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INFRARED PROPERTIES OF SERENDIPITOUS X-RAY QUASARS

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ABSTRACT

Near-infrared measurements have been obtained of 30 quasars originally found serendipitously as x-ray sources in fields of other objects. The observations show that the infrared characteristics of these quasars do not differ significantly from those of quasars selected by other criteria. Because this x-ray-selected sample is subject to different selection biases than previous radio and optical surveys, this conclusion is useful in validating previous inferences regarding the infrared colors of "typical" quasars.

I. INTRODUCTION

Chanan, Margon, and Downes (1981, hereafter referred to as CMD) have published optical identifications of 19 active galactic nuclei found by serendipitous observations in *Einstein Observatory* x-ray fields. Further identifications of similar serendipitous observations have since been obtained which more than double the sample of x-ray-selected quasars. Complete details on the entire sample are given by Margon, Downes, and Chanan (1982). Margon, Chanan, and Downes (1982) have found a significantly lower optical luminosity for this sample than for quasars found in previous surveys with similar visual thresholds but different selection techniques.

The sample of quasars selected serendipitously as x-ray sources potentially can serve as a basis for the study of properties which would be masked in radio or visually selected samples. In this paper a near-infrared study of 30 such serendipitously x-ray-selected quasars is presented.

II. OBSERVATIONS AND SAMPLE

In this study 30 objects were measured at the $f/70$ focus of the 5-m Hale Telescope at Palomar Mountain within the three photometric bands J(1.27 μm), $\Delta\lambda = 0.24\,\mu$m; H(1.65 μm), $\Delta\lambda = 0.32\,\mu$m; and K (2.23 μm), $\Delta\lambda = 0.40\,\mu$m. The detector was an InSb photovoltaic diode cooled to solid nitrogen temperature. The photometric calibration was with respect to standard stars listed by Elias *et al.* (1982). The flux densities in the near infrared were derived from the following calibrations for the flux density at 0 mag: $f_\nu(J = 0 \text{ mag}) = 1580$ Jy, $f_\nu(H = 0 \text{ mag}) = 1040$ Jy, $f_\nu(K = 0 \text{ mag}) = 650$ Jy. Observations in the photometric bands were obtained sequentially in a single night. The H and K observations of nine of the quasars were repeated on two nights separated in time by more than nine months; J magnitudes were generally only obtained on the latter of these nights.

The 30 objects studied in this sample include 18 objects presented by CMD as well as 12 others selected from fields which satisfy the criteria outlined by CMD. Briefly, the objects included in the present sample were selected on the basis of their x-ray emission and were subsequently found to exhibit visual emission lines characteristic of quasars. The optical search was complete to 18.5 mag; some of the identified objects were subsequently found to be fainter than this limit. The finite visual threshold implies that very faint red objects such as those found by Rieke, Lebofsky, and Kinman (1979) would not be identified. If there were quasars which were visually faint relative to their x-ray brightness, these would also be discriminated against. The finite x-ray threshold would similarly exclude objects of highly unusual optical to x-ray flux ratios.

The quasar 2251 − 178, discovered by Ricker *et al.* (1978) previous to *Einstein* observations, was also included in the current sample since it was selected by its x-ray emission. This object was also observed in the 10-μm photometric band at the 5-m telescope with a result $[10\,\mu\text{m}] = 6.7 \pm 0.3$ mag corresponding to a flux density of 80 ± 20 mJy (Soifer, Neugebauer, and Matthews, 1979). The x-ray fluxes reported here are from *Einstein* observations.

III. RESULTS AND DISCUSSION

The near-infrared magnitudes of the 30 objects observed are listed in Table I and various features of the sample are shown in the figures. Figures 1–4 show var-

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TABLE I. Observations of serendipitous x-ray quasars.[a]

