

# A new population of soft X-ray weak quasars

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**Abstract.** Quasars selected in optical surveys by means of their blue or UV excess are known to be strong emitters in the X-rays, except for Broad Absorption Line (BAL) objects. In this paper we study the X-ray emission of quasars selected through their emission line spectrum rather than their blue excess. X-ray data are obtained by cross-correlating two optical samples (the Hamburg Survey Catalogue and the Palomar Transit Catalogue) with the WGA catalogue of ROSAT observations. We find that a significant fraction of objects are strongly underluminous in the X-rays. We discuss the physical nature of these sources and we propose an interpretation for their optical and X-ray properties based on a dust-poor and gas-rich absorber. Our results suggest the existence of a population of AGNs having a type 1 optical spectrum and a type 2 X-ray emission.

**Key words.** galaxies: active – galaxies: X-rays: galaxies

## 1. Introduction

The broad band properties of quasars have been investigated in recent years through multiwavelength observations of several quasar samples: the mean Spectral Energy Distribution (SED) of quasars was estimated for a sample of optically selected, X-ray bright quasars by Elvis et al. (1994); the X-ray properties of optically selected quasars were determined for several large samples by using the Einstein all-sky survey (Avni & Tananbaum 1986; Wilkes et al. 1994) and the ROSAT all-sky survey (Green et al. 1995; Brinkmann et al. 1998; Yuan et al. 1998). The results of all these works were essentially that quasars emit a significant fraction of their bolometric luminosity (several % or more) in the X-ray band. An indicator widely used in the literature, in order to measure the X-ray emission relative to the optical, is the “Optical to X index”  $\alpha_{\text{OX}}$  defined as:

$$\alpha_{\text{OX}} = -\frac{\log(L(2500 \text{ \AA})/L(2 \text{ keV}))}{\log(\nu(2500 \text{ \AA})/\nu(2 \text{ keV}))} \quad (1)$$

where  $L$  and  $\nu$  are the monochromatic luminosity and the rest-frame frequency. The above authors find on average  $\alpha_{\text{OX}} \sim 1.5$ , with a dispersion  $\sigma(\alpha_{\text{OX}}) \sim 0.2$ . Moreover, this index is found to increase slightly with redshift and luminosity. Together with these “normal” quasars, a minority of objects is found to be very weak in the X rays ( $\alpha_{\text{OX}} \geq 1.8$ ): many of these sources are Broad Absorption

Line quasars (BAL), while others are optically normal objects<sup>1</sup>.

As one can easily estimate from Fig. 1, X-ray weak sources are a few per cent of the entire population of quasars.

Recent works suggest that the origin of the X-ray weakness of BALs is absorption rather than an intrinsically weak emission (Brandt et al. 2000). At the same time, BALs have no optical reddening, hence their optical colours are those typical of normal quasars: for this reason they have been detected by “standard” surveys based on  $U$  and  $B$  colour excesses.

Our search for a new population of soft-X-ray weak quasars is motivated by several results that suggest the existence of objects other than BALs with a mismatch between optical and X-ray classification, and/or optical colours redder than normal quasars:

- The optical identifications of the HELLAS sources (hard X-ray selected) indicate that some objects with very hard X-ray spectra are type 1 AGNs in the optical (Fiore et al. 1999);
- The optical and infrared photometry of a sample of flat spectrum radio quasars shows that a significant fraction of radio-selected objects have redder colours

<sup>1</sup> In this paper “normal quasars” refers to objects selected with standard color techniques. Their mean SED is derived from Elvis et al. (1994), normalizing the X-ray emission in order to have  $\alpha_{\text{OX}} = 1.5$ . The optical line spectrum is derived from Francis et al. (1991).

than “normal” quasars (Webster et al. 1995). A similar conclusion, even if based on a much smaller sample, has been reached by Kim & Elvis (1998) who searched for red quasars among soft X-ray selected sources;

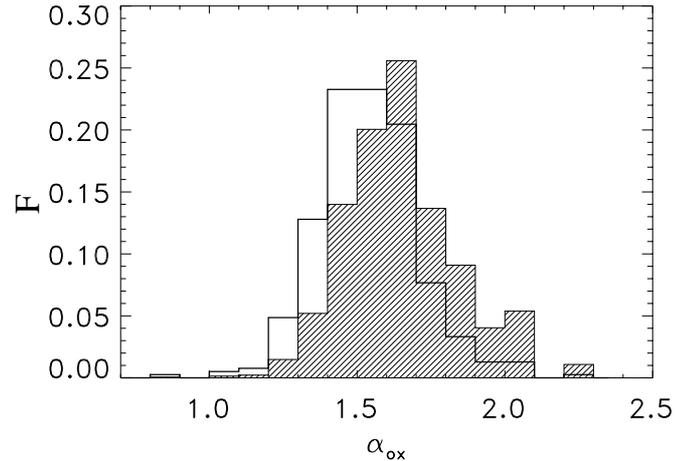
- An X-ray study of a sample of very luminous, high redshift quasars performed by the ASCA satellite revealed the existence of several objects with heavy obscuration in the 2–10 keV band (Reeves et al. 1997);
- A comparison between the absorbing column density  $N_{\text{H}}$ , measured through X-ray analysis, and the optical reddening  $E_{B-V}$ , measured through the Balmer decrement, performed on a sample of local Seyfert galaxies (Maiolino et al. 2001a), shows that for a large fraction of AGNs the  $E_{B-V}/N_{\text{H}}$  ratio is much lower than Galactic. The same conclusion is also suggested by the comparison between the X-ray and mid-IR emission of AGN-dominated Luminous Infrared Galaxies (Risaliti et al. 2000).

