# X-Ray Observations of Galaxy-Quasar Associations

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**Abstract** Five examples of close associations of quasars with bright, low redshift galaxies have been observed in X-ray wavelengths with ROSAT. In three cases where the galaxies are detected strongly, the nuclei of the galaxies have X-ray extensions in the direction of the adjacent quasars.

In all cases the active galaxies and quasars are located at the origin of apparent lines or pairs of X-ray sources, some involving filamentary X-ray connections to fainter quasars or candidate blue stellar objects. Brighter X-ray sources in these fields are found to be in excess of average survey values. The filaments and connections have measured fluxes of $1 \lesssim F_X \lesssim 60 \times 10^{-13} erg\ cm^{-2} s^{-1}$ and they tend to radiate more strongly in the harder end of the 0.1-2.4 keV energy band.

The most surprising result is the evidence that X-ray sources of optically diverse character are linked together in lines and extended filaments. Because of the rapid decay time of the high energy X-ray radiation, it is implied that we are observing some ongoing process possibly related to matter creation or emergence.

## Introduction

From 1966 on a number of galaxy-quasar pairs were discovered. In addition to the very low accidental probability of these quasars falling so close to bright galaxies, the galaxies themselves tended to be unusually active and disturbed. With the capability of pointed observations by the ROSAT X-ray telescope these associations could be observed in wavelengths where the possibility of observing interactions and connections between the high energy components of the quasars and galaxies would be maximized.

We consider the X-ray extensions from the nuclei of the three active galaxies observed here to be the result with the most immediate import. The apparent lines and filaments of X-ray sources are more surprising but potentially also of great importance. The mutually supporting results in the five fields presented here are particularly important for establishing the phenomenon of lines of sources and filaments which characteristically emerge from the strongest X-ray objects in the field.



*M. Kafatos and Y. Kondo (eds.), Examining the Big Bang and Diffuse Background Radiations*, 369–380.

**1. Mark474 and nearby objects** This field is particularly interesting because it illustrates the tendency for companions to large galaxies to be bluer, more active, have slightly higher redshifts and to be associated with more active objects such as Seyfert galaxies and quasars. (Arp 1987; 1994a). A prototype configuration of the Sa galaxy NGC5689, the companion $S_d$, NGC5682, and the Seyfert galaxy Mark474 was discovered by Arp and Khachikian (1973). A quasar within 95 arc sec of NGC5682 was reported by Arp, Baldwin and Wampler (1975). Observations of a large sample of companion galaxies have shown associations with quasars at an over density of a factor of about 20 (Arp 1983; 1987). In this particular case the probability of accidentally finding an unrelated quasar this close to NGC5682 was only of the order of $5 \times 10^{-3}$. However, the probability that the nearby galaxy would be a later type companion was of an order of magnitude less and the probability that such an active Seyfert galaxy would fall so closeby was several orders of magnitude less. Statistically this group appears to represent a highly significant physical association.

Many of the important results are introduced in Fig.1 where it is evident from the 12.8ks, ROSAT PSPC exposure that the Seyfert 1 galaxy, Mark474, is a very strong X-ray source. In these observations Mark474 registered a total of 10,830 counts which enabled an accurate spectrum to be derived. It was fitted to a power law spectrum of photon index $\Gamma = -2.31 \pm 0.06$ with an HI absorption between $3.6 \pm .23$ and $5.5 \pm 1.0 \times 10^{20} cm^{-2}$ (depending on the fitting of an additional black body component below 0.5 keV, see Bi 1994). It is also evident that the large Sa galaxy in the field, NGC5689, is erupting X-ray material from its nucleus just along its northern minor axis. Finally there is an apparent extension of X-rays between Mark474 and the quasar of $z = 1.94$ immediately to the northwest.

Fig.2 shows a larger scale view of the X-ray connection between Mark474 and the quasar to a somewhat lower isophote level in the same energy band, 0.5–2.4 keV (softer energy bands do not contain much relative signal in this field). The extension from Mark474 toward the quasar is about $2'$ in length and about $0\overset{'}{.}7$ in width. The width is, however, hard to judge because between the galaxy and the quasar is a low isophote. The most certain result of this feature, however, as shown in Figs.1 and 2, is that the isophotes around the quasar are extended along a line directly away from the nucleus of Mark474.There are about 30 counts associated with this quasar in the 0.5-2.0 keV bands. This is in a region not affected by extended emission arround Mark474 or NGC5682 and represents the clearest evidence for the association of the quasar with the galaxy.

