...
Hoag 1	9 56 58.2	+69 38 37	19.26	0.84	2.048	6.15	2.8	11
Hoag 2	9 57 19.8	+69 58 01	19.79	0.76	2.054	8.11	...	...
NGC 3031 U4	9 57 20.2	+69 35 37	20.1	0.70	.85	9.23	3.9	17
Hoag 3	9 57 23.5	+69 36 13	20.51	0.69	2.040	9.17	...	...
Bol 105	9 57 36.9	+69 38 12	21.4	...	2.24	9.45	...	...
M82 No. 69	9 57 49.5	+69 37 12	19.38	0.70	0.93	10.81	...	...
M82 No. 22	9 57 55.8	+69 32 56	19.04	1.31	0.96	13.31	...	...
Bol 75	9 57 57.0	+69 37 08	22	...	0.74	11.45	...	...

together with their remarkable distribution about M82, and finally the concentration of the redshifts about previously determined intrinsic values, all suggest that the QSOs have been ejected from M82.

M82 is the nearest active galaxy around which many QSOs have been detected. If they are physically associated with M82, since the distance modulus is 27.7, they are all intrinsically faint, with absolute magnitudes M_v in the range -8 to -10.

All of the other active galaxies around which QSOs have been found, such as NGC 4258 (Burbidge 1995), NGC 2639 (Burbidge 1997), NGC 1068 (Burbidge 1999), Arp 220 (Arp et al. 2001), or NGC 3628 (Arp et al. 2002) are much further away than M82.

The very different distances of those galaxies means that the QSOs found near to them with apparent magnitudes 18–20 mag are intrinsically much brighter than the QSOs around M82 described here. For example, for the case of Arp 220, which lies at a distance of about 90 Mpc ($H_0 = 60$ km s^{-1} Mpc^{-1}), the QSOs about 10′–20′ from its center have $M_v = -14.5$–15.5. Thus if Arp 220 has faint QSOs near it at the same projected linear distances as those near to M82 and similar to those QSOs, they will lie $\lesssim 1'$–$2'$ from the nucleus and will have apparent magnitudes $\sim$24–25 mag. Thus while they will contribute to the central luminosity of Arp 220, they will be so faint that they will not be detectable as individual optical sources.

However, if M82 has QSOs as bright as those found around Arp 220 associated with it, the equivalent linear distances from the center of M82 will be 10 times as far away from the center of that galaxy, i.e., distances of 2°–4°. QSOs at such large angular distances will not easily be identified as being associated with M82. They would have apparent magnitudes 15 or brighter; i.e., some of the brightest QSOs might have originated from such local galaxies. (In fact, brighter QSOs of this angular distance range from M82 have been pointed out by Arp & Russell 2001, Fig. 6.) Thus it may be the case that active galaxies can give rise to many QSOs with a wide range of luminosities both in optical flux and in X-rays. Their detection will then depend on how far from the nucleus they have traveled, and how bright they are.

4. POSSIBLE EVIDENCE FOR QSOs INSIDE M82

Studies over many years of the central regions of comparatively nearby starburst galaxies, and galaxies with active galactic nuclei, have shown that they often contain compact sources outside the centers which have been detected as both discrete radio sources and discrete compact X-ray sources. Some of these sources are known to be highly variable. In several high-resolution X-ray studies using *ASCA* and *Chandra*, a number of luminous X-ray sources have been detected. Apart from those resulting from supernovae, elsewhere we have made the general argument that sources of this kind are likely to be local QSOs in the process of ejection from the nucleus of the active galaxy (Burbidge, Burbidge, & Arp 2003). In particular, a luminous variable X-ray source CXO M82J095550.2+694047 has been detected by *ASCA* and *Chandra* some 9″ from the center of M82 and it shows large time variability. Its luminosity has varied between about 10^{40} and 10^{41} ergs s^{-1} in the 0.2–10 keV energy range (Matsumoto et al. 2001; Kaaret et al. 2001).

We believe that this may be a newly born QSO being ejected from the nucleus of M82. There are several tests of this hypothesis which are possible. If the hypothesis is correct, we would expect that if any spectroscopic features could be detected in X-ray, radio, or optical wavelengths, they would show anomalous redshifts, as do the QSOs outside the galaxy. Apparently such an object has recently been detected in the galaxy NGC 4868 (Foschini et al. 2002a, 2002b).

Second, based on X-ray–emitting QSOs, we estimate that these objects will be ejected at speeds of $\sim 0.1c$. Thus, for a galaxy as close as M82, it may be possible to measure proper motions. For ejection speeds in the range 10,000–30,000 km s^{-1}, we might detect motions of about 6–18 mas yr^{-1}. Since the sources are variable in flux, it may be hard to disentangle variability from the movement of the center of gravity of the source. However, a proper motion search could provide a practical test within 5–10 yr.

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