object	redshift z	V mag	I_x cts/1000s	J mag	H mag	K mag
0031-076	0.291	17.9	33	16.43±.24	15.46±.08	14.69±.10
0031-077	0.388	18.5	13	17.33±.10	16.33±.08	15.37±.08
0032-073	0.752	18.0	15	17.75±.13	16.94±.10	16.07±.12
0037+061	0.063	17.03	37	15.20±.11	14.27±.07	13.73±.07
0100+020	0.392	16.39	21	16.44±.08	15.55±.08	14.50±.07
0120+092	0.176	18.2	11	15.72±.08	15.01±.07	14.19±.07
0121+034	0.336	18.5	10	16.68±.07	15.82±.07	14.87±.07
0240+007	0.569	16.52	10	15.81±.11	14.94±.10	14.22±.10
0302-223	1.409	16.40	19	15.90±.40	14.64±.13	14.35±.14
0318-196	0.104	14.86	12	14.54±.07	13.76±.07	13.18±.07
0351+026	0.036	16.20	100	14.30±.09	13.37±.08	12.54±.08
0844+377	0.451	17.7	20	16.95±.09	16.34±.08	15.60±.12
0919+515	0.161	17.9	41	15.55±.14	14.82±.08	13.82±.08
1059+730	0.089	16.40	19	14.59±.09	13.86±.09	13.28±.07
1339+053	0.266	16.8	51	15.54±.14	14.69±.09	13.63±.08
1403+546	0.082	16.8	32	15.43±.10	14.71±.10	14.28±.09
1519+279	0.230	18.2	20	16.58±.08	15.77±.07	14.47±.07
1526+286	0.450	16.39	49	15.24±.11	14.81±.08	14.05±.08
1557+272	0.065	16.33	22	14.28±.09	13.54±.08	12.97±.09
1640+396	0.540	18.3	30	17.35±.23	16.30±.11	15.68±.13
1640+401	0.986	17.1	11	16.65±.08	16.40±.09	15.89±.10
1641+399[b]	0.594	19.3	13	17.65±.12	16.84±.10	15.87±.14
1701+610	0.164	17.0	14	15.44±.12	14.78±.08	14.10±.08
1704+607	0.080	17.73	7	15.87±.16	15.28±.09	14.74±.11
1726+499	0.815	19.3	12	16.60±.12	16.49±.09	15.54±.09
1847+335	0.509	17.7	36	16.85±.21	16.03±.10	15.04±.10
2215-037	0.242	17.20	41	15.18±.10	14.25±.09	13.10±.07
2216-043	0.243	18.5	15	15.58±.11	14.58±.11	13.51±.09
2251-178	0.064	14.0	606	13.13±.08	12.30±.08	11.42±.08
2344+184	0.138	15.9	13	15.64±.11	14.78±.09	14.13±.09

a Redshift, V and I_x from Margon, Downes, and Chanan (1982). V magnitudes quoted to 0.1 mag were derived from image diameters on the Palomar Schmidt Sky Survey Plates; V magnitudes quoted to 0.01 mag were obtained photoelectrically.

b Near to but distinct from 3C345.

ious relations between the infrared and visual magnitudes. For the nine quasars which were measured twice, average values are given in Table I, although about half of these showed evidence of variability. The infrared colors of those quasars which showed variability are, however, derived from observations taken on a single night. The maximum amplitude of variability observed, ~0.3 mag, is consistent with the variability seen in other quasars (Neugebauer, Soifer, and Matthews 1982) over comparable time periods.

The visual magnitudes were obtained either from image diameters on the Palomar sky survey prints (19 objects) or from photoelectric photometry (11 objects). The visual magnitudes thus refer to the fluxes at times quite different from those when the infrared data were obtained.

The x-ray properties of the sample are summarized in Figs. 5 and 6. The x-ray fluxes are from Margon, Downes, and Chanan (1982). Since complete energy distributions are not available for these objects, all photometric colors are in the observed frame. On each figure where color indices are given, power-law slopes α are also presented; the flux density is assumed to follow a law of the form $f_\nu \propto \nu^\alpha$. The Hubble constant and decel-