The basic idea of our work is that BAL quasars could be the tail of a population of X-ray weak quasars. In this view BALs would be extreme objects because, despite of their strong absorption in the X rays, their optical colours are typical of normal (i.e. blue) quasars. Between the two extremes of “normal” and BAL quasars, a population of objects could exist, with a strong X-ray absorption but a low optical reddening, enough to change slightly the optical colours (and, therefore, to exclude the sources from colour-based surveys) but the associated extinction would not be enough to obscure completely the optical broad lines. According to this scheme, this new class of objects should be classified type 1 AGNs if observed in the optical, but absorbed (type 2-like) if observed in the X-rays. In the following we will refer with “blue quasars” to colour-selected quasars, and with “red quasars” to the new population described above.

The best way to search for red quasars in the optical is by means of spectroscopic selection. The basis of the work described here is a cross-correlation of grism-selected samples of quasars with optical and X-ray surveys. We studied the optical colours and the X-ray to optical flux ratio of these objects and compared them with a sample of blue quasars.

The paper is organized as follows: in Sect. 2 we analyze the selection criteria adopted for the composition of the most studied quasar samples and we define the characteristics of the quasar population that could have been missed, then we describe our search for X-ray weak quasars, performed by cross-correlating spectroscopically selected quasar samples with the WGACAT catalogue of ROSAT observations (White et al. 1995). In Sect. 3 we present our results and in Sect. 4 we discuss their physical interpretation. In Sect. 5 we analyze the consequences of our study for several relevant arguments concerning AGNs and the X-ray background, and the future work in order to define the properties of this new population of objects.

Throughout this paper we adopt the cosmological parameters  $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $q_0 = 0.5$ .



**Fig. 1.** Open histogram:  $\alpha_{\text{OX}}$  distribution for the sample of optically selected quasars detected by ROSAT. Shaded histogram: best estimate distribution taking into account also non-detections (from Yuan et al. 1998)

## 2. Sample selection and X-ray data

### 2.1. Colour-based selection

The optical emission of “classical” quasars is characterized by two major features: an optical–UV excess in the continuum and several strong, broad emission lines. The technique used in most quasar surveys consisted in an automatic selection of a reasonably large sample of quasar candidates, followed by spectroscopic observations. Since quasars are rare objects and the spectroscopy is very time consuming, an efficient primary selection is needed. For this reason the color selection used in most surveys is very stringent: for example, in the PG survey a color  $U - B < -0.44$  is required and, although this is a very blue color, the efficiency of the selection is less than 10%, the vast majority of candidates being blue stars or white dwarfs.

This kind of selection automatically excludes objects with intrinsically redder spectra or with some absorption along the line of sight: for example, assuming a galactic dust-to-gas ratio, a typical quasar at  $z = 1$  with a very blue continuum would be excluded by the PG selection criterion if it is obscured by a rest frame column density higher than  $\sim 2 \cdot 10^{21} \text{ cm}^{-2}$ .

### 2.2. Broad line-based selection

The considerations made above suggest that the best way to search in the optical for red or moderately absorbed quasars is by means of a spectroscopic selection. The technique used in spectroscopic surveys is usually a two-step selection, with a first step at low resolution.

We have studied two spectroscopic samples of quasars. The first one is the Palomar Transit Grism sample (PT, Schneider et al. 1994), composed by  $\sim 1000$  objects selected only by means of emission line criteria, without any requirement about the continuum colours. Data available

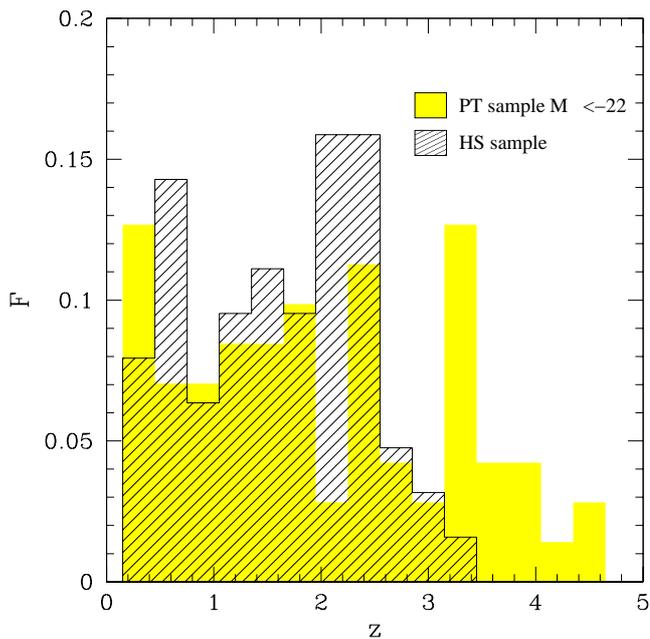


Fig. 2. Redshift distribution for the PT and HS samples

for these sources are the redshift, an  $r4$  magnitude and the flux, equivalent width and physical width of the line used for the selection. The search technique was optimized in order to discover many high-redshift quasars, nevertheless most of the sources are at low or intermediate redshift. The redshift distribution of the sample is plotted in Fig. 2.

