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X-RAY–SELECTED AGNs NEAR BRIGHT GALAXIES[1]

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ABSTRACT

During the course of an extensive program of spectroscopic identifications of faint X-ray sources discovered "serendipitously" with the *Einstein Satellite*, 10 X-ray–selected AGNs within three optical diameters of bright ($V < 18$), foreground galaxies have been discovered. These AGNs have significantly higher redshifts than X-ray–selected AGNs in general (confidence level $> 97.5\%$). This discovery is interpreted in terms of gravitational "microlensing" in which stars in the foreground galaxy have significantly brightened the X-ray emission from these higher redshift AGNs, allowing them to be detected. Taken together with other, previous evidence for an enhanced surface density of QSOs near bright galaxies, this result suggests that microlensing may be responsible for a significant alteration of the inherent QSO luminosity function, but further observations are needed to prove this assertion.

Subject headings: galaxies: redshifts — galaxies: X-rays — gravitation — X-rays: sources

I. INTRODUCTION

For several years now there has been some evidence for a slight statistical excess of QSOs projected on the sky near bright galaxies (factor of a few; Burbidge *et al.* 1971; Arp 1983; Chu and Zhu 1983). Over most of the history of these observations, the sole interpretation has been that these QSOs were physically associated with the bright galaxies near them and that the QSO redshifts, were, therefore, "noncosmological" (e.g., Burbidge 1981). Because this interpretation was contrary to the well-accepted cosmological redshift hypothesis, this evidence was largely dismissed on the grounds that the data were either statistical fluctuations or were due to an improper statistical analysis. More recently another interpretation has arisen following the discovery of multi-image QSOs (Walsh, Carswell, and Weymann 1979; Weymann *et al.* 1980) in which QSOs near foreground galaxies are brightened by the gravitational effects of individual stars in these galaxies near to our line of sight, so-called minilensing or microlensing (Einstein 1936; Canizares 1981). This new interpretation is consistent with the cosmological redshift hypothesis and has revitalized interest in the observational data on QSO–galaxy associations. However, two recent theoretical studies of the statistics of microlensing (Vietri and Ostriker 1983; Schneider 1986*a*, *b* summarized in Schneider 1986*c*) have concluded that microlensing is unlikely to account for the observed excess surface density of QSOs near bright galaxies unless the differential number counts of QSOs $[N(S)\,dS = N(0)S^{-\alpha}]$ remain as steep as $\alpha = 3.6$ beyond $V = 20$. Present data pertaining to the numbers of faint QSOs is sufficiently sparse (e.g., Koo and Kron 1982; Kron and Chiu 1981; Schmidt and Green 1983) that this question is as yet unsettled. Regardless, the surface density excess of QSOs near bright galaxies due to microlensing is expected to be quite small and therefore not easily detectable unless very large numbers of galaxies are surveyed.

In this *Letter* we present new observations pertaining to this question which were obtained in a manner somewhat different from the studies mentioned above (i.e., UV-excess and radio surveys near bright galaxies and cross-correlations of QSO and galaxy catalogs). In the course of an extensive optical identification program of faint X-ray sources found with the *Einstein Observatory* we have discovered numerous low-redshift, low-luminosity QSOs and a few BL Lac objects. Ten of these QSOs and one of the BL Lac objects are projected within three optical diameters of bright ($V < 18$), foreground galaxies. In § II we show that these QSOs near galaxies are at significantly higher redshifts than the sample as a whole. In § III we discuss the relevance of these observations to the microlensing interpretation.

[1] This paper uses data obtained at the Multiple Mirror Telescope Observatory (MMTO), which is operated jointly by the University of Arizona and the Smithsonian Institution.

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II. THE SAMPLE OF AGNs NEAR BRIGHT GALAXIES

The *Einstein Observatory* Medium Sensitivity Survey (MSS) is a flux-limited sample of X-ray sources in the flux range 10^{-11} to 10^{-13} ergs s^{-1} cm^{-2} in the 0.3–3.5 keV soft X-ray band which were discovered "serendipitously" in numerous Imaging Proportional Counter (IPC) exposures at high galactic latitude (Maccacaro *et al.* 1982). Optical identifications for a complete sample of 112 faint X-ray sources (Stocke *et al.* 1983; Gioia *et al.* 1984) found them to be primarily extragalactic in nature with the largest constituents being the active galactic nuclei (AGNs; quasars, QSOs, and Seyfert galaxies) at 50% of the full sample. Other identifications include cluster of galaxies (16%), BL Lac objects (5%), nearby "normal" galaxies (4%) and "normal" galactic stars (25%). Maccacaro, Gioia, and Stocke (1984, hereafter MGS) have described the statistical properties of the 56 AGNs from this sample including the X-ray luminosity function, cosmological evolution, and contribution to the X-ray background. As with other, similar X-ray–selected samples (Kriss and Canizares 1982; Reichert *et al.* 1982; Margon, Downes, and Chanan 1985), the MSS AGNs are mostly at low-redshift and low-luminosity with a mean redshift of 0.48.

