The X-Ray Luminosity Function of Active Galactic Nuclei

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Abstract. We derive an X-ray luminosity function for active galactic nuclei (AGN) that accounts for the X-ray source counts in the 0.5–2.0 and 2–10 keV energy ranges, the redshift distribution of AGNs in the ROSAT Deep Survey (RDS), as well as the X-ray background (XRB) from 1–10 keV. We emphasize the role of X-ray absorption, which has a large effect on the faint end of the 2–10 keV source counts, as well as on the integrated X-ray background.

1. Introduction

This contribution for Joachim Trümper’s birthday marks his initiative and involvement in the ROSAT Deep Survey (RDS). Little was known about the luminosity function of X-ray sources when we started the planning meetings for the survey some 13 years ago. Now that the main results of the RDS have been published (Hasinger et al. 1998, Schmidt et al. 1998), this celebration provides an excellent opportunity to review what we have learned about the luminosity function of X-ray sources. Since a large fraction of these are active galactic nuclei (AGN), we will concentrate on the AGN luminosity function.

Some of the earliest medium deep ROSAT fields were used by Boyle et al. (1993) in combination with the Einstein Medium Sensitivity Survey (EMSS; Gioia et al. 1990) to derive the AGN luminosity function and its evolution. They concluded that the data are consistent with pure luminosity evolution proportional to \((1 + z)^{2.5}\) for \(z < 2\) (for \(q_o = 0.5\)) and that the integrated contribution of AGNs to the 2 keV X-ray background is 35\%. The effect of the uncertainty in the relative calibration of EMSS and ROSAT (Page et al. 1996) can now be avoided by deriving the luminosity function solely from ROSAT data. Hasinger (1998) and Miyaji et al. (1999) have discussed all ROSAT survey material available and conclude that the luminosity functions of AGNs at different redshifts are incompatible with luminosity evolution but instead are consistent with density evolution. This result is important for our understanding of the XRB, for, as we shall see below, under density evolution the entire XRB can easily be explained as the integrated effect of AGNs.

The spectral difference between the X-ray background (XRB) and the typical cosmic X-ray source (AGN) is a consequence of the internal absorption in AGNs, which makes the spectrum of the more absorbed AGNs effectively very hard (Setti and Woltjer 1989). Global analyses of the luminosity function of AGNs, such as those of Comastri et al. (1995), and Miyaji et al. (1998a) include the effects of absorption in accounting for the source counts \(N(> S)\) and the XRB over a large energy range. The Comastri et al. models adopt the Boyle et al. (1993) luminosity function and luminosity evolution, while the Miyaji et al. models use a luminosity function involving density evolution.

Our derivation of the AGN luminosity function will be more detailed but less global than the above studies. We will only consider data from the brightest and deepest surveys at both 0.5–2.0 and 2–10 keV, as well as the XRB in the 1–10 keV range. We use a Hubble constant \(H_o = 50\) km sec\(^{-1}\) Mpc\(^{-1}\) and a deceleration parameter \(q_o = 0.5\) throughout this paper.

2. Methodology

We will follow the method of Schmidt and Green (1986) in deriving the luminosity function. We start from a well defined X-ray sample with optical identifications and redshifts (the \textit{generating} sample). For each of the sources in the generating sample, we derive the maximum redshift \(z_{\text{max}}\) at which it would be observed at the sample limit. Since some of the AGNs are very nearby, we take into account the local density enhancement (Santiago and Strauss 1992); specifically we assume that the enhancement is a factor of 3 for \(z < 0.003\), and that it is 4.5–500\(z\) for 0.003 < \(z < 0.007\). We use an assumed law for the density evolution (to be iterated) in evaluating the density-weighted volume \(V_{\text{max}}\) over which each source is observable within the limits of the generating sample. The local luminosity function is the sum of the delta functions \(1/V_{\text{max}}\) of all sources in the sample.
In deriving the redshift $z_{\text{max}}$, the spectral energy distribution of the source plays an important role. This may be characterized by one or more spectral indices, and absorption given by an effective hydrogen column (cf. Morrison and McCammon 1983). We assume that the energy spectral index of AGNs is $-1.3$ below 1 keV, and $-0.7$ above 1 keV (Schartel et al. 1997). Information about the distribution of absorptions in complete AGN samples is very rare: the HEAO1-A2 survey of X-ray sources at 2–10 keV (Piccinotti et al. 1982) is the only complete sample for which hydrogen columns of the AGNs are known (Schartel et al. 1997) at the present time. The survey contains 30 AGNs to a limiting flux of 2 $\times$10$^{-11}$ cgs and 0.162 sq. deg. to a limit of 1 keV over an area of 27,020 square degrees. We use the Piccinotti survey as the generating sample, thus ensuring that the observed properties of its sources, including the individual absorptions, are precisely incorporated in the derivation of the luminosity function.

