X-RAY AND OPTICAL OBSERVATIONS OF QUASARS

Harvey Tananbaum and Herman L. Marshall
Harvard-Smithsonian Center for Astrophysics

1. INTRODUCTION

The first Einstein observations established that quasars, as a class, are luminous X-ray emitters (Tananbaum et al. 1979). Since then, one of our major programs has been to carry out further X-ray and optical observations to improve our estimate of the contribution of quasars to the 2 keV extragalactic isotropic X-ray background and also to reconcile number counts of discrete X-ray sources with reported optical number counts of quasars (cf. Zamorani et al. 1981 and references therein). This paper is a preliminary report on our observations of the 1.7 square degree field studied originally by Braccesi and his colleagues (Formiggini et al. 1980 and Braccesi et al. 1980). A more detailed presentation of our results is in preparation (Marshall et al., 1981).

The method of selecting or counting quasars which has been used commonly is a search for "stellar" optical images with an ultraviolet excess (UVX) as determined from 2 or 3 exposures with different filters. Since emission lines present in the U-band can contribute significantly to the ultraviolet excess, this method becomes unreliable (or incomplete) for objects with redshifts greater than 2.2, when prominent lines (including Ly-α and CIV) have been redshifted out of the U-band and into the B-band.

Figure 1 is a partial compilation of counts of UVX objects obtained primarily by this method. At the brighter magnitudes - a preliminary Green and Schmidt (1978) 16^m survey and the Braccesi et al. (1970) 18.3 survey - the quasar counts are determined only after spectroscopic follow up observations have confirmed the presence of redshifted broad emission lines. This is necessary due to the contaminating presence of large numbers of stars with UV excess at relatively bright magnitudes. At magnitudes fainter than $18^{m}_{\cdot}3$ much less spectroscopic work has been done. Here the number counts show considerable scatter, some of which may be due to statistical fluctuations, but most of which is probably due to systematic effects. The solid line represents the expected

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source counts based upon a model which utilizes pure density evolution $\rho(z) = \rho(0)(1+z)^8$ with appropriate cutoffs at high redshifts. The steep power law with slope 2.16 fit to the source counts by Braccesi et al. (1980) requires density evolution at least as great as $(1+z)^8$. However, we note that Zamorani et al. (1981) found that such a steep power law for the optical source counts could not extend much above 20^m without encountering problems with limits set by the extragalactic 2 keV background and by the numbers of discrete X-ray sources actually observed in Einstein deep surveys. (See also Setti and Woltjer 1979, and Cavaliere et al. 1980.)

The support for a steep power law fit to the quasar counts at faint magnitudes was further reduced by the report of Bonoli et al. (1980) that a significant fraction of the UV excess objects fainter than $\sim 19^m.5$ in the 1.7 square degree Braccesi field show "extended" images, and therefore may not meet the operational definition commonly used to select quasars. The lowered estimates then generated for the source counts at $19^m.5$ and 20^m are also shown in Figure 1. A turnover in the source counts consistent with these data of Bonoli et al. and with Kron's (1980) limit based on a color-color analysis of stellar objects brighter than ~ 23.5 can be produced by models which invoke pure luminosity evolution. The dashed line in Figure 1 corresponds to such a model, with $L(z) = L(0)e^{\frac{8z}{1+z}}$.

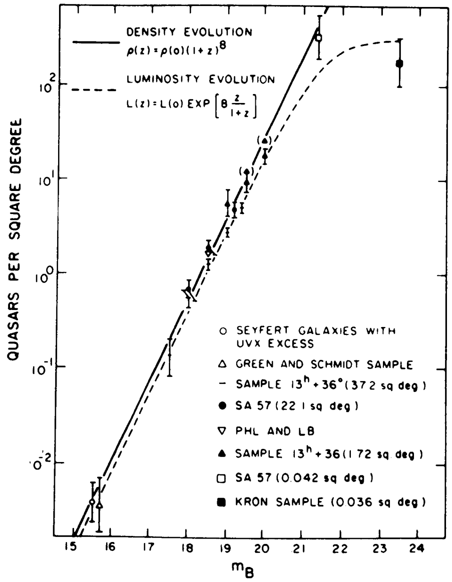

Figure 1: Optical source counts of quasar candidates selected by UV excess method. The logarithm of the number of quasar candidates per square degree brighter than a given magnitude is plotted versus magnitude.