During the last two years the sky coverage of the MSS has been greatly expanded from 90 to 780 deg^2 by analyzing all of the IPC exposures meeting the MSS definitions which are contained in the complete *Einstein* archives (Gioia *et al.* 1987). A systematic optical spectroscopic identification program of the 836 X-ray sources in the expanded MSS is now in progress with approximately 200 AGNs having been identified at this writing. These 200 AGNs in no way constitute a statistically complete subsample of the entire MSS (Gioia *et al.* 1987), but their redshift distribution is extremely similar to that of the MGS complete sample.

In the course of the optical spectroscopy several QSOs near bright galaxies have been discovered. To determine whether the properties of these particular AGNs differ from the MSS AGN sample as a whole, a sample of AGN–galaxy pairs has been constructed by applying the following criteria to all of the AGNs identified in the expanded MSS thus far (as of 1986 November):

1. The AGN lies within three optical diameters of a bright ($V < 18$) and thus nearby ($z \leq 0.15$) galaxy. These diameters were measured by eye from the Palomar Observatory Sky Survey (POSS) E plates and so do not correspond to a standard diameter. These diameters will not be used in any statistical test.

2. Based upon proximity to the X-ray centroid, the AGN and not the galaxy is the likely X-ray emitter (i.e., in almost all cases the AGN lies within the 90% confidence IPC error circle, the galaxy outside). Neither the AGN nor the foreground galaxy was the target of the IPC observation.

3. In the few cases where the X-ray emitter is a bright Seyfert galaxy in a small group of galaxies at the same redshift, we have not included such objects in this sample, requiring the nearby galaxy to be obviously foreground.

The resulting sample of AGN–galaxy pairs is shown in Table 1 along with brief descriptive information including $f(X)$, the X-ray flux detected by the *Einstein* IPC for each source, and the ratio R of the angular separation of the AGN from the galaxy divided by the galxy major diameter as measured on the POSS E-plate. All AGNs with $R < 5$ in the currently identified MSS have been included in Table 1 for completeness although the statistical sample is defined using $R \leq 3$. Where the optical magnitudes are listed to two significant figures, they were obtained using the Mount Hopkins 24 inch (61 cm) CCD system during the period 1982–1985.

TABLE 1

X-RAY–SELECTED AGNs NEAR BRIGHT ($V < 18$) GALAXIES

Name (1E)	Z(AGN)	V(AGN)	Z(Gal)	V(Gal)	R[a]	$f(X) \times 10^{-13}$ (ergs s^{-1} cm^{-2})	Comments
0038.8−0159	1.69	16.86	0.017	14.4	1.4	3.6	QSO is 4C 02.04; galaxy is UGC 0439.
0104.2+3153	2.03	18.72	0.111	17.5	0.9	4.2	Stocke *et al.* 1984
0200.9−0858	0.77	16.52	0.015	17.4	4.0	3.1	
0226.8−1041	0.62	18.32	0.036	17.5	2.8	2.9	
0317.9−1949	1.00	18.56	0.101	17.4	3.0	2.4	
0745.1+5545	0.17	17.55	0.004	15.3	2.4	8.5	Z(AGN) from Kriss and Canizares 1982; Zw 0745.1+5543
0950.2+0804	1.45	17.69	0.023	14.8	5.0	2.9	UGC 05340
1109.3+3544	0.91	18.1	0.027	14.5	0.7	3.8	NGC 3569
1218.7+7522	0.64	18.16	...	15.4	2.8	3.9	Zw 1210.9+7520
1229.3+6430	0.17	16.89	0.009	14.2	2.0	43.6	BL Lac near NGC 4510
1232.4+1550	0.04	15.2	0.004	13.3	1.0	21.9	AGN is IC 3528; galaxy is NGC 4540.
1317.3−1213	0.33	18.3	...	16:	0.7	7.3	
1333.7+0334	0.85	17.98	0.024	14.9	1.4	> 2.4[b]	Zw 1333.8+0335
1640.1+3940	0.54	18.16	0.034	15.2	4.7	6.6	Zw 1640.0+3945[c]

[a] Ratio of the angular separation of the AGN from the galaxy center to the major angular diameter of the galaxy (as measured on POSS E-plate).