Once the luminosity function is derived, we can predict the source counts, redshift distributions and the integrated contribution of the AGNs to the XRB. We then iterate the free parameters characterizing the density evolution by fitting to observed source counts from other complete samples and/or the XRB, as described in the next section.

3. Results

Since pure density evolution of the luminosity function leads to a severe overestimate of the XRB (see below), we assume that the density evolution depends on the X-ray 2–10 keV luminosity ($H_X$), such that the co-moving density of sources varies with redshift as $(1+z)^k$ where

\[ k = k_0 \quad \text{for} \quad H_X \geq H_{X_0} \]
\[ k = k_0 + k_1 (\log H_X - \log H_{X_0}) \quad \text{for} \quad H_X < H_{X_0} \]

At large redshifts, we adopt the evolution found for optically selected quasars, viz. a freeze of the density increase for \( z > 1.65 \) (Hewett et al. 1993) and beyond \( z = 2.7 \) a decrease of the co-moving density by a factor of 2.7 per unit redshift (Schmidt et al. 1995).

Our procedure is to set the free parameters characterizing the density evolution, \( k_0, k_1 \) and \( H_{X_0} \), such that we fit the number of AGNs in the RDS, as well as the XRB in the energy range 1-2 keV. The RDS covers 0.162 sq. deg. to a limit of 1.10$^{-14}$ cgs and 0.136 sq. deg. to 0.5510$^{-14}$ cgs. The sample contains 42 AGNs (Schmidt et al. 1998; source 36 has since been identified as an AGN at redshift 1.52; sources 14 and 84 have been tentatively identified with infrared objects in the K-band, presumably reddened AGNs). For the XRB, we use the results of a study by Miyaji et al. (1998b), recently updated by Miyaji et al. (1998c).

In iterating the free parameters for the density evolution, we first explore the case of pure density evolution, i.e., \( k_1 = 0 \). In this case, the RDS number density is reproduced for \( k_0 = 4.75 \), but the predicted XRB at 1–2 keV for AGNs is twice the observed intensity. We conclude that pure density evolution with \( k_1 = 0 \) is untenable.

Through trial and error, we find that both the RDS source count and the 1–2 keV XRB can be fitted with \( k_0 = 4.94 \), \( k_1 = 3.00 \), and log \( H_{X_0} = 44.00 \). This is the model that we discuss in the remainder of this paper. It predicts an RDS redshift distribution in the redshift intervals of 0–1, 1–2, 2–3, > 3 of 12.3, 23.3, 6.1, and 0.4, respectively, where the observed numbers are 16, 20, 4, and 0, with 2 unknown. Since luminosities and redshifts are strongly correlated in a flux-limited sample, the excellent agreement shows that the rate of evolution for different luminosities is essentially correct, confirming the luminosity dependence of the evolution to first order.

We test the model on the ROSAT Bright Survey (RBS, Schwope et al., 1998), which is based on the ROSAT survey bright source catalogue (Voges et al. 1995). The RBS contains 194 AGNs with 0.5 – 2.0 keV fluxes above 2.910$^{-12}$ cgs over an area of 20,320 sq. deg. Our model predicts 193 sources. Considering the small number of sources in our generating sample, the precise agreement is fortuitous, but it is encouraging that there is no discrepancy between these two large-area bright surveys in different energy bands. Fig. 1 shows the predicted source counts at 0.5–2 keV, as well as the separate contributions from sources with different columns \( N_H \). Further discussion of the \( N_H \) distribution is given below.
Fig. 2. Predicted AGN source counts (thick curve) in the energy range 2–10 keV. The thin curves represent the counts (from top to bottom, both at the extreme left and right sides), for sources with columns 0, \(10^{22}\), \(10^{23}\), \(10^{21}\), and \(10^{24}\) cm\(^{-2}\). The HEAO1-A2 AGN source count and a total source count representative of the ASCA and BeppoSAX deep surveys (see text) are indicated.

Next, we turn to the source counts at 2–10 keV. At the bright end, the AGN source count is provided by the Piccinotti survey, which is exactly reflected in the model. At the faint end, we represent the results of deep surveys with ASCA (Cagnoni et al. 1998) and BeppoSAX (Giommi et al. 1998) by a representative source density of \(45\) deg\(^{-2}\) at \(5 \times 10^{-14}\) cgs. Our model as presented so far yields only \(23\) deg\(^{-2}\). This discrepancy is a direct consequence of an apparent incompatibility between the 2–10 keV and the ROSAT 0.5–2.0 keV source counts. At a source count of, say, \(10\) deg\(^{-2}\), the 2–10 keV flux from the ASCA counts (Cagnoni et al. 1998) and the 0.5–2.0 keV ROSAT counts (Hasinger et al. 1998), if interpreted in terms of a single power law of the spectral energy distribution, require a spectral index of \(-0.5\). Typical observed spectral indices are \(-0.7\) in the 2–10 keV band, and \(-1.3\) in the 0.5–2 keV band (Schartel et al. 1997). The spectral discrepancy suggests the existence of some sources with a much harder spectrum or larger absorption than those of the typical sources. The distribution of the effective hydrogen columns for the Piccinotti AGNs given by Schartel et al. (1997) is \(18, 3, 5,\) and \(4\) for columns \(0, 10^{21}, 10^{22},\) and \(10^{23}\) cm\(^{-2}\), respectively. We now explore the effect of adding one or two sources with \(N_H = 10^{24}\) to this sample. This ad hoc addition is statistically not unreasonable: the probability of missing two marked sources out of 32 is around 13%.

