Hidden BL Lacertae Objects Near and Far

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Abstract. I describe two difficulties with current research into the cosmic evolution of BL Lacertae Objects: (1). Possible sample incompleteness due to unrecognized (i.e., “hidden”) BL Lacs; and (2). The absence of a viable physical model of the evolution, to which current and future observations can be compared.

1. Introduction

The unusual evolutionary trend seen in the number and/or luminosity of BL Lac Objects (a.k.a. “negative” evolution) has been the subject of many recent papers and of several talks at this conference. But two things remain frustrating (for me at least) involving these evolutionary studies:

1. Unlike quasars (or other AGN classes for that matter), the identification of a complete BL Lac sample is fraught with difficulty and uncertainty because BL Lac Objects are defined in “negative” terms (e.g., they lack the strong emission lines of quasars). Other defining qualities may also eliminate true BL Lacs from samples under study, making them incomplete in a systematic way.

2. But like the quasars (and other AGN classes as well), there is no physical model to which the evolutionary trends are compared; i.e., functions are fit and argued over (e.g., pure luminosity evolution vs. luminosity-dependent density evolution) but these are algebraic functions without much physical basis.

In this brief account I will address both of these issues with respect to current samples as well as what has been or will be seen in deep CHANDRA images.

2. Incompleteness in Current Samples

In this Section I will describe three ways in which true BL Lacs can be “hidden” in X-ray and radio-selected samples, potentially causing incompleteness:

1. Despite many X-ray selected BL Lacs (XBLs) having spectral energy distributions (SEDs) which peak in the optical/UV (so-called “high energy peaked BL Lacs”: HBLs), their optical spectra often have a significant contribution from host galaxy starlight. Browne & Marcha (1993) and Marcha & Browne (1995) pointed out that such objects could be confused with FR-1 radio galaxies in clusters so that the X-ray emission would be assigned incorrectly to the cluster. Thus, some XBLs, particularly those with modest optical non-thermal luminosity, could be misidentified as clusters of galaxies.
2. Investigators of radio surveys used to identify radio selected BL Lac (RBL) samples have set a radio spectral index cutoff to eliminate the large number of radio galaxies in these samples (e.g., the 1 Jy sample uses $\alpha \geq -0.5$; Stickel et al. 1991). However, some XBLs have radio spectral indices steeper than this, suggesting that a flat radio spectral index is not required for all BL Lacs. By this spectral index flat RBLs would be misidentified as radio galaxies.

3. Both RBLs and XBLs could be “hiding” in rich clusters of galaxies where the radio emission would be ascribed to a brightest cluster galaxy (BCGs like NGC 1275=3C84=Perseus A) and the X-ray emission ascribed to dense, cooling gas (i.e., a “cooling flow”). These BL Lacs would be misidentified as FR1 radio galaxies in “cooling flow” clusters.

2.1. Hidden XBLs

A large gallery of XBL spectra can be found in the recent compilation paper of the EMSS XBL sample by Rector et al. (2000). These spectra show that, unlike RBLs which often have weak (low equivalent width and low luminosity) emission lines in their optical spectra, XBLs only very rarely have emission lines but often have significant contributions from host galaxy starlight. In my first examination of XBLs (Stocke et al. 1991), I suggested a BL Lac classification criteria to separate BL Lacs from FR 1 radio galaxies using the strength of CaII H & K break at $\approx$4000Å rest. A Ca II “break strength” of $\leq$25% was required for BL Lacs, whereas 50% is typical of current epoch ellipticals (e.g., Dressler & Shectman 1987). It is important to understand that, like the radio spectral index limit, the Ca II break limit is arbitrary, and so Maria Marchâ in her thesis correctly pointed out that this criteria could prevent us from correctly identifying low luminosity BL Lac Objects in X-ray selected samples (Browne & Marchâ 1993; Marchâ & Browne 1995). Other, more imaginative, but still arbitrary, criteria have been proposed since then (e.g., Marchâ et al. 1996).

These investigations led us (Rector, Stocke & Perlman 1999) to use the ROSAT HRI to image some poor clusters in the EMSS which might actually be BL Lac Objects alâ Marchâ. She was correct! We found that some of these EMSS sources were pointlike at radio galaxy locations: new EMSS BL Lacs misidentified as clusters and thus “hiding” in these clusters. However, some of these new BL Lacs had optical spectra whose Ca II breaks violated both the old Stocke et al. (1991) and the newer Marchâ et al. (1996) criteria. Two are nearly indistinguishable from FR 1 radio galaxies or normal elliptical galaxies in their Ca II breaks, and yet they are still quite luminous X-ray point sources ($L_x \approx 10^{44}$ ergs s$^{-1}$). Optical spectra of these new BL Lacs can be found in Rector, Stocke & Perlman (1999).