[b] The X-ray source 1E 1333.7+0334 is obscured by the IPC window supporting structure, and so its observed flux is a lower limit. Because this source is partially obscured, it will not appear in the expanded MSS.

[c] Z(AGN) and Z(Gal) from Margon, Downes, and Chanan 1985.

Otherwise the magnitudes were obtained from the POSS (c. 1950) using the diameter method of King and Raff (1977). We emphasize that in all cases the optical and X-ray fluxes were not obtained simultaneously. The redshifts listed in Table 1 for both the AGNs and the galaxies were obtained in the ongoing program to identify the expanded MSS X-ray sample and used spectrographs on either the MMT or the Steward Observatory 2.3 m telescope.

Also listed in Table 1 is a BL Lac object which meets the above criteria although this object will not be included in any of the statistical tests. Finding charts for those X-ray selected objects in Table 1 which have not yet been published (Stocke *et al.* 1983; Gioia *et al.* 1984) are shown in Figure 1 (Plate L1). 1E 1640.1+3940 was originally identified by Margon, Downes, and Chanan (1985), and a finding chart for that source can be found there. A particularly spectacular example of a QSO near a galaxy has been previously reported (Stocke *et al.* 1984; Gioia *et al.* 1986), wherein the X-ray source 1E 0104.2+3153 is identified with a $z = 2.03$ QSO which is projected 10″ from the nucleus of an elliptical galaxy at $z = 0.111$. Although this galaxy is slightly closer to the IPC X-ray centroid, in this case alone observations with *EXOSAT* prove the QSO to be the source of the X-ray emission (Gioia *et al.* 1986) so 1E 0104.2+3153 is included in this sample.

The redshift distribution for the AGNs listed in Table 1 which have $R \leq 3$ are compared with the complete sample of X-ray–selected AGNs from MGS in Figure 2. The three AGNs near galaxies which are members of the MGS complete sample (1E 0038.0−0159, 1E 0104.2+3153, and 1E 1218.7+7522) have been purged from this sample before the statistical comparisons were made. The AGNs near galaxies are at significantly higher redshifts than the complete sample at > 97.5% confidence level utilizing the two-sample Kolmogoroff-Smirnov (K-S; Kim and Jennrich 1970) test. These AGNs near bright galaxies were detected in a manner identical to the complete sample (i.e., same range of X-ray fluxes; same detection procedure), and yet the K-S test rules out that they are chosen from the same parent population at a high level of confidence. This result is relatively insensitive to the choice of the limit on R (the ratio of AGN—galaxy separation to the major diameter of the galaxy) used to define the sample. If R is either increased to 5 or decreased to 1.5, the level of confidence according to the K-S test either remains the same or increases.

If, instead of using the MGS complete sample as the comparison sample, the 200 AGNs in the presently incomplete sample were used (minus the AGNs listed in Table 1), then the redshift distributions would differ in the same way as shown in Figure 2; this time the difference is statistically significant at the > 99.5% confidence level. This check ensures that some unknown bias in the ongoing identification process is not the cause for the peculiar redshift distribution shown in Figure 2*a*.

We conclude that X-ray–selected AGNs found near galaxies are at substantially higher Z (factor of 2). They may also possess higher ratios of X-ray to optical flux (factor of 2–3 when a "correction factor" due to the observed inverse dependence of $[f(X)/f(V)]$ on L [optical; Avni and Tananbaum 1982] is taken into account) than X-ray–selected AGNs in general. This latter result is tentative due to the use of the Avni and Tananbaum (1982) "correction factor" which may not be applicable to an X-ray–selected sample. We will repeat both the redshift and X-ray to optical flux ratio analyses once the entire expanded MSS has been optically identified.