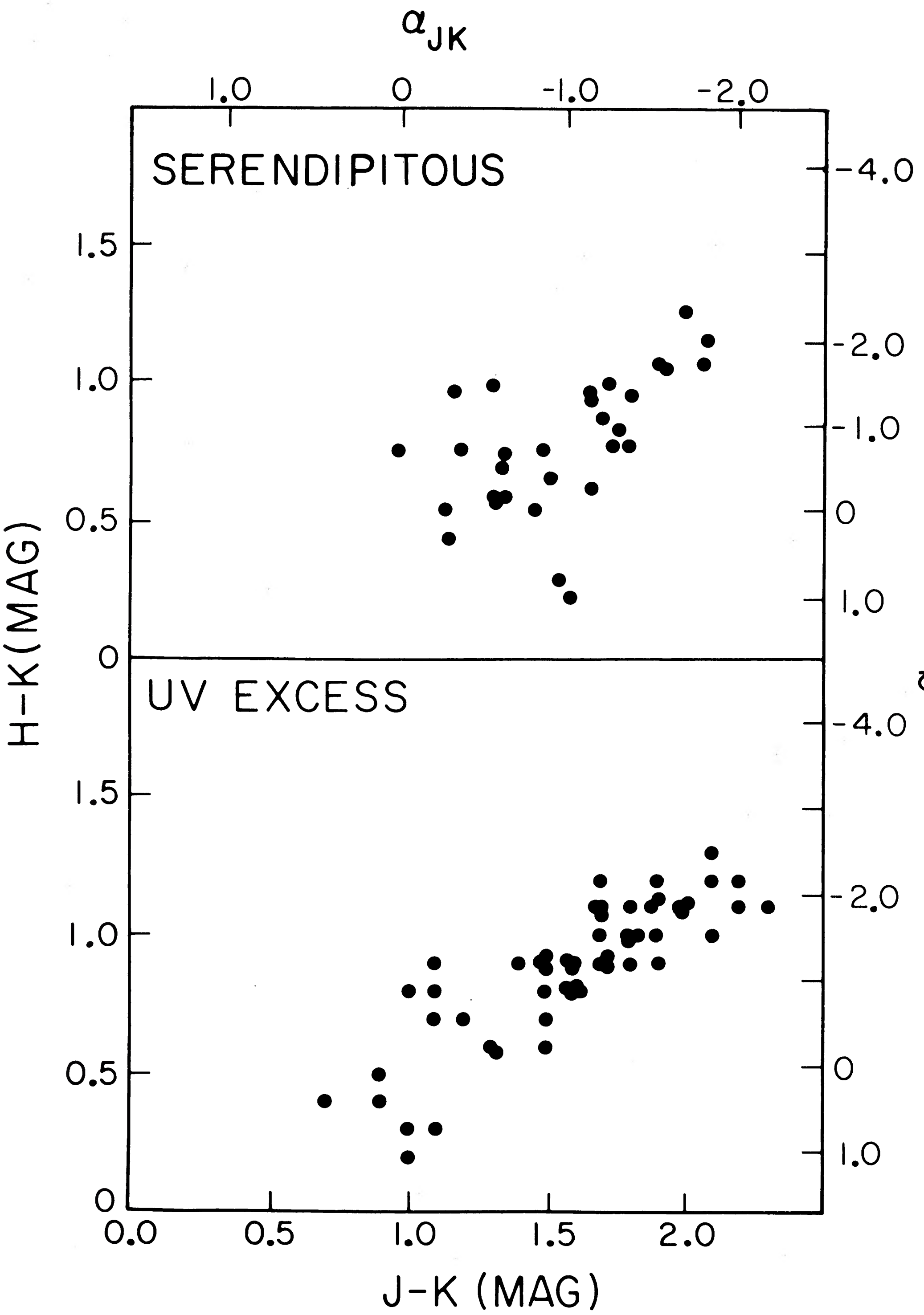

FIG. 1. The infrared colors of the serendipitous x-ray quasars (top) and of the Palomar Green-Schmidt sample selected for their ultraviolet excess (bottom). The slopes α_{JK} and α_{HK} are defined assuming a power-law dependence of the flux density $f_\nu \propto \nu^\alpha$.