An important result, however, is that even with these new BL Lacs included, the $<V_{V_{\text{max}}}>$ is still significantly less than 0.5, especially for extreme XBLs which have $<V_{V_{\text{max}}}> = 0.27 \pm 0.08$ (Rector et al. 2000), solidifying “negative” evolution for XBLs.

Are there other “hidden” BL Lacs of this sort? I suspect, yes! Here I mention only two interesting cases:

1. The Owen et al. (1996) optical spectroscopy of rich cluster radio galaxies which failed to find many BL Lac candidates (3C264 and IC310 in Perseus being two of the four possibilities). Given the above, I suspect that CHANDRA X-ray cluster imaging will find new examples of luminous point X-ray sources
associated with cluster radio galaxies without obvious non-thermal continua optically (see Section 2.3).

(2) Numerous investigators have been bewildered to find faint X-ray sources (some with quite hard X-ray spectra) associated with “passive” elliptical galaxies. By “passive” these investigators have meant that they fail to find obvious AGN signatures optically (e.g., non-thermal continuum + strong emission lines). By way of example, I direct the reader to the Nature article by Mushotzky, Cowie, Barger & Arnaud (2000) on optical identifications in a CHANDRA deep field, in which three relatively bright, “passive” ellipticals have been found. The optical characteristics of these galaxies are quite similar to the low-luminosity BL Lacs in Rector, Stocke & Perlman (1999). So, I predict that these sources will have SEDs similar to other BL Lac Objects (i.e., radio detections at sub-mJy levels). And one only has to redshift the SEDs displayed in Sambruna, Maraschi & Urry (1996) to realize that extremely hard soft X-ray spectra are possible for BL Lacs without requiring any internal absorption (as has been proposed for other potential hard-spectrum X-ray background contributors like obscured Seyferts).

2.2. Hidden RBLs

Radio continuum images of XBLs in Perlman & Stocke (1993) and Rector, Stocke & Perlman (1999) show that many have luminous extended structure, which is likely to be steep in radio spectral index. Single epoch radio spectral indices have been obtained for only 8 XBLs (Stocke et al. 1985), for which only half would pass the -0.5 spectral index cutoff used to define a BL Lac candidate list in the 1 Jy sample (Stickel et al. 1991). Spectral index observations of the entire EMSS sample are now being obtained to see how important the arbitrary spectral index cut imposed upon RBL samples is (Wolter, Rector & Stocke, in progress). But, given the current data, I suspect that there could be many BL Lacs “hidden” amongst the large number of radio galaxies in the 1 Jy. Some of these could have optical spectra similar to the low-luminosity XBLs in Rector, Stocke & Perlman (1999), further complicating their identification (e.g., 3C264). Unfortunately, optical polarimetry blueward of the Ca break may be the only viable observation useful in testing this prediction. But, if enough of these new BL Lacs are found in the 1 Jy, their presence could alter the \(< V/V_{max} >\) statistic for that sample.

2.3. Other Hidden BL Lacs

A detailed imaging survey of BL Lacs conducted at the Canada-France-Hawaii 3.6m several years ago (Wurtz et al. 1996, 1997) presented a confusing result: BL Lacs were not found in the brightest cluster galaxies (BCGs) or in the richest clusters (Abell richness classes > 1) in the current epoch. How can this be if the parent population of BL Lacs are FR1s, which are abundant in nearby rich clusters (e.g., Owen et al. 1996 and references therein)? A possibility, not yet fully explored, but now possible with CHANDRA, is that cluster X-ray emission “hides” some BL Lac Objects. This is especially true in the case of “cooling flow” clusters, whose central X-ray excesses are thought to be due to a dense, cooling ICM. However, if some BCGs in these rich clusters are unrecognized BL Lac Objects, their X-ray emission could contribute to the
excess thought to be a “cooling flow”. Because the soft X-ray spectra of XBLs are similar to ICM emission (see e.g., the Beppo-SAX spectra in Wolter et al. 1998), these XBLs could “masquerade” as “cooling flows”. But, one might argue that the optical spectra of BCGs in “cooling flow” clusters rules these objects out as BL Lacs, since strong emission lines are present (particularly [OII] and Hα). But these emission lines arise in spatially very extended gas (tens to hundreds of kpc) and so are not the nuclear emission lines of an AGN. I predict that CHANDRA ACIS imaging of nearby “cooling flow” clusters will discover luminous point X-ray sources associated with many BCGs (BCGs in “cooling flow” clusters are very often radio galaxies!; Burns 1990). The presence of these point sources will indicate previously unknown BL Lac Objects and will reduce substantially the required mass inflow for the “cooling flow”. We have searched the EMSS clusters for such circumstances using ROSAT HRI images and have found only one cluster which could contain a BL Lac in its BCG: MS1455.0+2232. While CHANDRA images will test this suggestion, this one “hidden” BL Lac will not alter the statistics of the EMSS sample.