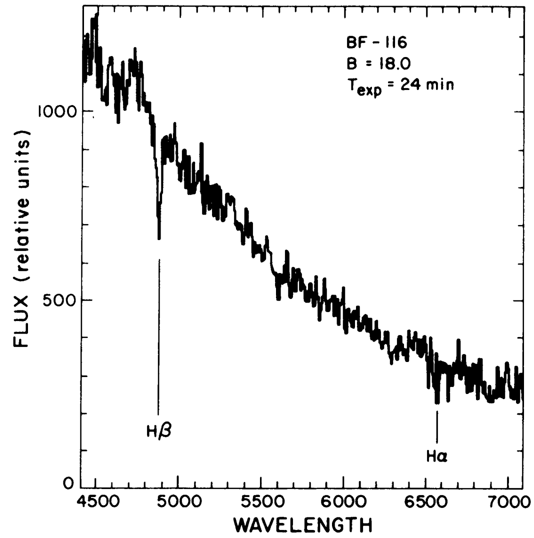

Figure 2: MMT Spectrum of BF-116 showing Hβ and Hα absorption lines.

2. OPTICAL OBSERVATIONS

The scatter of the data in Figure 1 suggests that spectroscopic observations are needed to confirm quasar candidates at relatively faint magnitudes. We have begun such a program by using the Multiple-Mirror Telescope (MMT) slit spectrograph to observe UV excess quasar candidates selected by Braccesi and his colleagues in the 1.7 square degree survey region. We ultimately will obtain a complete quasar sample to photoelectric B magnitude = 19.8; at present we have a complete spectroscopic survey containing 16 candidate objects with B $\leq 19^m.2$ (corresponding to Braccesi et al. (1980) photographic magnitude b $\simeq$ 19.35).

Figure 2 shows an MMT spectrum obtained for one of the quasar candidates. The data are conspicuous by the absence of quasar emission lines; the spectrum shows Hβ and Hα absorption lines characteristic of a star. The continuum slope shown is not real, since we have not yet normalized the data for the detector response function.

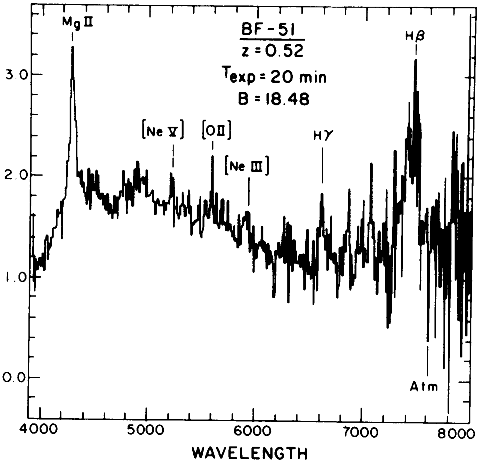

Figure 3: MMT spectrum of BF-51 showing broad, permitted emission lines from Hγ, Hβ, and MgII as well as the more narrow forbidden lines of NeIII, OII, and NeV.

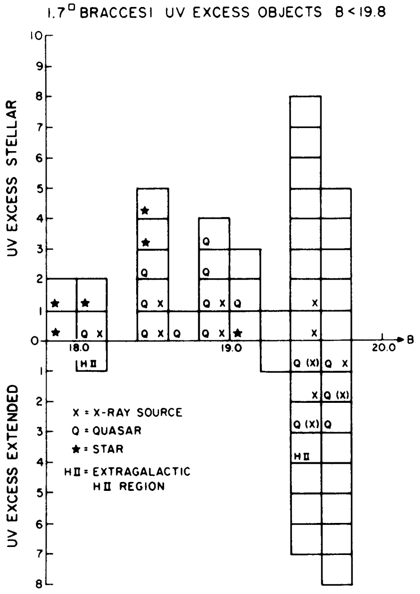

Figure 4: Histogram versus blue magnitude for UVX "stellar" objects in the top half and for UVX "extended" objects in the bottom half.

Figure 3 shows another MMT spectrum, a 20 minute exposure for the $18^m.5$ quasar candidate BF-51. This time we see broad, permitted emission lines from Hβ, Hγ, and MgII as well as the more narrow forbidden lines of NeIII, OII, and NeV. This rather typical quasar spectrum is fit with a redshift of 0.52.

