Selecting AGN through variability in SN datasets

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Abstract. Variability is a main property of active galactic nuclei (AGN) and it was adopted as a selection criterion using multi epoch surveys conducted for the detection of supernovae (SNe). We have used two SN datasets. First we selected the AXAF field of the STRESS project, centered in the Chandra Deep Field South where, besides the deep X-ray surveys also various optical catalogs exist. Our method yielded 132 variable AGN candidates. We then extended our method including the dataset of the ESSENCE project that has been active for 6 years, producing high quality light curves in the R and I bands. We obtained a sample of \( \sim 4800 \) variable sources, down to \( R=22 \), in the whole 12 deg\(^2\) ESSENCE field. Among them, a subsample of \( \sim 500 \) high priority AGN candidates was created using as secondary criterion the shape of the structure function. In a pilot spectroscopic run we have confirmed the AGN nature for nearly all of our candidates.

1. Introduction

Since the discovery of AGN, variability was established as a main property of the population and it was among the first ones to be explored (Smith et al. 1963). The luminosities of AGN have been observed to vary in the whole electromagnetic range and the majority of the objects are exhibiting continuum variations of about 20% on timescales of months to years (Hook et al. 1994). From a physical point of view, variations can set limits on the size of the central emitting region and the differences in the variability properties in the X-ray, optical and radio bands provide important information on the underlying structure. The mechanism of variability itself is still unknown and a variety of models have been proposed (Terlevich et al. 1992; Hawkins 1993; Kawaguchi et al. 1998). Thus,
the study of the AGN variability is very important and can put constraints on the models describing the AGN energy source and the AGN structure.

On the other hand, supernovae (SN) are very powerful cosmological probes and their systematic discovery outside the local Universe has led to major scientific results, like the confirmation that the Universe is accelerating (Riess et al. 1998; Perl et al. 1999). Such studies require well sampled light curves and large statistical samples which can be achieved by monitoring wide areas of the sky to very faint limiting magnitudes. This kind of surveys produce huge amounts of data that can be suitable also for other scientific studies. For example, given that the time sampling is adequate, data gathered during SN searches can be used to detect AGN through variability. One of the main purposes of this work is to explore this possibility and create suitable tools for the efficient selection of AGN in such databases. The two projects that have provided us with their data are: the Southern inTermediate Redshift ESO Supernova Search (STRESS, Botticella et al. 2008) and the ESSENCE (Equation of State: SupErNovae trace Cosmic Expansion) survey (Miknaitis et al. 2007).

2. AGN in the STRESS survey

The STRESS survey (Botticella et al. 2008) includes 16 fields with multi-band information. Each of those covers an area of 0.3deg² and has been monitored for 2 years with the ESO/MPI 2.2m telescope. For this study we choose to use the so-called AXAF field, which is centered at α=03:32:23.7, δ=-27:55:52 (J2000) and overlaps with various surveys, which provide us with further data, such as the COMBO-17 survey (Wolf et al. 2003) with measurements in 5 wide and 12 narrow filters, resulting in a low resolution spectrum, the ESO Imaging Survey (EIS, Arnouts et al. 2001), the GOODS survey (Giavalisco et al. 2004) and the two X-ray surveys, Chandra Deep Field South (CDFS, Giacconi et al. 2002) and the Extended-CDFS survey (ECDFS, Lehmer et al. 2005).

For our variability study of the AXAF field we have used 8 epochs obtained in the V band, during the period 1999-2001, thus covering 2 years. For each source, detected in at least 5 epochs, we have measured the average magnitude and its r.m.s. variation which is then compared with a 3σ threshold we have obtained averaging the r.m.s in bins of magnitude. Details on the calculation of the variability threshold can be found in Trevese et al. (2008). This procedure has yielded a catalogue of 132 AGN candidates down to V=24 mag.