The second sample we used in our work is the Hamburg Quasar Sample (HS, Hagen et al. 1995; Engels et al. 1998; Hagen et al. 1999). In this case a first selection of the objects was performed by using a color criterion (see Hagen et al. 1999 for details), while a second filter consisted in the requirement of broad emission lines in the observed spectrum. Even if a colour selection is still present in this sample, the requirements on the colours are less stringent than in “classical” quasar samples, like the PG, and therefore many quasars with slightly redder colours can be included.

### 2.3. Cross-correlation with the X-ray catalogue

The X-ray catalogue that we used for the cross-correlation with the optical samples is the WGACAT, obtained by analyzing all the fields observed in pointing mode by the ROSAT PSPC instrument.

We found that 180 sources of the PT and 85 of the HS are in the WGACAT fields. Among the 180 PT sources, we made a further selection in order to exclude objects with apparent magnitude  $E > 18$  and absolute  $O$  mag  $M_O > -22^2$ . A luminosity cut is required to avoid contamination from the host galaxy. The optical brightness cut is due to our interest in X-ray weak objects: we therefore exclude the sources that would be undetected in the WGACAT even if their optical-to-X ratio were normal:

<sup>2</sup>  $E$  and  $O$  magnitudes are obtained from the APM digital catalogue.

indeed, in these cases we would only obtain X-ray upper limits that are useless to constrain the X-ray properties of these sources. The brightness cut could bias the sample in favor of objects with large  $\alpha_{OX}$ . However, our control sample is the PG, with an even stronger brightness cut. So the “differential” effect cannot be spurious.

The final sample contains 30 PT quasars.

In the following we compare the X-ray properties of these sources, relative to their optical emission, with the analogous properties of the PG quasar sample. The PG sample is used as reference both because it is the best studied quasar sample and because it is selected according to the “historical” definition of quasars (i.e. compact objects with high luminosity and a strong UV excess).

Among the 30 PT sources, only 9 are detected in the WGACAT, while for the remaining 21 only an upper limit is available. Among the HS sources, that are on average brighter than the PT sources, about half are detected. The upper limits have been estimated at the 90% confidence level, taking into account the vignetting and the PSF of the ROSAT PSPC instrument. Further details are given in the Appendix.

### 2.4. Definition of an optical-to-X index

The simplest way to compare the samples would be that of calculating the  $\alpha_{OX}$  index for line-selected sources, as defined in Eq. (1), and following the prescriptions given in previous works (Green et al. 1995; Wilkes et al. 1994). On the other hand, the calculation of  $\alpha_{OX}$  poses several problems in the extrapolations needed: in particular, the monochromatic flux at  $E = 2$  keV is strongly dependent not only on the WGACAT count rate (that is the only information directly available), but also on the spectral properties of the source. The standard method consists in assuming a powerlaw spectrum with spectral index  $\sim 1-1.5$ , that is typical for quasars in the ROSAT energy band. However, we suspect that our sources are much more absorbed in the X-rays than normal quasars: this would imply a possible photoelectric cutoff and/or a much flatter spectral index.

An analogous problem arises in the optical, even if in this case the errors should be lower.

For these reasons we define a new optical-to-X index, by using directly the available data: for the HS sample we use the  $B$  magnitude for the optical and the WGACAT count rates for the X-rays, while for the PT sample we use the  $O$  and  $E$  magnitudes obtained from the APM sky catalogue and the WGACAT count rates.

In order to perform a homogeneous comparison, we took the PG quasars in the WGACAT ( $\sim 70$ ) and we defined the count rates and the upper limits in the same way as for the HS and PT samples. The  $B$  magnitudes are directly available in the literature (Schmidt & Green 1983), while the  $O$  and  $E$  magnitudes were calculated from the  $B$  and  $V$  magnitudes assuming the quasar template of Francis et al. (1991). We note that this extrapolation

is much safer than those discussed above, because these bands are much closer to  $B$  and  $V$  than  $2500 \text{ \AA}$ .

The optical–X index used in this work is defined as follows:

$$I_{\text{OX}} = \log \frac{10^{(20-m)/2.5}}{\phi(\text{cts s}^{-1})} \quad (2)$$

where  $m$  is the optical magnitude and  $\phi$  the ROSAT count rate. Since the optical magnitude does not always refer to the same band, we define a different  $I_{\text{OX}}$  for each band and compare only same-band indices. Finally, we note that in our definition we do not take into account the K correction, even if many of our sources are at intermediate or high redshift. We discuss this point in detail in the next Section.

### 3. X-ray properties of emission line selected AGNs

In order to understand the physical properties of the selected objects, we divide our sources in two groups, to be studied separately: the HS sample and the PT sample. This division is necessary since the two parent samples have different redshift distributions (Fig. 2) and selection criteria.