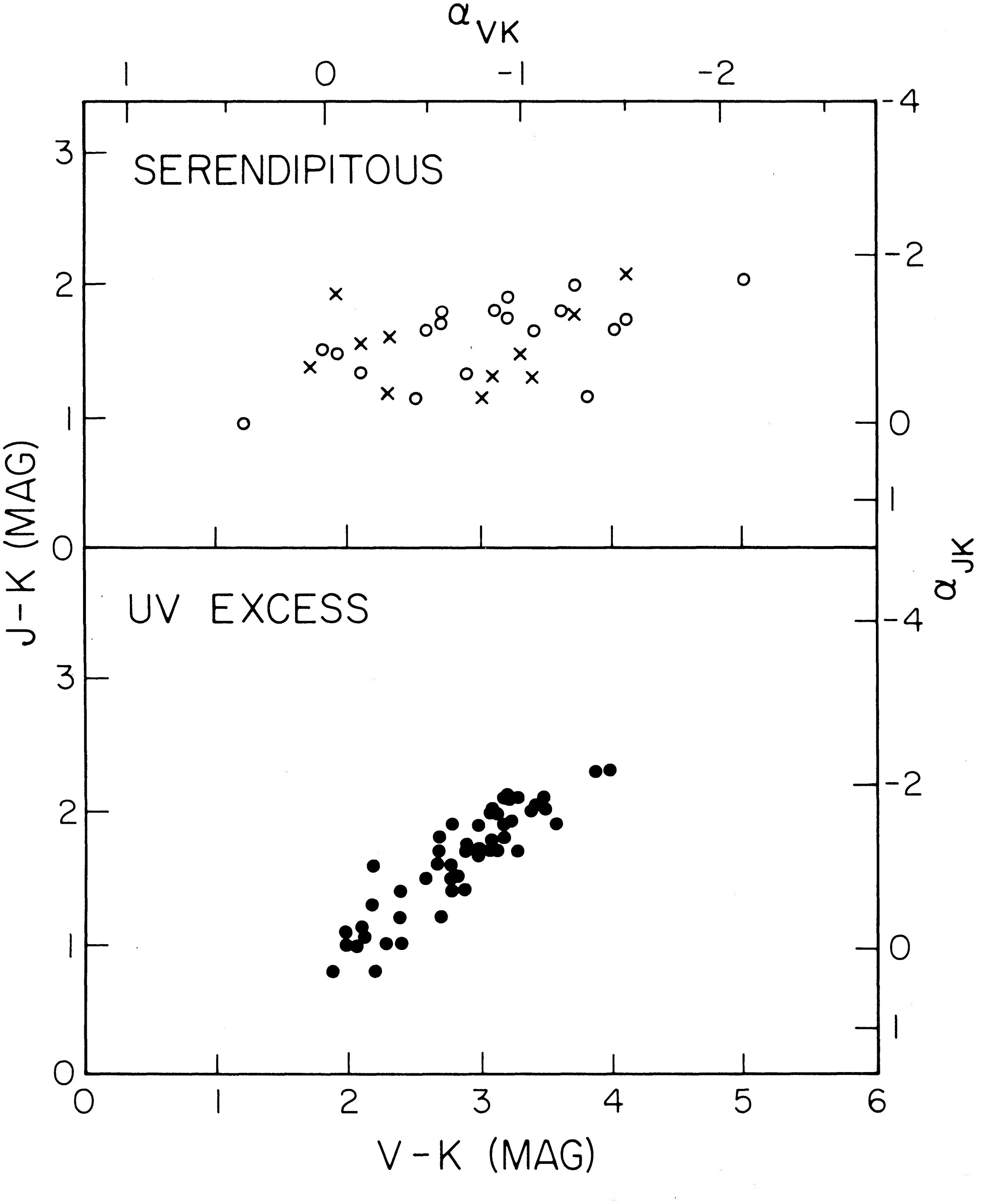

FIG. 2. The infrared colors vs the visual–2.2-μm color of the serendipitous x-ray quasars (top) and of the Green-Schmidt sample (bottom). The V magnitudes were found from the image diameters on the Palomar Sky survey prints (open circles), from photoelectric measurements (crosses), or from numerical integrations of multichannel data (closed circles).