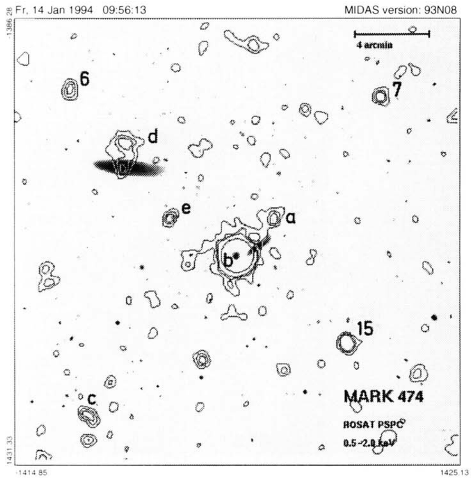


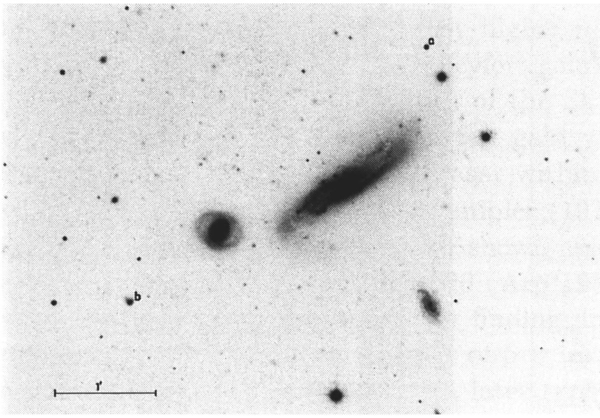


Fig. 1(left) A12.8ks exposure overlayed on a 200-inch photograph shows the strong X-ray Seyfert Mark474, the $S_d$ companion just to the NW, the $S_a$ with X-rays emerging along the minor axis, and the quasar of $z = 1.94$ connected back to the Seyfert. Fig.2 (right) enlargement with lowest X-ray isophotes at about 3, 4, 5 sigma.

In Fig.1 the sources are: a) $z = 1.94$ quasar; b) compact blue galaxy identified in halo of Mark474 by application of deconvolution program (Bi 1994); c) extended source, grouping of faint objects some of which may be blue; d) $S_a$ galaxy NGC5689; e) seven reddish galaxies distributed linearly in shape of a "V". The X-ray source, however, coincides with a 20 mag BSO. Other X-ray sources which coincide with blue stellar objects are (BSO); 7) 21 mag. BSO 15) 20 mag. BSO; 6, 10 and 11) 20 mag. BSO.

**2. NGC4651 and 3C275.1** Cross correlation of a complete survey of radio (3CR) quasars with bright galaxies (Burbidge et al. 1971) showed the chance of the observed association between the two samples being accidental was only $5 \times 10^{-3}$. This result was later confirmed by Kippenhahn and de Vries (1974). For this particular pair the chance of accidental association was $3 \times 10^{-3}$. What was not included in this improbability, however, was the fact that the galaxy showed more striking evidence for physical ejection than almost any other galaxy in the Reference Catalog.

The picture of the luminous jet and counterjet emerging from NGC4651 (Sandage et al. 1956) revealed, however, that the jet from the galaxy did not point directly at the quasar but instead was at a position angle about 20° different. This was taken by many as a reason for not



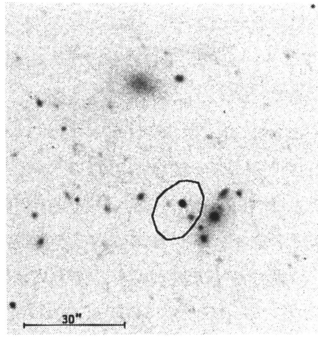


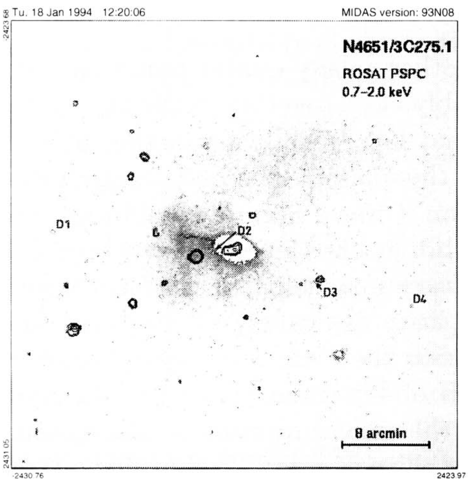
Fig.3 (left) Quasar (a) and compact blue galaxy (b) shown aligned across Mark474. Fig.4 (right) BSO X-ray source in a non-equilibrium configuration of galaxies (source e).