#### 3.1. Analysis of the HS sample

In Fig. 3 we plot the  $I_{\text{OX}}$  distribution for the entire HS sample (Fig. 3a) and for three redshift intervals. We note that no object in the HS sample is at redshift  $z < 0.1$  and that high redshift sources are on average weaker in the X-rays than intermediate redshift ones. A dependence of the  $\alpha_{\text{OX}}$  index (as defined in Eq. (1)) with the redshift is suggested by several statistical studies of large quasar samples, as reminded in the Introduction. For this reason the comparison of the high-redshift HS objects with the PG comparison sample could be not strictly correct, because the latter is composed mostly of low-redshift sources. However, the redshift dependence that has been proposed in the literature (a factor  $\sim 3$  between  $z = 0$  and  $z > 1$ , Yuan et al. 1998) is much weaker than the effect found in the HS sample, where the X-ray emission of a significant fraction of objects is more than one order of magnitude lower, with respect to the optical, than in normal quasars.

Since the HS is a flux-limited sample, the redshift dependence of the  $I_{\text{OX}}$  distribution could be due either to a real dependence on evolution or to a luminosity effect. This issue will be discussed further in Sect. 4.

#### 3.2. Considerations on the K correction

For logarithmic indicators, as our  $I_{\text{OX}}$  index, the K correction is  $\sim (\gamma_1 - \gamma_2) \log(1 + z)$ , where  $\gamma_1$  and  $\gamma_2$  are the spectral index of the X-ray and optical spectrum respectively (assuming a powerlaw spectrum,  $F_\nu \propto \nu^{-\gamma}$ ). Assuming a standard quasar spectrum, with  $\gamma_1 = 2$  and  $\gamma_2 = 1.5$ , the

K correction is 0.15 at  $z = 1$  and 0.24 at  $z = 2$ , much lower than the observed effect.

It is well known, for example from the analysis of the X-ray emission of BAL quasars (e.g. Gallagher et al. 1999), that X-ray weak quasars have on average flatter X-ray spectra than normal quasars. This is also found in low-luminosity AGNs: if the complex 2–10 keV spectra of heavily absorbed Seyfert 2s is fitted with a simple power-law, the photon index varies between  $\sim 0.5$  and  $\sim 1.5$  (see for example Turner et al. 1997 and Maiolino et al. 1998). Therefore, the X-ray spectral index of our objects could be significantly lower than the canonical value of 2, and this effect goes in the direction of lowering and perhaps inverting the K-correction for  $I_{\text{OX}}$ .

We conclude that a physical effect different from the K correction is responsible for the unusually high values of  $I_{\text{OX}}$ .

#### 3.3. Analysis of the PT sample

The  $I_{\text{OX}}$  distribution for the PT sources is plotted in Fig. 4 for two different cuts in magnitude. A highly significant difference between our sample and the PG quasars is evident even in the  $E < 18$  sample: more than half of the objects are underluminous in the X-rays of at least a factor 5 with respect to a “normal” quasar. The X-ray weakness is however more significant in the small  $E < 17$  subsample. The increase of the discrepancy with brightness shows that grism selection is indeed effective in finding out X-ray weak quasars, but in the case of the PT sample the flux limits in the WGACAT are too high to investigate the correlation between the optical and X-ray emission.

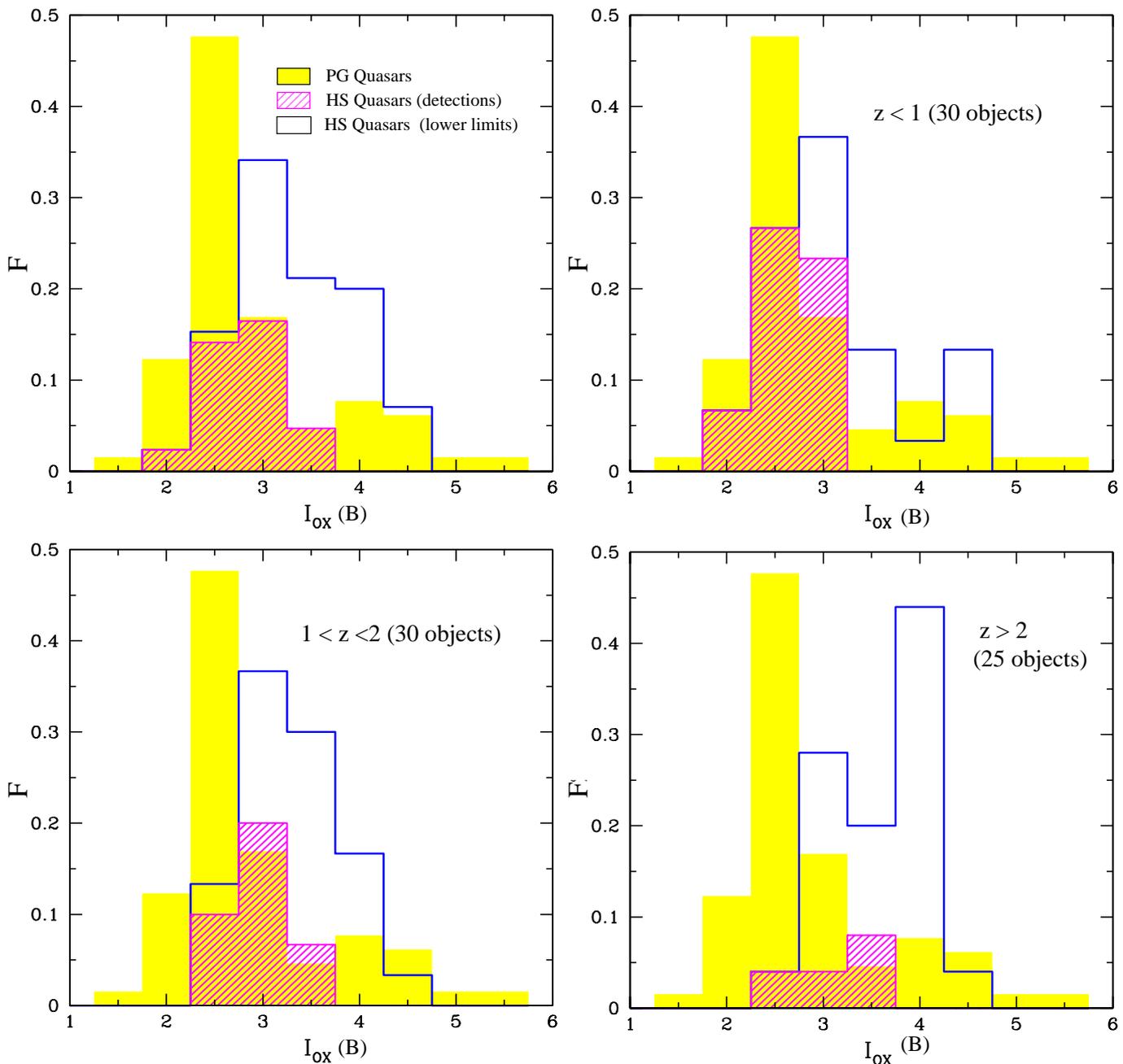
### 4. Selection effects and interpretation