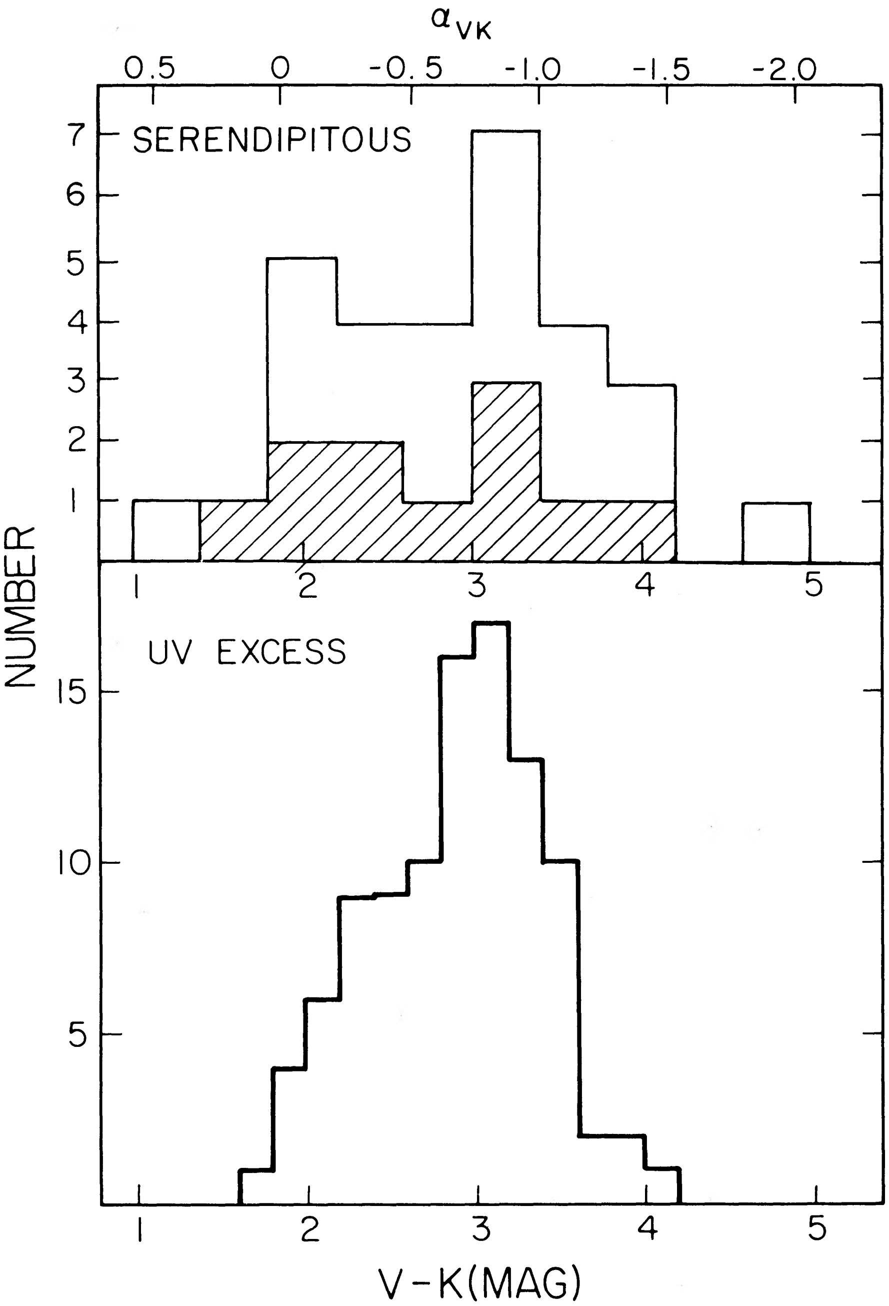

FIG. 3. Histograms of the $V-K$ color for x-ray-selected quasars (top) and for quasars selected for their ultraviolet excess (bottom). The quasars whose visual magnitudes were measured photoelectrically are indicated by the striped area.

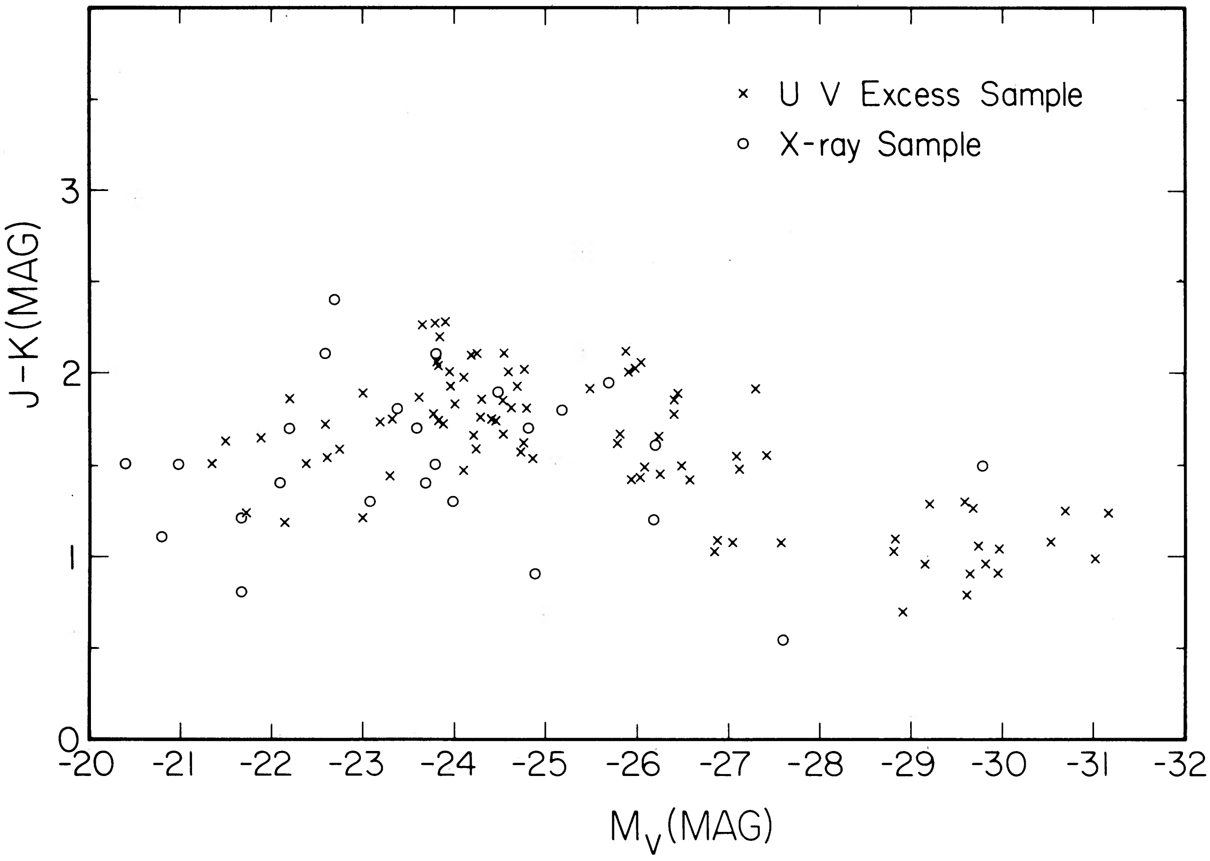

FIG. 4. The infrared color as a function of the absolute visual magnitude for the x-ray-selected sample (open circles) and the sample selected on the basis of its ultraviolet excess (crosses).

eration parameters in these figures and throughout this paper have been taken as $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$.