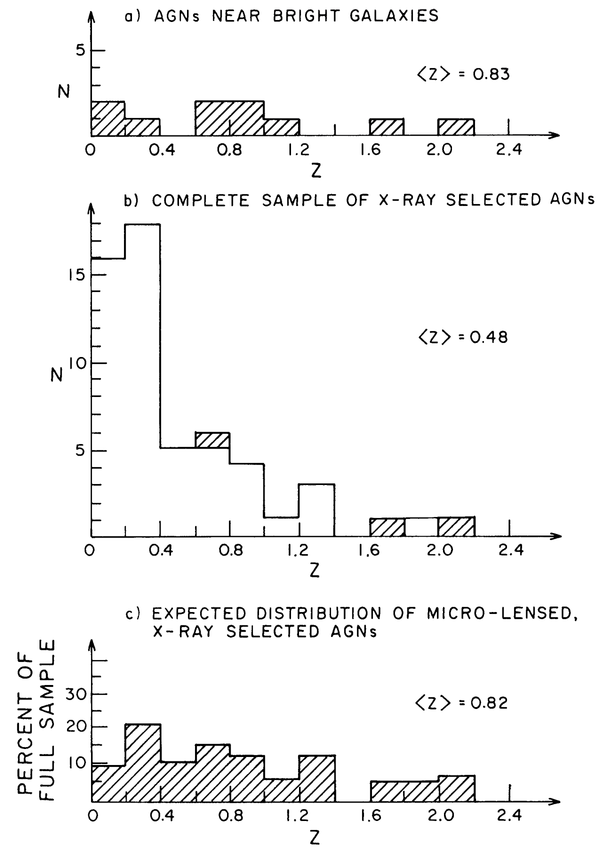

FIG. 2.—The redshift distributions for the statistical sample of X-ray–selected AGNs near bright galaxies in Fig. 2*a* and for the complete sample of X-ray–selected AGNs from Maccacaro, Gioia, and Stocke (1984) in Fig. 2*b*. The shaded boxes in (*b*) are the three AGNs near galaxies which are also members of the complete sample and so are not included in the complete sample for the statistical tests. The two-sample K-S test rules out that these two distributions were drawn from the same parent population at > 97.5% confidence level. The distribution of redshifts shown in Fig. 2*c* is that expected for the percentage of X-ray–selected AGNs which are microlensed based upon probabilities for microlensing taken from Schneider (1986*d*). There is no statistically significant difference between the distributions in (*a*) and (*c*) indicating that the unusual redshift distribution for the X-ray–selected AGNs near galaxies can be explained by the effects of microlensing.

III. DISCUSSION

There are two obvious interpretations of these results:

1. From the point of view of the noncosmological redshift hypothesis (e.g., Burbidge *et al.* 1971; Arp 1983), AGNs closer to their parent galaxy consist of "younger" material and thus exhibit larger redshifts.

2. Assuming the cosmological interpretation of the redshift, AGNs projected near foreground galaxies are susceptible to transient gravitational lensing due to foreground stars, so-called microlensing (Canizares 1981; Vietri and Ostriker 1983; Schneider 1986*a*, *b*, *c*). If one or more foreground stars are