Of the 16 objects brighter than $19^{m}.2$, we have found 6 stars and 10 quasars. The colors of the objects are such that simple modifications of the color selection criterion could not have excluded the stars and retained the quasars. The number of stars found (6) is somewhat higher than the 2 predicted from the 10-15% contamination rate estimated by Braccesi et al. (1980) for this magnitude range. Figure 4 summarizes the observations with a histogram versus blue magnitude for UVX "stellar" objects shown in the top half and for UVX "extended" objects discussed by Bonoli et al. shown in the bottom half. Objects we find spectroscopically to be stars are so indicated, while quasars are denoted by the letter "Q". For the complete sample brighter than $19^{m}.2$, we see that the contamination by stars is a problem at the brighter end. "X"'s are used to denote objects detected in our IPC X-ray observations; the figure shows that 5 of the 10 quasars in our complete sample from 18.0 to $19^{m}.2$ have been detected as X-ray sources, as have a number of fainter UV excess objects. The "Q" notation is also attached to 5 of the extended UV excess objects; the significance of this result is discussed below.

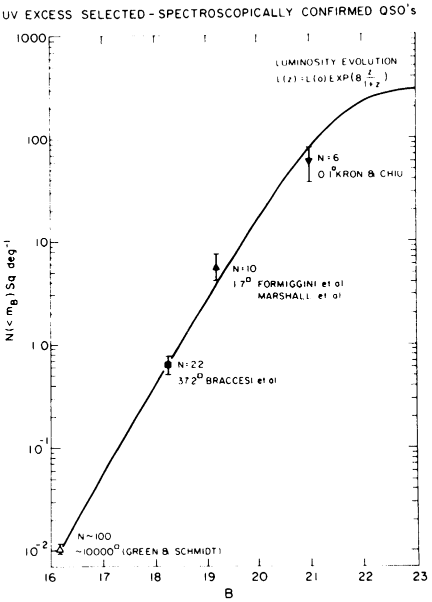

Figure 5: Number-magnitude relation for quasars selected by UVX criterion and verified spectroscopically.

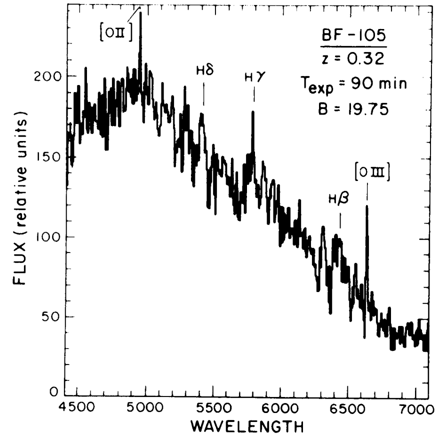

Figure 6: MMT spectrum of BF-105 showing broad emission lines from Hδ, Hγ, and Hβ and forbidden lines from OII and OIII.

Figure 5 shows the available number count data for quasars which have been verified by spectroscopic observations of candidates selected by the UV excess criterion. Data points indicate the ~100 quasars brighter than $16^{m}.2$ observed in ~10,000 square degrees in the Green and Schmidt (1981) survey, the 22 quasars brighter than $18^{m}.3$ in the 37.2 square degree Braccesi sample, the 10 quasars brighter than $19^{m}.2$ from the present observations of the 1.7 square degrees Braccesi field, and the 6 spectroscopically confirmed quasars brigther than 21^{m} in 0.1 square degrees studied by Kron and Chiu (1981). The solid line represents the quasar counts calculated from pure luminosity evolution proportional to $e^{\frac{8z}{1+z}}$, taken directly from Figure 1 without an attempt to fit or normalize to the current data. Since the model calculation does not take into account the $z \simeq 2.2$ cutoff in the UV excess selection method, the observed number of quasars so selected should be ~25% below the model curve at 21^{m} and ~60% below the model curve at 22^{m}. It should be clear that spectroscopic observations for complete samples (using all selection methods including objective prism grating surveys and X-ray surveys, as well as UV excess) in the region from 19^{m} to 22^{m} are required for determining accurate quasar counts and for evaluating various models for evolution.

The importance and the feasibility of making spectroscopic observations for faint objects is illustrated by our MMT data for BF-105 shown in Figure 6. This $19^{m}.75$ object was observed for 90 minutes, because it was a prime candidate for identification with one of our IPC X-ray sources, even though Bonoli et al. had described it as extended and therefore not a quasar. The spectrum is very similar to that of the quasar BF-51. Broad emission lines from Hβ, Hγ, and Hδ are indicated as are forbidden lines from OII and OIII. The redshift determined for this object is 0.32. In addition, the tentative identification of BF-105 with an X-ray source has been confirmed to an accuracy of better than 5" by a follow up observation with the Einstein HRI. Kron (1981) has carried out spectroscopic observations of several other UV excess objects described as "extended" by Bonoli et al., and finds spectra characteristic of quasars. Three of these objects are also tentatively identified with IPC X-ray sources. Veron and Veron (1981) have obtained a 3.6m plate in excellent seeing for ~1/3 of the 1.7 square degree field. They find that all of the UV excess "extended" objects in their field appear stellar and attribute the result of Bonoli et al. to the graininess of the plates used. Thus, the higher quality imaging data, the spectroscopic data, and the X-ray data demonstrate that most of these objects are in fact quasars.

