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Variable Galaxies Detected with the Hubble Space Telescope

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Abstract. Recent results from imaging surveys with the Hubble Space Telescope WFPC2 to detect and study the properties of active galaxies at z≃1 are presented. Of particular importance is the nature and evolution of low-luminosity AGN (i.e., Seyferts and LINERs), which become increasingly difficult to observe at high redshifts as the apparent brightness of the nuclear light becomes fainter and difficult to disentangle from the host galaxy light. Using multi-epoch images of field galaxies, we isolate and measure nuclear variability on timescales of 5 to 7 years. Issues concerning WFPC2 calibration with emphasis on charge transfer efficiency loss over time are discussed. The main science goal of this project is to determine the evolution of the AGN luminosity function, which has broad implications for our understanding of the physical mechanisms that power QSOs and Seyfert galaxies.

Key words. Galaxies: active – Galaxies: nuclei – Quasars: general

1. Introduction

One of the most important goals of modern cosmology today is to understand the evolution of active galaxies and their relationship to normal galaxy evolution. A key piece of information needed to further this understanding is an accurate knowledge of the luminosity function (LF) for AGN over a wide range of absolute magnitudes and redshifts. The AGN LF is populated by quasars at the brighter, primarily high redshift end and Seyfert galaxy nuclei, considered to be their intrinsically fainter counterparts, at the low luminosity, low redshift end (Cheng et al. 1985; Huchra & Burg 1992; Maiolino & Rieke 1995). While bright QSOs are easily observable at all redshifts, fainter Seyfert nuclei become increasingly difficult to detect at redshifts beyond the local universe.

Understanding how the faint end of the AGN LF evolves is of particular importance for determining the frequency and total space density of AGNs at earlier epochs. This has obvious implications for determining their total contribution to the X-ray, IR and UV backgrounds. Large numbers of low-luminosity AGN have been postulated to explain ionization of the intergalactic medium at high redshift (Steidel & Sargent 1989). In addition, the faint end is particularly important in constraining evolution models for the AGN LF such as pure lu-

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minosity and luminosity-dependent density evolution (e.g. Hartwick & Schade 1990).

In this study, we have searched for optical nuclear variability in distant (z$\simeq$1) galaxies to identify the population of active galaxies at these redshifts. We report preliminary results for two studies using Hubble Space Telescope WFPC2 images separated by 5 and 7 years. The advantage of HST over ground-based surveys for this work is the ability to do accurate photometry within smaller apertures than can be done from the ground thus allowing us to probe much lower AGN/host galaxy luminosity ratios.

The primary data sets analyzed for galactic variability are the original HDF-N (Williams et al. 1996) from December 1995 with 113,050s in F606W and a second V-band image of the HDF-N obtained in December of 2000 with 91,000s. We also present results from the Groth-Westphal Survey Strip (Groth et al. 1994), a 150 arcmin^2 strip of the sky observed originally in the V-band (F606W) in April of 1994 (2800s) and again in April of 2001 (4200s).

Indeed, it is possible to detect a large fraction of varying AGN with only 2 epochs of observations separated by several years. The structure function for QSOs shows significant luminosity variations on the order of a few tenths of a magnitude over timescales as short as 2 years (Trevese et al. 1994). Simulations using a sample of 42 PG QSOs with 7 years of photometric data sampled every few months (Giveon et al. 1999) have shown that 80% of these would be significantly detected above the photometric noise with only 2 observations separated by at least 3 years. Even though the fainter AGN targeted in our survey are located within host galaxies, we are still sensitive to variability amplitudes similar to those of "naked" QSOs. However, our photometric errors may be somewhat higher depending on the brightness and morphology of the underlying host galaxy (see Sarajedini, Gilliland & Phillips 2000).

2. Source Selection and Photometry

Objects were selected in both the HDF-N and Groth-Westphal Survey Strip (GSS) using DAOFIND in IRAF[1] on the deeper of the two epochs. The catalogs were edited to remove any selected sources that did not appear to be galaxy nuclei (i.e. multiple detections within single galaxies, saturated stars, etc.). If no clear nucleus could be determined because of the amorphous nature of the galaxy, all bright "knots" appearing in the galaxy were retained in the catalogs. Aperture photometry was performed using PHOT in IRAF. Small apertures consistent with the FWHM of stellar sources in the images were used. In the over-sampled, dithered HDF-N WFC images (0.025$''$/pixel), the FWHM for an unresolved source is 5.5 pixels corresponding to $\sim$0.14 arcsec. We therefore chose an aperture size for the photometry of 6 pixels in diameter. For the GSS standard WFC images (0.1$''$/pixel), an aperture size of 3 pixels was adopted.

In the 3 WF CCDs of the HDF-N, we performed aperture photometry for 990 objects. For the GSS, only 17 of the total 28 WFPC2 fields were available with 2 epochs at the time of this presentation. Photometry was performed on all sources detected in the WF CCDs for these 17 fields totaling 5936 objects.

3. Charge Transfer Efficiency Losses

To determine photometric differences across the 2 epochs for the HDF-N and GSS, it is necessary to correct for the charge transfer efficiency losses that plague the HST CCDs. As in Sarajedini, Gilliland & Phillips (2000), a 2-year variability survey in the I-band for the HDF-N, we find a clear correlation of the photometric dif-

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of University for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

ferences with Y-position on the CCD and magnitude. This is the well known CTE effect (Whitmore et al. 1999; Biretta et al. 2001), which varies as a function of object position on the CCD, magnitude and time. The positional dependence is most significant in the Y-direction, but some correlation was found in the X-direction for several of the HDF-N and GSS WFCs. We typically found an ∼8% change in the magnitude differences over the entire CCD in the Y-direction. Because of the large number of non-varying sources in each field (∼330 for each HDF-N WFC and ∼115 for each GSS WFC), we were able to fit and remove the CTE dependencies on position and magnitude for each WFC independently.