The results presented above suggest the existence of a class of AGNs with broad lines in the optical/UV but with an X-ray emission much lower than expected from the optical flux and a PG-based extrapolation.

The quasars of the HS sample show a significant correlation of their broad-band properties with redshift (or, analogously, with luminosity, since the sample is flux-limited). We performed a KS test on the distributions plotted in Fig. 3, and we found that the  $z < 1$  and  $1 < z < 2$  distributions are different at a level of confidence of 96%, while the  $z < 1$  and  $z > 2$  distributions differ at 99%.

We note that the level of significance of the lower limits on  $I_{\text{OX}}$  is the same at all redshifts, because both the optical and the X-ray parent samples are flux limited at constant fluxes. The increase of  $I_{\text{OX}}$  with redshift can therefore be due to a “luminosity effect”: optically more luminous quasars are on average weaker in the soft X-rays (with respect to the optical emission).

In Fig. 5 we show the  $O - E$  colour for the HS sample, obtained from the Palomar All Sky Survey (POSS). The theoretical lines represent the typical  $O - E$  colour of quasars in function of the redshift, for three different values of optical extinction. Since the blue colour excess



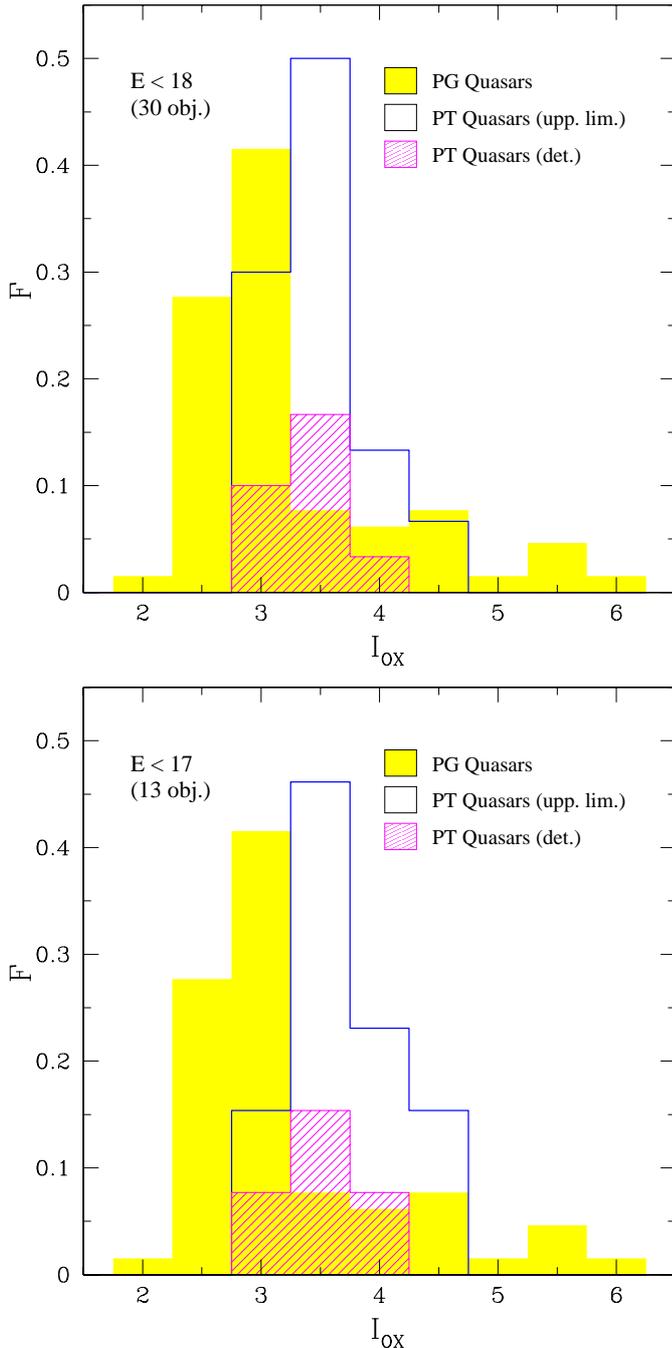
**Fig. 3.**  $I_{\text{OX}}$  distribution of the HS sample for the whole sample (panel a) and for three redshift intervals. Lower limits on  $I_{\text{OX}}$  are derived from the upper limits on X-ray count rates