3. X-RAY OBSERVATIONS

In July 1980, we used the Einstein Observatory to obtain 3 deep IPC exposures, with durations of ~40,000 seconds, to cover the 1.7 square degree Braccesi field. At least 40 X-ray sources can be detected in the field. Nine X-ray sources are identified with confirmed quasars - UV excess objects with measured redshifts. In addition, 3 UV excess objects are coincident within 5 arc seconds with HRI X-ray sources. These 3 objects are almost certainly quasars, but this still must be confirmed spectroscopically.

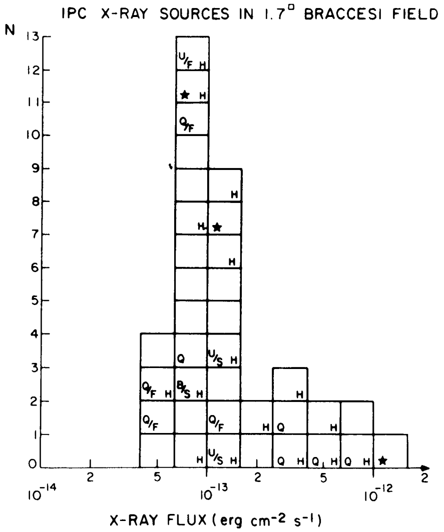

Figure 7: Histogram of 36 IPC sources than 4 x 10^{-14} erg s^{-1} cm^{-2} versus flux; the histogram is incomplete at the lowest X-ray fluxes.

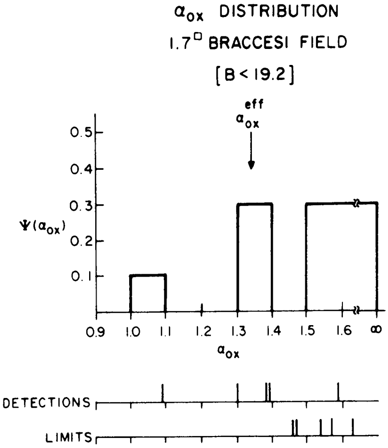

Figure 8: Lower portion: Values of α_{ox} for X-ray detected quasars and lower limits on α_{ox} for quasars not yet detected in X-rays.
Top portion: Maximum likelihood estimate for the differential distribution $\psi(\alpha_{ox})$.

The Einstein IPC observations for the 1.7 square degree field are summarized in Figure 7. Here we show a histogram of 36 IPC sources brighter than 4 x 10^{-14} erg $s^{-1}cm^{-2}$ versus flux; the histogram is incomplete at the lowest X-ray fluxes. The 9 spectroscopically confirmed quasars are indicated by "Q" and "Q/F" for "stellar" and former "extended" objects respectively. Three X-ray sources identified with stars brighter than $10^{m}.5$ are also indicated. An "H" labels sources that have been more accurately located in HRI follow up observations that covered portions of the 1.7 square degree field. The 3 UV excess objects confirmed as X-ray emitters via the HRI observations are noted by "U/S" and "U/F". At least 7 IPC sources have accurate HRI locations but no UV excess quasar candidates brighter than $19^{m}.8$ at present. Identification of these sources, as well as others detected by the IPC, is one ot the objectives of our ongoing program. We expect that many of these sources will be identified with UV excess quasars fainter than 19.8, and also that some will be identified with non UV excess quasars at redshifts greater than 2.2. One such candidate is indicated by "B/S" in this figure; it is a stellar object of magnitude 19.6, with blue color but without UV excess (u-b>0), and it is coincident within 5" with the HRI location for the X-ray source.

4. CONTRIBUTION TO THE X-RAY BACKGROUND

Tananbaum et al. (1979) and Zamorani et al. (1981) have used the parameter α_{ox} plus optical source counts to estimate the contribution of quasars to the 2 keV X-ray background. α_{ox} is the power law energy index between the monochromatic optical luminosity at 2500 Å in the source frame and the monochromatic X-ray luminosity at 2 keV in the source frame. Zamorani et al. found that α_{ox} is different for radio loud and radio quiet quasars and also that it varies with redshift and/or optical luminosity. Since they did not have X-ray observations of a complete sample they computed a weighted average for α_{ox} of 1.45, to be used in estimating the contribution of quasars to the X-ray background.