The main result of this paper is that there is no strong difference between the near-infrared properties of quasars in this sample and of quasars discovered by other means. This is illustrated by the figures in which the results of the x-ray selected sample are compared with similar results for quasars selected via other criteria. In Figs. 1–4 the second sample, selected by Green on the basis of ultraviolet excess, is from the Palomar bright quasar survey (Schmidt and Green 1981). The comparison objects in Fig. 5 are not from a well-defined sample, but were chosen because x-ray fluxes were available in either Ku, Helfand, and Lucy (1980) or in Zamorani *et al.* (1981) and infrared measurements were available at Caltech. This sample represents a variety of radio and visually selected objects. In all cases the infrared observations of the second samples were obtained at the 5-m telescope.

The data of Fig. 1 indicate a good correlation between the $H-K$ and $J-K$ color indices as is expected from measurements at such close wavelengths. More importantly, however, both the mean slopes and the intercepts of the x-ray-selected sample and the optically selected sample are the same within small uncertainties. Figure 1 represents observations each taken nearly simultaneously and under good photometric conditions. The similarity of the distributions is thus a prominent feature of these data.

Figure 2 shows an apparent difference in slope of $V-K$ vs $J-K$ between the x-ray-selected and ultraviolet-excess selected quasars. Caution is needed in interpreting this difference, however, as most of the x-ray sample has photographically determined V magnitudes of low accuracy ($\gtrsim 0.5$ mag), while the size of the sample with accurate visual photoelectric photometry ($\leqslant 0.05$-mag accuracy) is so small that it poorly determines the slope compared with the determination from the much more extensive Schmidt and Green (1981) sample. Both the slope and intercept of a linear fit to the observations of x-ray-selected quasars with photoelectrically determined V magnitudes differ by 2σ from those of the ultraviolet selected quasars. Furthermore, visual magnitudes of the ultraviolet sample were obtained closely in time with the infrared data, while, as stressed previously, the