believing that the quasar was related to the galaxy. But, close inspection of the Sandage picture showed evidence for ejection from NGC4651 not only in the direction of the long filament but evidence also for ejection at greater position angles; down to p.a. $\simeq 94°$, much closer to the position angle of the quasar at p.a. $= 100°$. The recently exposed, Palomar, deep IIIa-J survey plate shown here in Fig.5 confirms the optical evidence for material at greater position angles than the main filament and hence closer to the position angle of the quasar. As it turns out in the X-ray observations discussed in the following section as well as in a growing number of optical cases (see for egs. M82 and NGC1097 in Arp 1987) there is evidence that active galaxies tend to eject in cones as well as lines and also in more than one direction. (See also Wilson and Tsvetanov 1994.)

The most important results from the 10.5 ks PSPC exposure are presented in Fig.5 and 6 where it is seen that the galaxy NGC4651, which we have seen is so optically active, has an X-ray jet, or extended X-ray emission, from its nucleus pointing directly at the quasar 3C275.1.

In Fig.6 the broad energy band (0.1–2.0 keV) has been deliberately undersmoothed (FWHM= $24''$) to maximize the resolution and the lowest contour at $2\sigma$ plotted in order to emphasize the close approach of the X-ray extension from the nucleus of NGC4651 to the quasar. The overall length of the X-ray extension from the nucleus of NGC4651 is $\sim 2\rlap{.}'4$ at the 3 sigma

https://doi.org/10.1017/S0074180900110216 Published online by Cambridge University Press



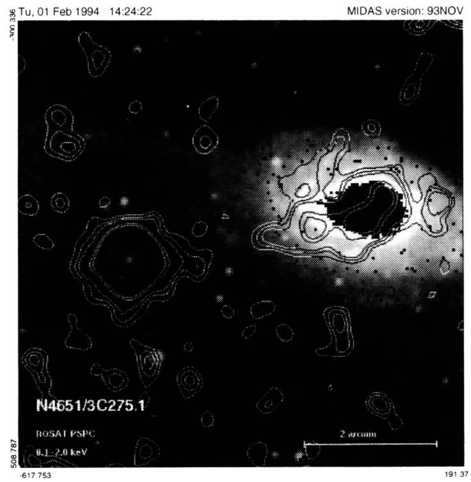




Fig.5. (left) X-ray sources are shown by contours superposed on a IIIa-J photograph from $2^{nd}$ Palomar Sky Survey. Symbols DG identify very low surface brightness dwarf galaxies. Fig.6. (right) Enlarged view of galaxy and quasar with X-ray isophote levels of 2, 3, 4 and 8 sigma.

level. The extension from the nucleus toward 3C275.1 is 112″ and in the direction away from 3C275.1 it is only 32″. In this 0.1-2.0 keV broad band there are about 90 photons giving a flux of $2 \times 10^{-13} erg\ cm^{-2} s^{-1}$. In the hard energy range, 0.7-2.0 keV, the extension is also pointed directly at the quasar but does not reach so far ($\sim 100''$).

The quasar itself, however, is also extended, in the broad band about 76″ toward the nucleus of the galaxy (the radius orthogonal to this is only 51″ on average). In the hardest (0.9-2.0 keV) band, however, the quasar is only slightly extended toward the galaxy and strongly ($\sim 83''$) extended away from the galaxy.

Therefore the maximum extension between the quasar and the galaxy is in the broad band and the maximum extension away from the galaxy is in the hardest band. Both NGC4651 and 3C275.1, integrated, are among the hardest sources in the field. The galaxy hardness ratio (HR1=.78) is even harder than the quasar (HR1=.54), however, perhaps lending support to the idea that we are seeing a fairly young jet.