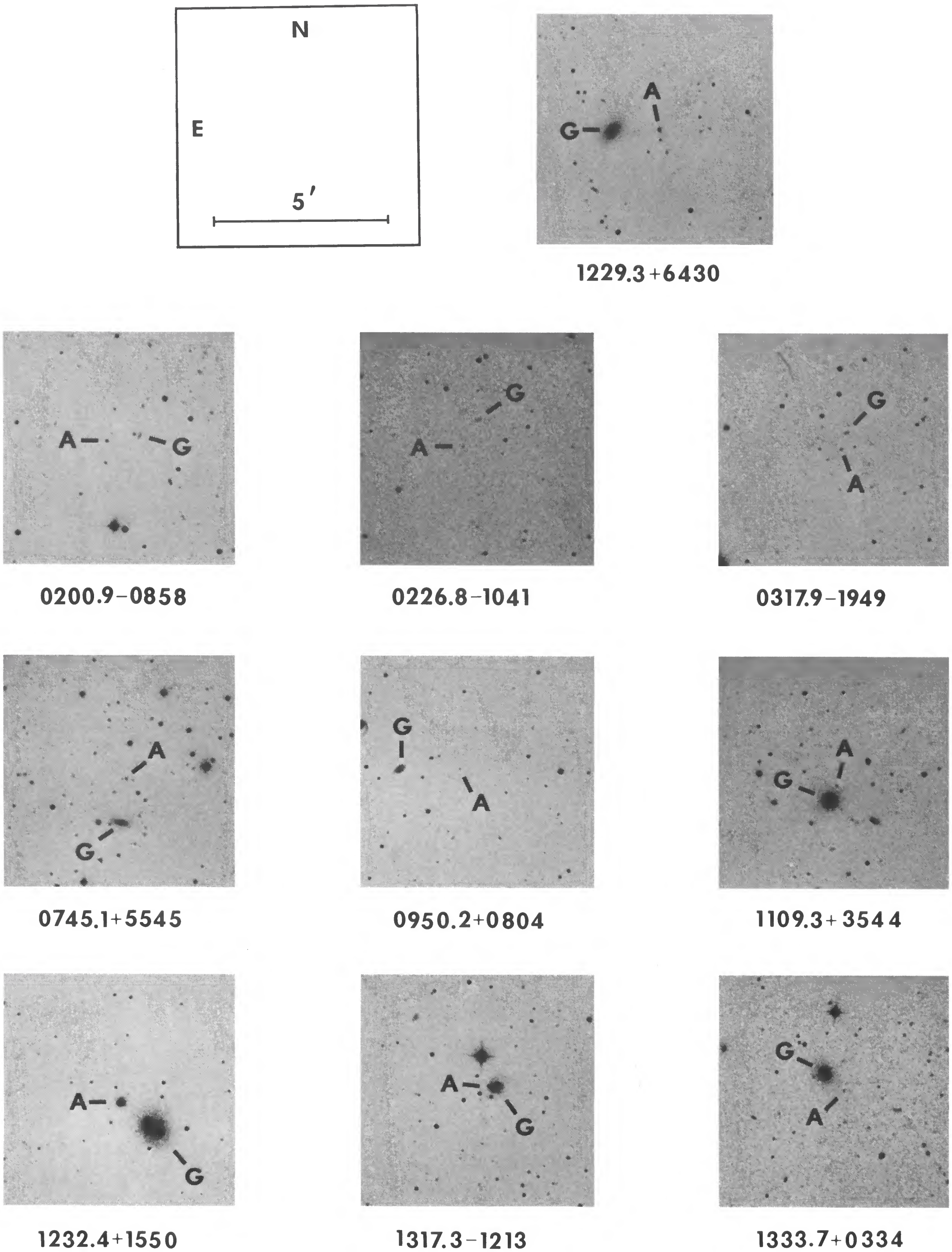

FIG. 1.—Finding charts for the X-ray–selected AGNs near galaxies which have not been previously published. In each of these charts the X-ray centroid is at the center of the chart, and the scale and orientation are as given for the first chart. The X-ray–selected AGN is marked with an A and the foreground galaxy with a G. The BL Lac object near NGC 4510 is shown in the first chart marked with an A. Finders for 1E 0038.8−0159, 1E 0104.2+3153, and 1E 1218.7+7522 can be found in Gioia *et al.* (1984) and for 1E 1640.1+3940, in Margon, Downes, and Chanan (1985).

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near the AGN light beam, then its brightness can be greatly enhanced, and thus intrinsically fainter AGNs can be detected. Since for the X-ray–selected samples (e.g., MGS) the X-ray flux correlates well with redshift, detecting fainter AGNs means detections at higher redshifts.

We favor the latter interpretation both because it is consistent with the cosmological redshift hypothesis and because the microlensing hypothesis can potentially explain the flat distribution of redshifts observed by the following argument. The higher the redshift of a source, the greater the probability that the line of sight will pass a star(s) in a foreground galaxy. The relative probability for lensing as a function of the source redshift depends upon the size of the emitting region (r) and the slope of the luminosity function (s) while the absolute probability depends on the mean cosmological density (Ω) and the fraction of that density in condensed objects like stars (P). Schneider (1986*d*) has computed these probabilities for a variety of input parameters, and we use here the values from his Figure 2 for which $r = 10^{15}$ cm, $s = 3.6$, $\Omega = 1$, and $P = 0.2$. For a differential luminosity function slope of 3.6 which is typical of the X-ray emission from AGNs above $L(X) = 10^{43}$ ergs s^{-1} (MGS, Piccinotti *et al.* 1982), the probability for lensing goes nearly as $Z^{3/4}$. Using the exact dependence obtained from Figure 2 in Schneider (1986*d*), Figure 2*c* shows a redshift distribution for a sample of objects constructed using two selection criteria:

1. X-ray selection in the flux range of the *Einstein* MSS and thus with a z-distribution shown in Figure 2*b*.
2. An additional selection probability determined by gravitational microlensing and thus increasing nearly as $Z^{3/4}$.