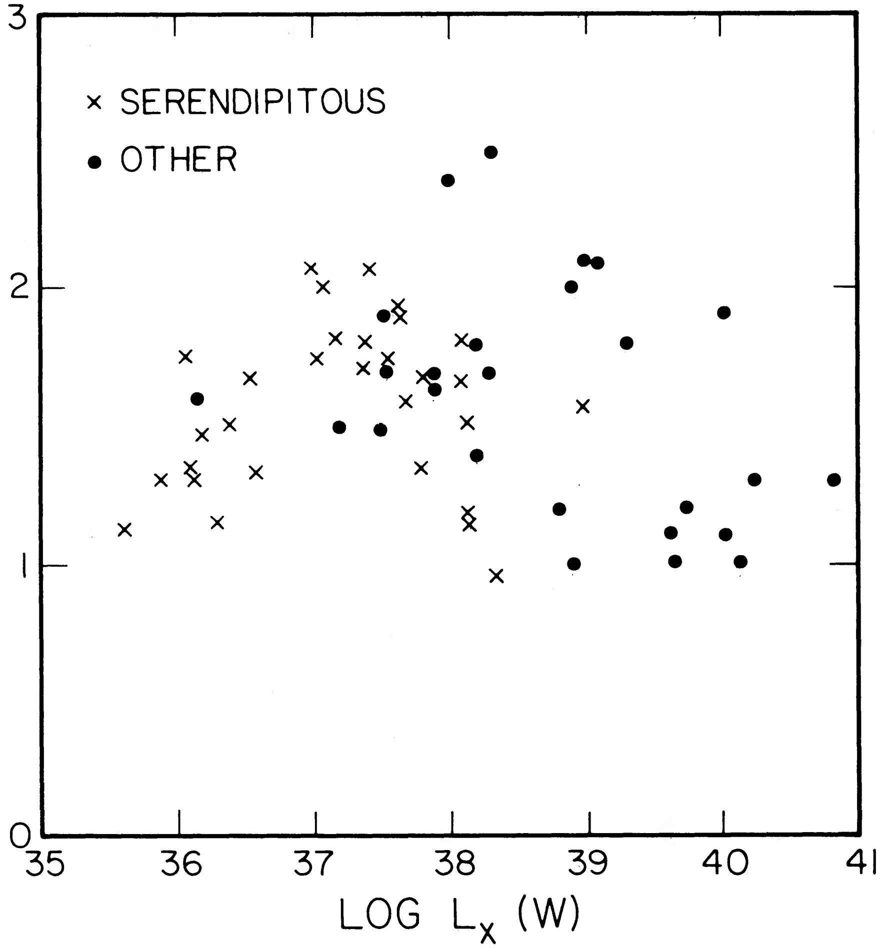

FIG. 5. The infrared color as a function of the x-ray luminosity for the x-ray-selected sample (crosses) and for other quasars measured at x-ray wavelengths (closed circles); see text.

Although the quasars of this sample have a lower luminosity than others, this decreased luminosity is not ac- infrared and visual photometry for the x-ray sample was separated in many cases by > 1 yr. Thus any flux variability of the x-ray sample, even if it is color independent, will introduce further spurious scatter into Fig. 2. Although there is a marginally significant difference between the two samples displayed in Fig. 2, we feel the similarities shown in Fig. 1 are based on more controlled observations and thus we cannot assert that there is definite evidence that these very different selection procedures are sampling different parent populations. Similarly, Fig. 3 shows an apparent difference in the $V-K$ widths of the x-ray- and ultraviolet-selected samples, but the above considerations again lead us not to attach strong significance to this effect.

Figures 4 and 5 indicate that the dependence of infrared color on either visual or x-ray luminosity is independent of the sample. Both figures emphasize the fact that quasars selected as serendipitous x-ray sources are less optically luminous than those found by other selection techniques, as has been noted previously (Margon, Chanan, and Downes 1982). Here we present the result that this first infrared study shows no overwhelming evidence for a prominent infrared color effect in this sample which can be attributed to the x-ray selection process. Conversely, because this x-ray-selected sample of quasars is subject to different biases than previous samples of optically and radio-selected quasars, this commonality of infrared colors between samples is an important validation of previous inferences (Neugebauer *et al.* 1979; Hyland and Allen 1982) regarding the infrared colors of the "typical" quasar.

Figure 6 shows that the range of both infrared and visual flux densities is comparable to the range of the x-ray fluxes, although there is no strong correlation between the strength of the x-ray flux and either the visual or infrared (2.2 μm) fluxes. The effect of the x-ray flux-limited sampling is plainly seen at $I_x \sim 10$ counts s^{-1}. The power-law slopes between visual and x-ray frequencies (α_{vx}) are compared with the slopes within the near infrared (α_{JK}) in Fig. 7. The colors show a statistically marginal correlation in the sense that quasars with the steeper infrared slopes exhibit shallower visual to x-ray slopes.

In each of the figures where a comparison is made, the quasars initially selected by their x-ray emission are indistinguishable from those selected by other techniques.