As Fig.6 shows there are two apparent condensations on either side of the nucleus of NGC4651. As far as can be determined they are equally spaced across the nucleus (57″ either side). It is an intriguing question as to whether, in the whole extension from the galaxy nucleus, it is more like knots in a continuous filament or separate condensations which are blended

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instrumentally to resemble a jet.

**3. NGC3067 and 3C232.** This is another galaxy-quasar pair that Burbidge et al. (1971) found to fall improbably close together in the sky. Later the surprising discovery was reported that low redshift absorption lines of the galaxy appeared in the spectrum of the quasar. The investigators who modeled the galaxy under the assumption it was a normal equilibrium object (Boksenberg and Sargent 1978; Rubin et al. 1982), however, ignored the obvious fact that NGC3067 was a very unusual, high surface brightness, star burst galaxy. In continuum light the galaxy is shattered and chaotic and in the light of H alpha emission there are conspicuous ejection filaments. (Arp 1989) Most recently HI observations showed an extraordinary hydrogen filament leading from the galaxy directly to the quasar. (Carilli, et al. 1989) Therefore, the probability of association of this quasar with the galaxy was extremely high.

The field was observed for 5.6ks with the ROSAT PSPC. The primary result on the galaxy-quasar pair is shown in Fig.7. There it is seen that X-ray material is emerging in a bipolar direction from the nuclear regions of the disturbed, active galaxy, NGC3067. In a high resolution photograph with the KPNO, 4 meter telescope, there appears to be more obscuration on the North side of the galaxy suggesting that is the near side. If this is so we are looking at the underside of the galaxy and the X-ray ejection would be more obscured by the disk of the galaxy on the north side.

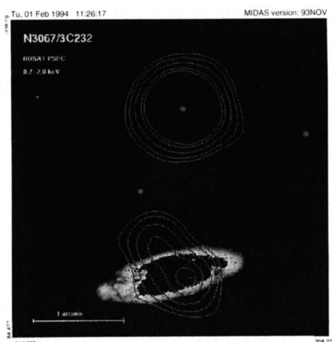


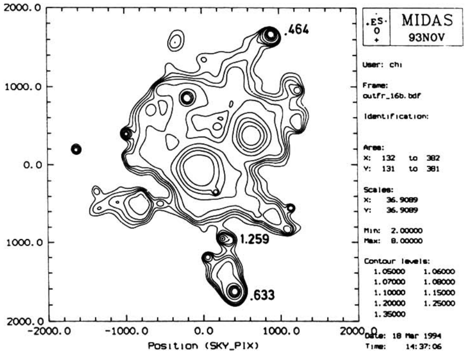

Fig.7. Hard X-ray isophotes are plotted around the quasar 3C232 and the starburst galaxy NGC3067. The isophotes suggest a bipolar ejection from the nucleus of the galaxy. Absorption in the galaxy suggests the stronger X-ray lobe is on the nearer, less obscured side and that the longer one is curving over slightly toward the quasar as it extends.

The overall extension measured for the jet is 1'.4. Measured from the optical center of the galaxy it is 46″ in extent, i.e. about 21% longer in the direction toward the quasar than in the direction away from the quasar. The northern X-ray extension starts out at a position angle $\sim 35°$ away from the quasar but then appears to start curving gently over in the direction of the quasar. If the relatively short exposure of 5.6ks had been as long as the 10.5ks of the preceding NGC4651 field, it is possible that the NGC3067 extension would have reached relatively closer to the quasar. In the 0.7-2.0 keV band there are 20 net photons yielding a $F_X = 0.5 \times 10^{-13} erg cm^{-2} s^{-1}$ for the whole nuclear feature in NGC3067. The quasar 3C232 (like 3C275.1) is very hard (again HR1 = .54). But again the galaxy, NGC3067 is the hardest source in the field at HR1 = .63.

**4. X-ray Observations with HRI of NGC4319/Mark205.** The bright apparent magnitude, quasar-Seyfert galaxy Markarian 205 falls only 44″ south of the extremely disrupted spiral galaxy NGC4319. Extensive optical observations have established that a luminous filament connects these two objects of much different redshift. (Arp 1971; Sulentic 1983) Since the optical connection is only 2/3 arc min long, the maximum resolution of the ROSAT HRI was required to investigate the area of interest. The immediately apparent result of the 12.4 ks exposure, was that detectable X-ray radiation filled a large part of the central field out to about 8′ radius. The compact, active Mark205 was detected strongly, but also NGC4291, a morphologically undistinguished companion galaxy at 6.′4 distance, as well as a number of point sources which are shown in Figs.8 and 9.