We now have X-ray data for a small, but complete sample of optically selected, spectroscopically confirmed quasars in the range $18.0-19^{m}.2$. The lower portion of Figure 8 shows the values of α_{ox} determined for the 5 quasars detected in our IPC observations of this sample. Lower bounds on α_{ox} are shown for the 5 quasars not yet detected in X-rays. We apply the non-parametric maximum likelihood method developed by Avni et al. (1980) for using both the detections and bounds to determine the best estimate of the binned differential distribution $\psi(\alpha_{ox})$, which is shown in the top portion of Figure 8. From this distribution we determine the nominal value and uncertainty for $\alpha_{ox}^{effective}$, which corresponds to the average ratio of X-ray luminosity to optical luminosity for our sample. The data in the figure give $\alpha_{ox}^{effective} = 1.34$, while a slightly more accurate calculation using unbinned values of α_{ox} gives $\alpha_{ox}^{effective} = 1.37$. The 1σ uncertainty in $\alpha_{ox}^{effective}$ is ±0.10. These values for α_{ox} are consistent with those previously determined for quasars at brighter optical magnitudes.

Using $\alpha_{ox}^{effective} = 1.37$ and our observed distribution of optical source counts from $18.0-19^{m}.2$, we determine that these objects contribute~17% of the 2 keV X-ray background. With X-ray data for a complete sample of optically selected quasars, a more direct calculation of the contribution to the background can be made by applying the method of Avni et al. directly to the observed X-ray fluxes and upper limits. In this way we find that the quasars from $18.0-19^{m}.2$ comprise 15% of the 2 keV extragalactic background, with a ±1σ range of 9% to 23%.

With number counts consistent with those predicted by the luminosity evolution model proportional to $e^{\frac{8z}{1+z}}$ and $\alpha_{ox}^{effective} = 1.45$, Zamorani (1981) has computed that quasars brighter than 20^{m} contribute 18% of the 2 keV background; quasars brighter than 21^{m}, 40%; and quasars brighter than 22^{m}, 60%. We find $\alpha_{ox}^{effective} = 1.37 \pm 0.10$ for our small, complete sample, and we note that the "extended" objects reported by Bonoli et al. (1980) are in reality quasars that contribute to the X-ray background. These results suggest that the Zamorani numbers may well be conservative estimates, and reinforce our earlier conclusion that quasars make a very significant contribution to the 2 keV extragalactic background.

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DISCUSSION

BARNOTHY: You mentioned that some of the UV excess objects found in the search area were not included among the quasars because of their nonstellar size. This is what one would expect if quasars were produced by gravitational lenses (J. M. Barnothy A. J. 70, 666, 1965). The effect should be particularly pronounced for high redshift objects, because in these cases a large intensification is needed to bring the apparent brightness of the object, the Seyfert galaxy nucleus, into the range of visibility. Intensification, on the other hand, is proportional to the image area, hence, very large intensification has a great propensity to produce large sizes (M. F. Barnothy & J. M. Barnothy BAAS 4, 339, 1972). I think that one should drop from the attributes of quasars the one requiring a quasar to be a "quasistellar" object, to avoid that, adhering to this characteristic, some objects which are quasars would not be included into the list of quasar candidates and hence not investigated further.

TANANBAUM: I agree that the "stellar" attribute is a requirement which may improperly exclude some quasar candidates from further study, although my concern is based primarily on the potential for excluding relatively low redshift quasar candidates associated with resolvable galaxies. In the case of the UV excess objects originally found to be extended by Bonoli *et al.*, I have stated that further studies have been carried out demonstrating that these objects are in fact quasars with "stellar" images.

WILLS: (a) Bev Wills and I obtained some grism plates of this area earlier this year at KPNO; it will be interesting to compare these two techniques for finding QSOs. (b) Why do you classify BF 105 (with $m = 19.75$ and $z = 0.32$) as a QSO, rather than as a compact blue galaxy?

TANANBAUM: (a) I agree. (b) For BF 105 $L_{opt}^{2500Å} \approx 1.7 \times 10^{29}$ erg s^{-1} Hz^{-1}, which is above the minimum luminosity we require for a quasar.