is still one of the main selection criteria here, more than half of the HS quasars do not have, on average, colours redder than normal quasars. However, another  $\sim 25\%$  of the sources have an  $O - E$  colour that corresponds in normal quasars to an optical extinction  $A_V > 1$ . This is a further indication that also quasars with a relevant absorption were selected in the Hamburg Quasar Survey. In Fig. 6 we show the  $I_{\text{OX}}$  distributions for the HS objects with  $z < 2$  and located respectively below (upper panel) and above (lower panel) the  $A_V = 1$  line in Fig. 5. Redder objects are clearly also on average weaker in the X-rays. This results confirm one of our main working hypotheses,

i.e. that X-ray weak quasars are missed in surveys based on a strong colour selection.

Sources at  $z > 2$  are significantly X-ray weaker than normal quasars, irrespectively of their optical colour. This is in agreement with the “luminosity effect” discussed above. Again, this class of objects could easily have been missed by colour-based surveys, since the  $U - B$  criterion becomes inefficient at  $z > 2.2$ .

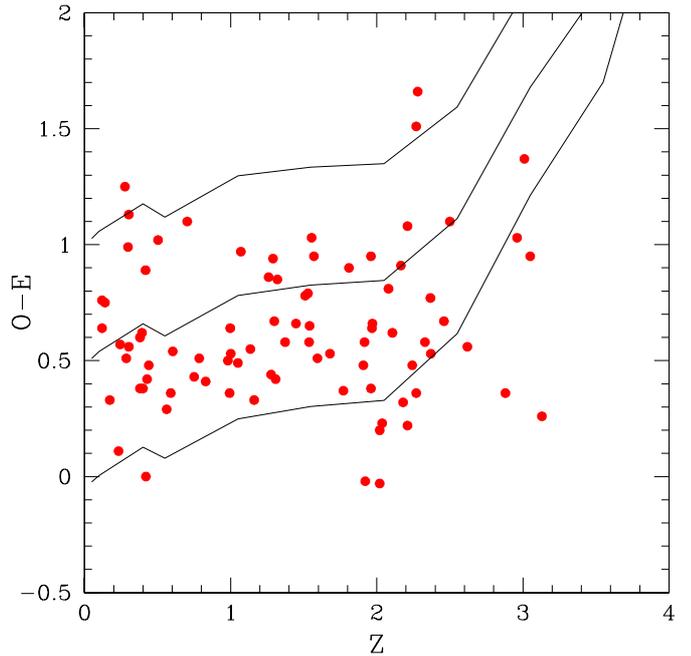
Since the HS survey is still biased towards blue objects, this result could imply that a non negligible population of “red” quasars could exist, analogously to what found by Webster et al. (1995) for flat-spectrum radio quasars.



**Fig. 4.**  $I_{\text{OX}}$  distribution for the objects of the PT sample with  $E < 18$  (upper panel) and with  $E < 17$  (lower panel)

The discussion made above for the HS quasars can be repeated for the PT quasars. In this case, even if we are able to find a significant fraction of X-ray weak quasars, the result is weaker, due to the fainter optical magnitudes of these sources.

The  $O-E$  colour distribution for the PT sample is similar to that of the HS, revealing a significant fraction of objects redder than normal quasars (Fig. 7). This result confirms that spectroscopic selection is able to find quasars that would be missed in classical color-based surveys.



**Fig. 5.** Optical  $O-E$  colour versus redshift for the HS sample. Lines are for a standard quasar spectrum with three different rest frame optical extinctions:  $A_V = 0$  (bottom line),  $A_V = 1$  (middle line),  $A_V = 2$  (top line)