Specifically, we have added one hypothetical source to the Piccinotti sample, with a flux of \(3.2 \times 10^{-11}\) cgs, a redshift of 0.028 and \(\log N_H = 24.0\). The effect of this additional source on the 0.5–2.0 keV source counts is negligible, as shown by Fig. 1, as is its effect on the 1–2 keV XRB. Therefore, we can leave the evolution parameters \(k_o, k_1,\) and \(H_{X_0}\) unchanged. In contrast, the effect on the predicted 2–10 keV source counts is dramatic: at \(5 \times 10^{-14}\) cgs the addition of this one source doubles the predicted counts, which now agree with the observed counts. Fig. 2 shows that the log \(N_H = 24\) fraction of the counts rises with decreasing flux, reaches a maximum between \(10^{-13}\) and \(10^{-14}\) cgs and then declines again. This complex behavior is a consequence of the spectral properties of a heavily absorbed source moving through the 2–10 keV band as its redshift increases. The redshift of 0.028 for the hypothetical source was chosen to maximize the effect on the source counts. For redshifts of 0.024 and 0.064, respectively, the effect on the 2–10 keV source counts would be half as large, so two such sources would be required for the
same effect. There are 10 sources in the Piccinotti sample with redshifts in the range 0.024–0.064.

The X-ray background is illustrated in Fig. 3. The curve labeled "all AGN" is the sum of the five components with different $N_H$ values. The "total" curve includes an estimate of the background expected from galaxies, and clusters of galaxies. The good fit to the observed XRB (Miyaji et al. 1998b,c) at 1–2 keV is the result of our choice of $k_0$ and $k_1$, see above. The log $N_H =$ 24 component, generated by our hypothetical source, has a substantial effect on the predicted background above 4 keV, resulting in good agreement with the observed background at higher energies.

4. Discussion

We have succeeded in deriving a model of the AGN luminosity function and its evolution that:

1. at 0.5–2.0 keV reproduces the number of AGNs in the RBS and the RDS, as well as the redshift distribution in the RDS;
2. at 2–10 keV reproduces the number and redshift distribution of AGNs in the HEAO1-A2 survey, as well as the source counts in the deep ASCA and BeppoSax surveys;
3. reproduces the observed XRB from 1–10 keV.

Essential ingredients of our derivation of the luminosity function are (a) the luminosity-dependent density evolution, with a cutoff at high redshift, and (b) evaluation of the effect of a realistic distribution of absorption columns. The success of our model analysis supports the proposals by Setti and Woltjer (1989), Madau et al.(1994), and others that the spectral difference between the XRB and the typical cosmic X-ray source (AGN) is a consequence of the internal absorption in AGNs, which makes the spectrum of the more absorbed AGNs effectively very hard. It appears from our model that the high source counts at 2–10 keV compared to those at 0.5–2.0 keV are caused by the same effect.

The small number of AGNs in the HEAO1-A2 survey inherently limits the statistical accuracy of the model we have discussed here. The model predictions for the number of sources expected in the RBS, the RDS, etc. generally have a corresponding statistical error of around 25%. At energies above 2 keV, the lack of statistics about the fraction of sources with log $N_H =$ 24 is a major source of uncertainty, as we discussed in Sec. 3. Our attempt to represent this component by a single hypothetical source in the Piccinotti sample that we used as a generating sample, allowed us to illustrate the effect of these sources. Statistical information on the frequency of high absorption columns will be required to confirm or refine luminosity function models such as presented in this paper. Recent BeppoSAX observations of a sample of low luminosity AGNs selected on the basis of [O III] fluxes, assumed to be an isotropic luminosity indicator, show that the number of highly absorbed sources is substantially higher than previously assumed on the basis of existing 2–10 keV data (Maiolino et al. 1998). Once the statistical data on absorption columns are available, the question of how to take into account the wide variety of absorption spectra seen in AGN spectra (cf. Reichert et al. 1985), which has been ignored in this paper, should also be addressed.

Further systematic surveys are desired, especially at higher energies, preferably beyond 10 keV, both shallow over a large sky area as well as deeper surveys over smaller areas. Optical identifications and redshifts for all sources, or well defined subsamples, are needed, as well as X-ray spectra of sufficiently large samples so that the distribution of absorption columns to $> 10^{24} cm^{-2}$ can be determined.

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