**X-ray Connections from Mark205.** In order to study the lower surface brightness features in the field, the results were smoothed with a special filter that smoothed the 8″ image pixels in the field which had one photon with a 16 ×8″ = 128″ gaussian filter, those pixels with two photons with an 11.3 × 8″ = 90.″4 gaussian filter and then successively $n/\sqrt{2}$ where $n$ goes from 8 to .5. Image pixels with more than 12 photons were not smoothed. Finally all smoothing levels were added into one final picture. This program gives the greatest detectivity for faint surface brightness features by smoothing over large areas and at the same time retains good resolution on the strongest features.

Fig.8 shows the startling result that a number of the point X-ray sources are connected back to the central Mark 205 by luminous X-ray filaments. Of particular importance is the fact that the two brightest quasars to the northwest and south are connected by long, continuous filaments leading from the central region of Mark 205 in roughly opposite directions to each quasar (16.′3 from Mark205 to the northern X-ray source and 13.′8 to the southern source). The third identified quasar of $z = 1.259$ lies along the filament extending to the southernmost quasar. (These quasars were measured as part of the Einstein, Medium Sensitivity Survey, Stocke et al. 1991).



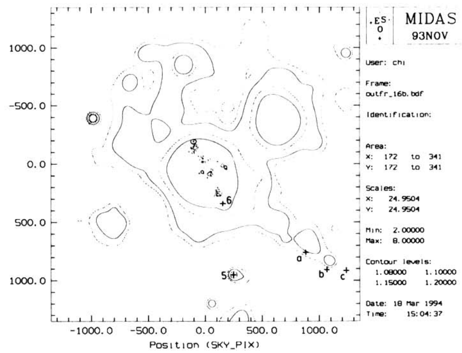




**Fig.8 (left) HRI observations show Mark205 to be the strongest X-ray source. Smoothed with a variable filter which gives maximum detectivity to low surface brightness features, the X-ray filaments lead to quasars with the marked redshifts. Fig.9 (right) An enlarged view of higher surface brightness jet emerging 13′ from Mark205. Radio ejections from NGC4319 (Sulentic 1986) are shown inside central isophote.**

The fact that Mark 205 is actually ejecting is shown by Fig. 9 where a broad, strong jet emerges at a position angle of $p.a. = 235°$. Tracing this 13′ jet of Fig.9 back shows a pair of sources only 30″ either side of the nucleus at $p.a. = 236°$. Apparently there is a strong, perhaps more recent, ejection from Mark205 at $p.a. = 236°$ and a fainter, thinner ejection at $p.a. = 195°$. The latter extends further and may be somewhat older. This is the ejection that now contains the bright quasars identified in Fig. 8.

There seems to be no trace of an X-ray nucleus in NGC4319. A possible explanation is that violent events have disrupted the morphology of the galaxy and this could account for the now minimal X-ray nucleus. In support of this, optical observations by Sulentic and Arp (1987) showed that some process has removed the hydrogen gas from NGC4319.

**5. X-ray Observations of NGC5832 and 3C309.1** This galaxy-quasar pair is another of the high probability associations from the complete 3C radio survey but the galaxy is optically not very disturbed and its separation from the quasar is the largest in the group at 6.′2. The PSPC observations reported here for the relatively short exposure time of 4.3 ks.

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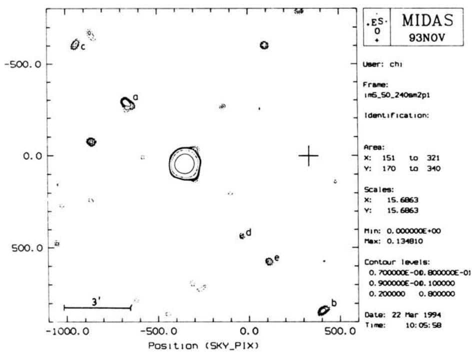
None of the reductions of this observation showed any trace of X-ray emission at the positions of NGC 5832. Unless longer exposures showed some at the position of the galaxy nothing can be said about any X-ray relation to the quasar. Contour maps of this field are shown in the medium hard band in Fig.10. The apparent alignment of sources there serves to introduce the final result that there is a surprising but ubiquitous tendency for bright apparent magnitude, active X-ray sources to have lines of fainter X-ray sources emerging in at least one, sometimes two directions.