## 5. Discussion and conclusions

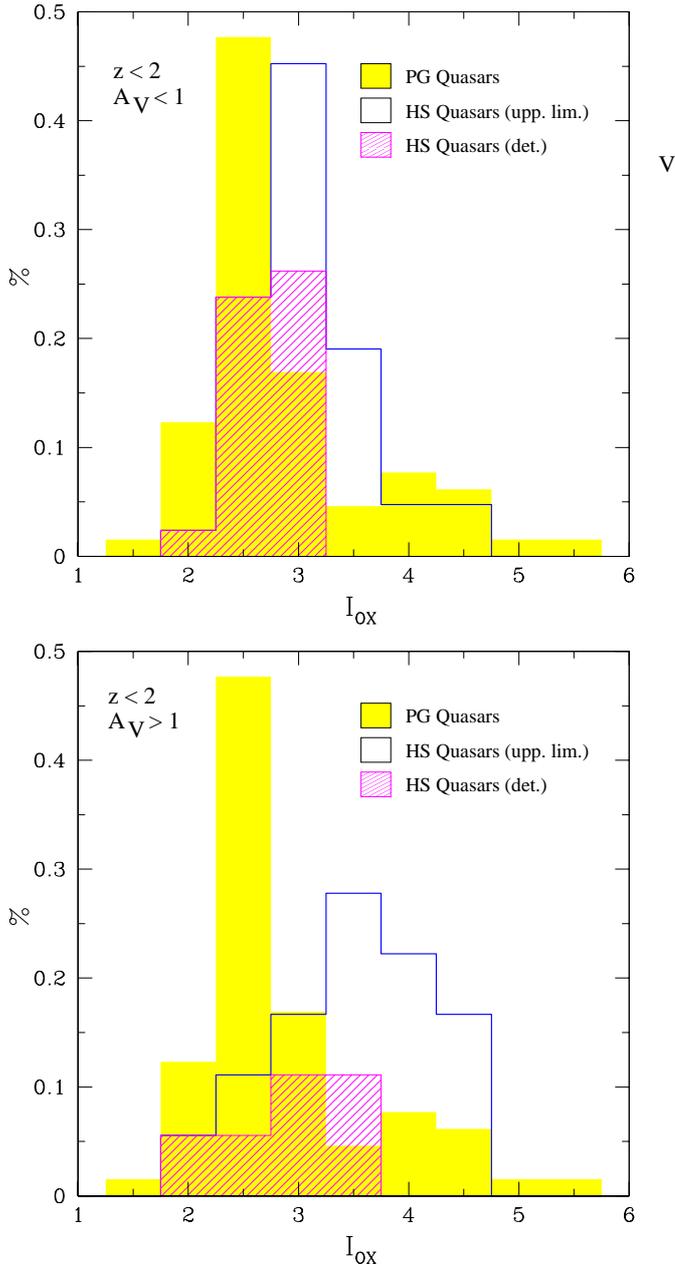
The X-ray and optical analysis of the HS and PT samples, presented in the previous Sections, points out the existence of a population of X-ray weak AGNs, with optical colours not very different from “normal” quasars, but red enough to be missed by classical colour-based surveys.

Our results on the  $I_{\text{OX}}$  distribution imply that at least 50% of our objects are significantly weaker in the soft X-rays than normal “blue” quasars.

The high  $I_{\text{OX}}$  measured in our sources could be due to an intrinsic X-ray weakness, or to a low  $A_V/N_{\text{H}}$  value. Several considerations make the first hypothesis unlikely:

- Soft X-ray emission is a general feature present in all known classes of AGNs (except for BALs, but see the next paragraph). Moreover, since the strong emission lines detected in the optical require a powerful UV source, it is unlikely that a physical process provides an intense UV emission without any significant tail in the soft X-rays;
- As briefly mentioned in the Introduction, BAL AGNs, that are the only sources similar to ours with respect to the X/optical properties, are likely to be heavily absorbed rather than intrinsically weak. This is suggested (a) by the correlation between the X to optical ratio and the C IV absorption features (Brandt et al. 2000) and (b) by detailed analysis of the X-ray emission of some BAL quasars, that shows an absorbed spectrum in the 2–10 keV band (Gallagher et al. 1999).

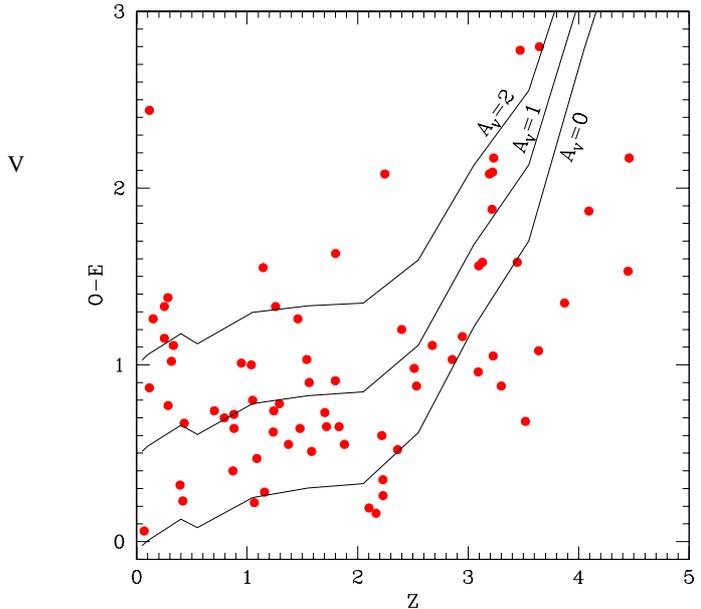
On the other hand, there are several indications that a low  $A_V/N_{\text{H}}$  (relative to the Galactic value) could be



**Fig. 6.**  $I_{\text{OX}}$  distribution for the  $z < 2$  HS sample below (upper panel) and above (lower panel) the  $A_V = 1$  line in Fig. 5

common to several classes of sources (see the Introduction). Moreover, this possibility is supported by the correlation between high  $I_{\text{OX}}$  values and high  $O - E$  colours, suggesting a common physical origin of the two phenomena.