Despite all the active surveys in our area, only 31% of our candidates have public spectroscopic information. For this reason we have performed a spectroscopic follow up using EMMI at the ESO/NTT (La Silla). We obtained low resolution spectra for 27 sources belonging to the bright part of our sample (V<21.3mag). We now have 55% of our candidates spectroscopically confirmed. The remaining objects are typically fainter than what we have been able to observe so far. Based on this dataset a complex picture emerges. Out of the 27 sources for which we have obtained spectra, 17 are Broad Line AGNs (BLAGNs), 1 is a normal galaxy, and a considerable amount (7) are Narrow Emission Line Galaxies (NELGs). The remaining two sources are stars. The spectra of all the sources we have observed with details about their properties are presented by Boutsia et al. (2009).
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Figure 1. Luminosity in the R band vs. luminosity in the hard (2-8keV) X-ray band (left panel). Large dots indicate BLAGNs, diamonds represent NELGs and squares are normal galaxies. The smaller symbols indicate non variable sources detected in the X-rays in our field. The objects with ID 94 and ID 125 indicate sources with X-ray measurements derived from the recent 2Ms survey [Luo et al. 2008]. The source with ID 26 is one of our sources with optical spectra typical of BLAGN but undetected by color and X-ray emission.

Redshift histogram of the AXAF variable candidates (right panel) that have been confirmed as BLAGN based on their optical spectra. The black line refers to all variable candidates with known redshift and the shaded section represents the part of the redshifts determined during our campaign.

Among the normal galaxies and the NELGs, which make up the low luminosity part of our candidates, we may distinguish two groups. A fraction of these sources (7/14) displays high variability and their colours ($U - B$ and $B - V$) as well as X-ray to optical ratio ($X/O$), are consistent with AGN (see Fig.1). The other 7 sources, are less variable, have lower $X/O$ ratios and their colours are dominated by the host galaxy. According to our analysis, these latter sources have properties consistent with Low Luminosity AGN (LLAGN), contaminated by the light of the host galaxy. All these sources have extended morphologies and would not have been detected by the color technique, that is limited to point like sources, nor by their X-ray emission since they are not detected in the hard X-ray band (2-8keV) despite the 1Ms exposure time for the CDFS. For the NELGs with the necessary lines detected to place them in the diagnostic diagram [Kewley et al. 2004], we find that they tend to lie in the locus of the composite sources.

Out of the 65 known BLAGNs in our field, 47 (72%) are found to display significant variability. The confirmed BLAGNs of our sample have an average $X/O$ of 0.55. This value is consistent with the $X/O$ of 0.31 obtained by Fiore et al. (2003) for optically selected samples, while the X-ray selected sources present a ratio of $X/O \sim 1.2$. This is a further indication that by using variability as a selection technique we probe a different part of the AGN population, favouring the identification of X-ray weak sources. This fact, in combination with the known correlation between variability amplitude and luminosity (in the sense
that AGN of lower luminosity show larger variability amplitudes) makes variability an ideal tool in selecting LLAGNs. Still 45% of our candidates remain without optical spectroscopy because of their faintness. In order to better understand the complex LLAGN population, spectroscopy to fainter flux limits is needed.

3. AGN in the ESSENCE survey

The ESSENCE survey (Miknaitis et al. 2007; Wood-Vasey et al. 2007) has been active for 6 years (2002-2007) and was carried out with the Blanco 4m telescope at the Cerro Tololo Inter-American Observatory (CTIO). The cadence of the observations was every other night, for 20 nights around New Moon, for 3 months per year in the R and I band. This resulted in very well sampled light curves for all sources in the 12deg\(^2\) field.

In order to test our variability method we have used only part of the available light curves that cover a 2 year period. As it was proven by our previous experience in the AXAF field, such timespan is a good compromise between selecting AGN and discriminating against supernova outbursts. In such a wide time-baseline with an average of 30 epochs per light curve, the variation caused by the SN is well limited in time and gets diluted, thus the source does not appear as variable. In fact less than 10 of our variable sources resulted to be known SN discovered by the survey.