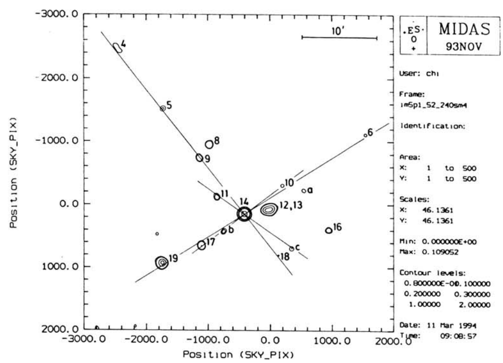
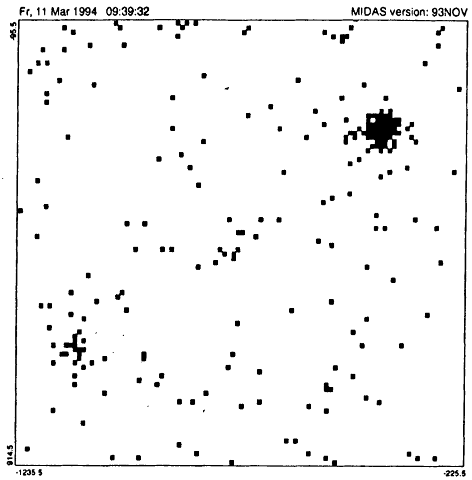




Fig.10. (left) The X-ray source is 3C309.1. The optical position of NGC5832 is indicated by a cross. In the .5-2.4 keV band shown here the sources are 1-1.5 cts ks$^{-1}$. In the 0.1-2.0 keV band $a$ and $b$ are 10 and 14.5 cts ks$^{-1}$. Fig.11. (right) All sources in the 0.5=2.4 keV energy range in the NGC4651/3C275.1 field. Lowest contour = .08 photons per 5$''$ image pixel. Lines of sources originating from the quasar are indicated. No. 4 is catalogued quasar of $z$ = 1.477.

**6. Alignments of X-ray Sources.** The clearest lines of X-ray sources are seen in Fig.5 and particularly Fig.11 emanating from the quasar 3C275.1. Three strong sources extend in a line SE (b, 17 and 19). On the other side are sources 10 and 6. Even more conspicuous in Fig.11, however, is another line of X-ray sources running NE to SW. This includes sources 4, 5, 8, 9 and, on the other side, 18 and c. A strong source at the end of the NE line is no.4 which is a catalogued quasar of $z$ = 1.477. Although its outer isophotes are extended due to its 29$'$ distance from the field center, its inner isophotes are conspicuously extended back toward 3C275.1, a characteristic not shared by other sources at this distance from the field center.

As independent support for the significance of these alignments we show Fig.12 where the individual photons are recorded between 3C275.1 and source 17. It is apparent that source *b* is actually a linear distribution of photons stretching from the quasar along the line to the SE.



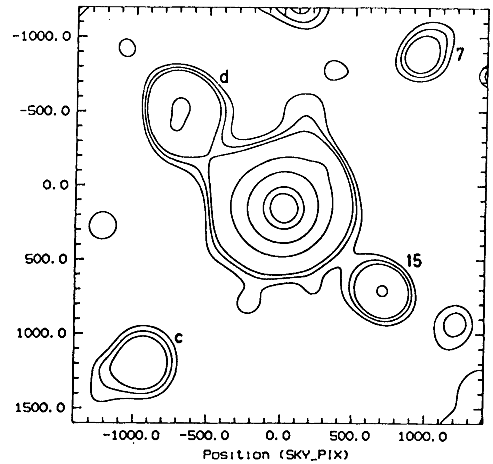




Fig.12 (left) Individual hard photons show source *b* is elongated by a ratio of about 4 to 1 along the SE line from 3C275.1. Fig.13 (right) Low surface brightness contours in the field of Mark474 showing sources 7, 15 and *c* are extended away from the Seyfert along previously defined lines.