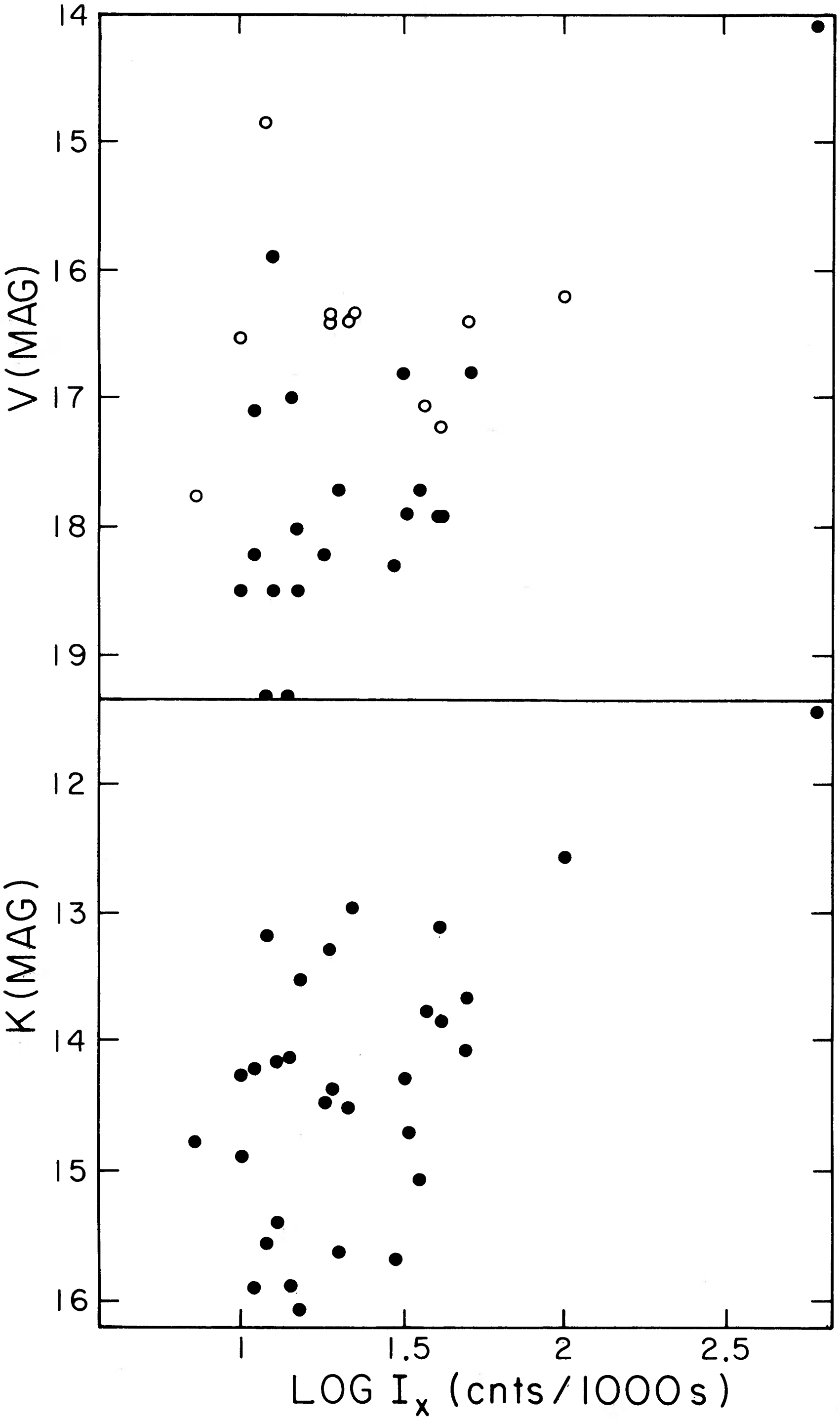

FIG. 6. The x-ray intensity as a function of the apparent visual magnitude (V) and of the apparent 2.2-μm magnitude (K). Open circles represent observations with photoelectrically measured magnitudes.

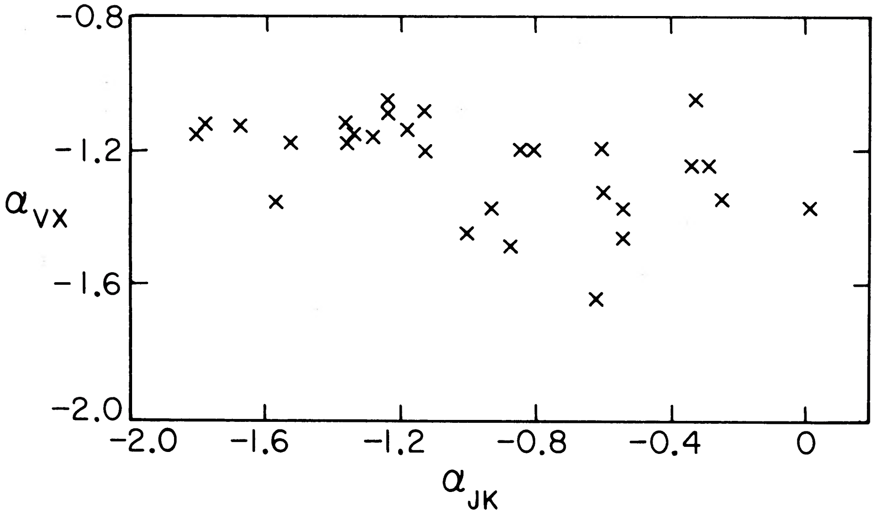

FIG. 7. The power-law slope (α_{JK}) between 1.25 and 2.2 μm vs α_{VX}, the power-law slope between the visual and x-ray frequencies, for the x-ray-selected sample.

companied by any marked characteristic in the slopes or strength of the continua. Recent studies of the visual and near-infrared continua of quasars have failed to show strong correlations between these continua which might have elucidated the nature of the emission mechanisms producing the visual and near-infrared fluxes in the quasars. Indeed, there is growing evidence that the mechanisms producing the radiation at infrared and shorter wavelengths are remarkably ubiquitous, although the individual parameters defining the quantitative appearance vary significantly. The present observations show that the selection of quasars on the basis of their x-ray emission has apparently also found objects which have similar emission mechanisms at the visible and near-infrared wavelengths.

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