The adopted strategy for the ESSENCE dataset is not exactly the same as in the AXAF field, mainly because we have used the light curves produced directly by the pipeline of the survey for the needs of the project. Here the variability threshold was linked to the noise of the data and not the intrinsic variability of the distribution. In order to minimize spurious detections, the sources had to show significant variability in both bands in order to be classified as candidates. Following this criterion we have created a list of \(\sim 4800\) variable objects down to a magnitude of 22 in the R band.

Since our light curves are composed by a large number of epochs (an average of 30 epochs in each light curve), we may also derive the structure function (SF) for each object. The Structure Function (SF) is a method of quantifying time variability and according to de Vries et al. (2005), it is defined as:

\[
S(\tau) = \left\{ \frac{1}{N(\tau)} \sum_{i<j} [m(t_i) - m(t_j)]^2 \right\}^{1/2}
\]

(1)

where, \(N(\tau)\) is the number of epochs for which \(t_i - t_j = \tau\) and the relative magnitude measurements are summed. We have defined subsamples of candidates, depending on the shape of their SF. A flat SF shows that the examined timelag is larger than the characteristic time of variability and should indicate sources that are not variable or the period of their variability is much shorter than the probed period. In the case of AGN, variability is known to increase with time and for the time baseline of the 2 years sampled by our light curves, it should result to an ascending SF. Thus, for our spectroscopic follow-up we have chosen candidates with ascending or generally non-flat SF. In Fig.2 we can see...
examples of light curves and SFs of sources that were subsequently confirmed as AGN by our follow-up.

Figure 2. Typical light curves in both R and I band (left panel) and binned structure functions in the R band (right panel) for two variable candidates that were confirmed as BL AGN after our spectroscopic follow-up. Notice the ascending shape of the SF for both sources although the shape of their light curves is not comparable.

Figure 3. Distribution of the variability measurement $\sigma_R$ versus the R band magnitude for all sources that we have observed during our spectroscopic follow-up. The large dots represent the confirmed AGN, the square represents the source which is a normal galaxy and the line shows the adopted variability threshold. The histogram shows the redshift range of the AGN that were observed in the spectroscopic follow-up of our sample.

During the same spectroscopic run with EMMI at NTT, we have obtained low resolution spectra for 58 sources that belong to the subsample with the ascending SF and their magnitudes range between 18.5 and 20.5 in the R band. 53 (91%) were confirmed as Broad Line AGN and we have a secure redshift determination. 3 sources show only one broad emission line and a power law
continuum, typical of AGN and although we can not claim an accurate redshift for these sources, we can still consider them as bona fide AGN. This brings our success rate to \( \sim 97\% \). The remaining sources show absorption features of which, one is being recognized as normal galaxy. In Fig.3 we show the position of the observed sources in the distribution of their variability versus their magnitude. The average redshift of the observed candidates is \( \langle z \rangle = 1.40 \). Details about the variability method and the comparison of our sample with other AGN samples existing in the same fields will be presented in Boutsia et al. (in preparation).

4. Conclusions

We have applied a variability selection method to data collected by SN searches in order to detect AGN through variability. We have been very successful in detecting new AGNs, which had escaped traditional selection techniques and have confirmed a large number of already known AGNs in these fields. This proves that the AGN field can benefit from such synergic AGN-SN surveys. After a spectroscopic follow-up, a considerable fraction of our variable candidates turned out to be “variable galaxies” with narrow emission lines and properties consistent with LLAGNs diluted by the host galaxy. By combining the criterion for variability with a secondary criterion concerning the shape of the SF, we created highly reliable AGN samples, since \( \sim 97\% \) of our candidates belonging to such a sample was confirmed as BLAGN. In an era that large survey telescopes are being developed, such variability studies can give valuable feedback both for determining the strategy of the observations as well as for the development of software and pipelines that will allow the scientific community to fully exploit the huge datasets that will be produced.

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