Initially, in Fig.1 we saw alignments of sources across Mark474. Sources a and b were aligned across the Seyfert at $p.a. = 314°$ and $132°$. Sources 7 and c were aligned at $p.a. = 319°$ and $138°$ and paired at 11!9 and 11!6 distance. Then almost orthogonal to this is the alignment of NGC5689 nucleus (d) across the Seyfert nucleus with 15 ($p.a. = 50° \pm 1$ and spacing 7!9 and 7!6). Also roughly along this latter line are sources 6 (BSO) and e (BSO). Now Fig.13 shows the low surface brightness contours of these sources around Mark474 extend away from the Seyfert along the previously identified lines of sources–another independent check of the physical significance of the source alignments.

Of course we saw luminous filaments connecting the quasars back to Mark205 in Fig.8 and alignments of faint sources from 3C309.1 in Fig.10. For the fifth galaxy quasar pair, NGC3067 and 3C232 we show low surface brightness contours in Fig.14.

**Discussion.** For some the "quasar" Mark205 is technically a Seyfert Galaxy. This is because on the cosmological hypothesis a quasar is arbitrarily defined as $M \approx -23$ mag. and Mark205, at $z = .07$, is only

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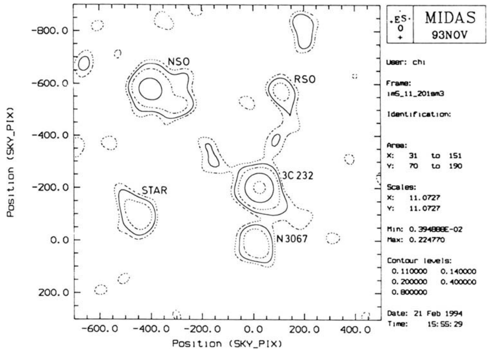


Fig.14. An area $10' \times 10'$ around NGC3067/3C232 shown in broad energy band, 0.1-2.0 keV. The line of emission extending NE and SW from 3C232 is primarily "soft" while the extension N-S is most conspiouous in hard bands. Smoothing is $35''$ FWHM. Continuation of the northern X-ray material, $17'$ from NGC3067 leads to a $7'$ diameter ring of 5-6 BSO's, all strong quasar candidates.

$M = -22.5$ mag. The important point, however, is that it is connected by luminous X-ray filaments to three quasars of much higher redshift. Two of these quasars are optically $m \approx 18mag$ and statistically they have only a $10^{-3}$ chance of being accidentally associated with Mark205 at their angular distances. If the X-ray fluxes are plotted on the log N, log S relation for average fields (Hasinger et al. 1993) it is seen that the Mark205 field sources are more than an order of magnitude in excess of normal. This would seem to add up to inescapable evidence that these quasars of high redshift are physically associated with this active object of low redshift.

In three additional cases of the five examined here, active galaxies which had compelling statistical probability of association, were found to have jets or extensions pointing at or near the adjacent, high redshift quasars. The implication of these four cases is that active galaxies eject smaller, higher redshift objects. This process is supported by the fact that the active objects, both galaxies and quasars, have lines of X-ray sources emerging from them. Even in the fifth case observed here, which showed no adjacent active galaxy, the quasar 3C309.1 ($z = .904$) exhibited lines of small X-ray sources emerging from it. These lines from the quasars themselves (such as 3C275.1) contained some confirmed, additional higher redshift quasars as well as numerous blue stellar objects (BSO's) which could easily be confirmed as additional quasars.

The ejection interpretation seems reasonable because radio ejections are well known to emerge in opposite directions from active galaxies, X-ray jets are often seen inside radio jets, and the rotation with time of ejection would naturally explain the slightly different alignment of inner sources with outer sources as seen in Mark474 and 3C275.1.

There is some difficulty with plus and minus ejection velocities, however, and the apparent varying ages of the objects along the ejection path. Also X-rays confined to a filament will decay more quickly than optical or radio photons, counter to what is observed. All this might cause us to consider the possibility of continuous creation along "white lines". This modification would avoid ejection of material bodies and instead suggest emergence of objects at nodes along a "string" at different times. Their intrinsic redshifts would be explained as a function of their age since creation (Narlikar and Arp 1993). In this case the "jet" could represent the energized material in active galaxy nuclei guided out along a creation line.

Regardless of the ultimate theoretical interpretation, however, the ROSAT X-ray observations of galaxies and quasars appear to require a change in basic assumptions which will lead to entirely new distances, masses and ages of objects which comprise the universe.

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