3. Models for AGN Evolution?

So, despite the substantial concerns about completeness described above, the EMSS XBL sample has been very thoroughly scrutinized for “hidden” BL Lacs and continues to exhibit “negative” evolution. Further, recent work on other AGN samples (e.g., Urry & Padovani 1995) find that BL Lac and FR1 evolution can be characterized as \( L(z)/L(z=0) = (1+z)^\Gamma \), with \( \Gamma = -4.0 \), while FR2 samples have \( \Gamma = +3.8 \). These results suggest that FR2s evolve (i.e., fade to become) FR1s. Other indications that this is the case comes from the investigations into the environment of quasars (Ellingson, Yee & Green 1991), FR2 radio galaxies (Harvanek et al. 2000) and FR1 radio galaxies (e.g., Longair & Seldner 1979; Yee & Lopez-Cruz 1999). Briefly, from these works: quasars are found in clusters only at \( z \geq 0.45 \), FR2s are found in clusters only at \( z \geq 0.2 \) and FR1s are found in clusters at all redshifts out to 0.8 (e.g., Stocke et al. 1999).

What can we make of these results? Is a physical model suggested or is any suggestion premature? To me these results suggest two things: (1) the orientation unification advocated by Bartel (1989) is ruled out since some FR2 radio galaxies are found in clusters at lower redshifts than any quasars are found in clusters; and (2) an evolutionary scheme by which quasars fade to become FR2 radio galaxies which fade to become FR1 radio galaxies on an e-folding timescale of 0.9 Gyrs (Harvanek et al. 2000) is quite plausible for cluster AGN. After all, what has become of the quasars which inhabited rich clusters at \( z \sim 0.5 \)? This hypothesis is also consistent with the evolutionary trends for BL Lacs/FR1s and FR2s mentioned above.

The interesting question is: what physical phenomenon drives this rapid fading of cluster AGN (and perhaps AGN in general)? Ellingson, Yee & Green (1991) list two possibilities: (1) the evolution of the cluster potential well greatly reduces the number of interactions and mergers between gas rich galaxies which could “feed” an AGN (e.g., Roos 1981); and (2) the rapidly increasing ICM density prevents, in some as yet not understood way, the “feeding” of the AGN (Stocke & Perrenod, 1981). Both of these hypotheses are supported by the
direct X-ray observations of clusters which show that: (1) in the richest clusters of galaxies a dense ICM is already in place at $z \sim 1$ (e.g., Donahue et al. 1999) and (2) in poorer clusters at $z \sim 0.5$ (wherein quasars are found) there is no evidence for a dense ICM (e.g., Rector, Stocke & Ellingson 1995; Hall et al. 1997; Harvanek et al. 2000), but similar richness clusters at $z \sim 0$ have dense ICMs as well as FR1 radio galaxies. In fact, there is little to distinguish these two hypotheses at low-z, since they both prevent further feeding of the AGN as the ICM thickens and heats due to the deepening of the potential well.

However, at the highest redshifts these two hypotheses predict opposite outcomes. Extrapolating to $z \geq 4$, before the epoch of quasars, the Roos (1981) interaction hypothesis would predict even greater numbers of interactions (because the Universe was smaller and the number of galaxies could only have been larger than today). Thus, by this hypothesis, the highest observed quasars are the first AGN, whose highest observed redshifts are due to supermassive black hole formation timescales. However, by the Stocke & Perrenoud (1981) hypothesis, the Universal ICM is denser at high-z, so that an AGN evolution opposite in sense to what we observe at $z \leq 0.5$ is possible; i.e., in this case, the Black Holes are already formed at even higher redshifts as FR1s. Then these BL Lac/FR1s brighten to become FR2s, which brighten to become quasars with cosmic time. This idea was first presented at the Como Conference on BL Lac Objects (Stocke 1987). If this idea is correct, then very high-z BL Lac Objects should be extremely numerous but hard to discover. Using the observed SEDs of typical XBLs redshifted to $z \geq 4$, the Sloan digital sky survey (SDSS) would be the most sensitive search mechanism. And, indeed, one strange AGN at $z=4.7$, which in many ways resembles a BL Lac Object, has been found in the SDSS commissioning data (Fan et al. 2000)! If this radical hypothesis for quasar evolution at high-z is correct, the SDSS should discover other examples of this new class of high-z BL Lacs, which could contribute significantly to the very faint X-ray source count (and to the X-ray Background). Using the observed SEDs and luminosity functions of low-z BL Lacs, and assuming that all quasars were once BL Lacs at higher redshifts ($z \geq 4$), this new class could contribute up to $\sim 1000$ X-ray sources deg$^{-2}$ at fluxes of $10^{-15}$ ergs cm$^{-2}$ s$^{-1}$. And, if these objects have SEDs similar to low-z BL Lacs, they would be spectrally very hard.

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