Current models of the circumnuclear medium of AGNs do not clarify which physical process can be responsible for an  $A_V/N_{\text{H}}$  value substantially lower than Galactic. Qualitatively, a high absorption in the X-rays, together with a low extinction in the optical can be due to two different reasons: a low dust-to-gas ratio or a size distribution of dust grains different from the standard one. For a more detailed discussion on this issue, the reader is referred to Maiolino et al. (2001b).



**Fig. 7.**  $O - E$  colour for the PT quasars. The lines are the same as in Fig. 5

Whatever the physical origin of the low  $A_V/N_{\text{H}}$ , the main conclusion of this discussion is that a population of quasars does exist, with X-ray properties of type 2 AGNs and optical spectrum of type 1s. In Fig. 8 we propose a simple classification scheme for AGNs in the  $A_V - N_{\text{H}}$  plane. In this diagram, “blue” quasars and BALs are the objects revealed by classic, colour-based optical surveys. The line-selected objects are located in the “X-ray type 2 zone” ( $N_{\text{H}} > \text{a few } 10^{22} \text{ cm}^{-2}$ ) but in the “optical type 1 zone” ( $A_V < 2 - 3$ ). “ROSAT red quasars” refers to the soft X-ray selected objects of Kim & Elvis (1998). It is worth noting that even in the “optical type 2 zone” a relevant number of objects could have low  $A_V/N_{\text{H}}$ : for example, comparing the near IR broad lines with the X-ray spectrum of the type 2 AGN IRAS 05189-2524, we estimated an  $A_V/N_{\text{H}}$  substantially lower than Galactic (Severgnini et al. 2000).

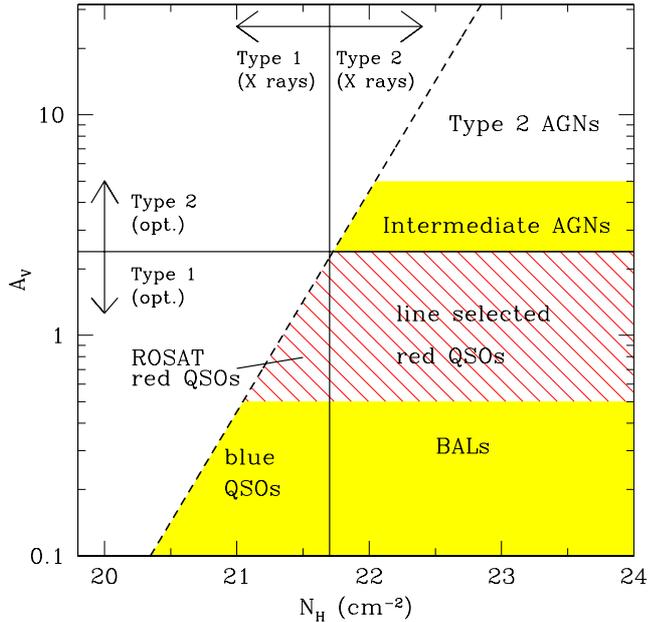
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## Appendix A: Evaluating upper limits from the WGACAT catalogue

Here we discuss how to obtain a correct estimation of the upper limits (in counts  $\text{s}^{-1}$ ) for a non-detection in the WGACAT catalogue.

The basic selection criterion in the WGACAT is the request of a signal-to-noise ratio higher than 2. This implies that, if the background counts are  $B$ , the minimum



**Fig. 8.** AGN classification in the  $A_V - N_H$  plane. The dashed line represents a Galactic  $A_V/N_H$  value. See text for details

number of counts for a detected source,  $S_m$ , is obtained from the equation:

$$S_m = 2\sqrt{S_m + B}. \quad (\text{A.1})$$

In case of a non-detection, a 90% upper limit is obtained multiplying  $S_m$  by a correction factor  $a$ , such that a source with  $aS_m$  counts has a probability  $<10\%$  to be undetected (i.e. to fall below the detection limit  $S_m$ ). This factor is therefore obtained solving the equation:

$$\sigma\sqrt{aS_m + B} = S_m(a - 1) \quad (\text{A.2})$$

where  $\sigma = 1.25$  is the number of standard deviations corresponding to a 1-sided probability of 90%. We found that typical values for this correction are  $a \sim 1.65 - 1.7$ .

The crucial point in order to obtain a correct value of  $aS_m$  is the estimation of  $B$ .

For each undetected source, we calculated the background counts for a nearby detected source and we re-scaled this value for the vignetting and PSF of the PSPC instrument.

A tabulation of the vignetting as function of the distance from the center of the field of view,  $y(r)$ , can be obtained directly from the WGACAT. To obtain the PSF we calculated the background counts  $B$  for a large number of randomly selected sources (about 10% of the WGACAT) and we fitted the dependence from the radius with

a 3rd order polynomial,  $P(r)$ . Finally we re-scaled the background counts of the nearby detected source with the ratio  $[P(r_1)y(r_1)]/[P(r_2)y(r_2)]$ , where  $r_1$  and  $r_2$  are the distances from the center of the undetected and the detected source, respectively.

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