There is no statistical difference between the distributions shown in Figures 2*a* and 2*c*, suggesting that the unusual redshift distribution shown in Figure 2*a* may be due to microlensing. Although Arp (1984) has noticed that optically selected QSOs found near bright galaxies have slightly larger redshifts than other optically selected QSOs, the difference is much less obvious than for this sample. This is presumably because the X-ray–selected sample is mostly at low redshift and thus is composed primarily of unlensed objects. The difference between the histograms in Figures 2*b* and 2*c* represents the distribution of unlensed, X-ray–selected AGNs and would be even more strongly peaked toward low redshifts than is Figure 2*b*. The arguments in this paragraph are dependent only on the relative probability for lensing as a function of Z. So the exact choices of Ω and P made above are not necessary to produce the redshift distribution shown in Figure 2*c*.

There are currently disagreements in the literature concerning the absolute probability for microlensing and whether it significantly alters the QSO luminosity function thus biasing studies of their cosmological evolution (Canizares 1982; Peacock 1982; Vietri 1985; Schneider 1986*c*, *d*). There is also disagreement about whether the observed excess surface brightness of QSOs near bright galaxies can be due to microlensing (Vietri and Ostriker 1983; Schneider 1986*a*, *b*). These disagreements can be traced to two inputs or assumptions which differ between these various models: (1) whether the QSO source counts flatten significantly beyond $V = 20$ and (2) whether the intrinsic source size significantly affects the statistics of microlensing (Schneider 1987). But based upon the sample described herein, there appears to be some observational evidence that microlensing may indeed be important in explaining the excess surface density of QSOs near bright galaxies. At twice the mean redshift, the AGNs near galaxies in Table 1 are also over twice as bright in X-rays as expected from their optical brightness. Given the observed integral source count slope for X-ray AGNs of $n(S) = S^{-2.6}$ this brightening produces a five-fold increase in AGN surface density, comparable to the excess amounts seen by Arp (1983) near bright galaxies.

Therefore, the observational evidence suggests that microlensing may account for the excess of QSOs seen near bright galaxies which at first sight seems inconsistent with the theoretical expectations. However, Schneider (1986*d*) points out that the previous theoretical work assumed that the observed luminosity function is the *intrinsic* luminosity function (i.e., the effects of microlensing are modest in altering the QSO luminosity function). If instead the intrinsic luminosity function slope is much steeper than the observed slope *because of gravitational microlensing*, then most, if not all, bright QSOs are lensed by stars in intervening galaxies. Mostly these galaxies are at a redshift high enough that they would escape notice, but a few are near enough to be included in studies like the present one.

By turning this argument around, we see that the observational evidence for an excess surface density of QSOs near bright galaxies found in this and other studies argues that *most if not all bright QSOs are significantly amplified by the gravitational effect of foreground stars in other galaxies*. If this is true, then the luminosity function we observe for QSOs is not the intrinsic luminosity function at all but the luminosity function as modified by microlensing.

We suggest that the effects of microlensing are more easily identifiable in an X-ray–selected sample of QSOs because (1) the X-ray emission is likely to emanate from a smaller region than the other observable wavebands making the amplification factor due to gravitational microlensing the largest for the X-ray band; and (2) the intrinsic emission mechanism in AGNs biases X-ray selection toward low-redshift, low-luminosity objects (cf. the inverse correlation between the X-ray to optical flux ratio and optical luminosity found by Avni and Tananbaum 1982). This selection effect means that most of the X-ray–selected AGNs are not microlensed because they are too low in redshift. Thus the few that are lensed are more readily identified.

The hypothesis that most bright QSOs are microlensed will be acceptable only if large light variations with the characteristics of microlensing can be observed (see Schneider and Weiss 1986). Optical monitoring of the microlensing candidates in Table 1 at a rate of twice per season would be expected to detect light variations due to the passage of a foreground star in or near our line of sight. The variability time scale is $\sim 10\ (M/M_{\odot})^{1/2}$ yr (where M is the mass of the microlens) unless the emitting source components are moving at high transverse velocities (> 1000 km s^{-1}). Due to the theoretical expectations that the amplitude of variability is inversely related to the size of the emitting region, multiwaveband photometry could, in principle, lead to a more thorough understanding of the sizes of the emission regions in AGNs as a function of wavelength (see also Schneider and Weiss 1986). Other observers wishing to coordinate photometric observations of this sample should contact Dr. R. Schild at the Center for Astrophysics.

Finally, we note that several of these AGNs are sufficiently bright and close to the foreground galaxy that they can be used to study the gaseous halos of the intervening galaxies by observing optical and ultraviolet absorption lines at high resolution (e.g., Boksenberg and Sargent 1978; Morton, York, and Jenkins 1986). The 15th mag Seyfert galaxy 1E 1232.4 + 1550 is particularly suitable for this type of investigation.

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