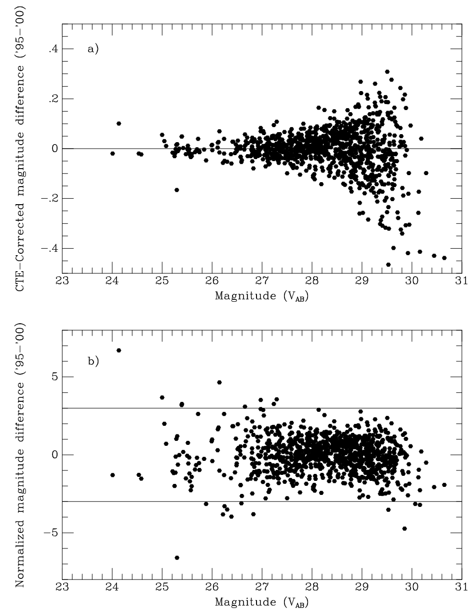

Fig. 1. a) The magnitude difference for galaxies in the HDF-N vs. nuclear magnitude over 5 years. b) The magnitude difference normalized by the photometric error as a function of nuclear magnitude. Solid lines represent the 3σ significance level for variability.

4. Variable Galaxies in the HDF-N

Figure 1a shows the CTE corrected magnitude differences for objects in the HDF-N as a function of nuclear magnitude. Some clear outliers are already visible in this figure. However, to select the significantly varying sources, we needed to determine the expected photometric noise level for objects which are not varying. To do this we divided the full set of individual exposures into two sets composed simply of the odd-numbered frames and the even-numbered frames. Each set represents an "epoch" without any real time difference. These images effectively carry through the effects of object and sky Poisson noise, readout noise, and possible errors in the adopted sky zero points. The magnitude of each galaxy was then measured in the odd and even datasets and the difference in magnitude vs. the average nuclear magnitude reveals the expected photometric error as a function of magnitude.

We determine the RMS scatter in magnitude bins for this "null" experiment and use this to normalize the photometric differences for each source shown in Figure 1a. The result is seen in Figure 1b, where the solid lines represent the 3σ variability significance threshold. The vast majority of objects lie within these solid lines as would be expected in a normal distribution. A greater number of significant variables appear to be detected at brighter nuclear magnitudes (V≤27). This may be a result of uncertainties in the selected photometric accuracy at the bright end of the distribution which was difficult to model with the null experiment. In Figure 1b we have adopted a reasonable photometric accuracy of 1.5% at the bright end of the distribution. A more thorough discussion of the selection of the variable sources based on the selected photometric accuracy will be presented in a future paper.

There are 17 objects which fall outside of the 3σ threshold in Figure 1b. This represents ∼2% of the 895 galaxies above V=29.5 in the HDF-N. A detailed discussion of each source is presented in Sarajedini et al. (2003). To summarize, the 17 galaxies represent a wide range in morphologies and magnitudes. There are published redshifts available for 14 of the 17 objects. The closest variable galaxy lies at z=0.09 and the most distant has a redshift of 2.6, but the vast majority lie in the range 0.4≥z≥1.2.

If these varying galaxies are AGN, we might expect to see evidence of this in the spectra. Only two sources have been reported in the literature as having broad emission lines in the HDF-N (Cohen 2000). One of these is our second most varying galaxy. Broad lines are not reported as having been detected in any of the other 13 variable galaxies for which redshifts are found in the literature. We cannot rule out the possibility, however, that some may be narrow-line AGN (i.e. Seyfert 2s or LINERs). Further investigations into the spectroscopic signature of these galaxies will be presented in a future paper.

Perhaps most interesting is the overlap of our sample with several Chandra X-ray sources. AGN have long been recognized as strong X-ray emitters, being associated with a wide range of activity levels from the brightest quasars to low-luminosity Seyferts. The 1Ms Chandra exposure of the HDF-N has revealed 13[2] faint X-ray sources (Hornschemeier et al. 2000; Hornschemeier et al. 2001; Brandt et al. 2001a; Brandt et al. 2001b). We find that six of our variable galaxies match the positions of X-ray sources, representing 46% of the X-ray survey objects and 35% of the variable sources in our survey. The X-ray emission detected for this subsample of variable galaxies is supporting evidence for the likely AGN nature of these sources. Additionally, four of these 6 are also detected in the 1.4GHz radio survey of Richards (2000).

We have also compared our sample to the mid-IR survey of the HDF-N by Aussel et al. (1999) in the 6.5 and 15 micron bands. A significant number of AGN are found to be bright in the mid-IR (Hornschemeier et al. 2001; Alexander et al. 2002). Highly absorbed AGN, such as Seyfert 2s viewed through a dusty torus, are expected to reprocess much of their near-IR through soft X-ray light into the mid-IR bands. We find that eight of the variable galaxies detected here overlap with ISOCAM mid-IR sources and four of these were *not* detected in the Chandra X-ray survey. These eight represent 47% of our variable galaxies and 25% of all of the ISOCAM sources in the HDF-N.

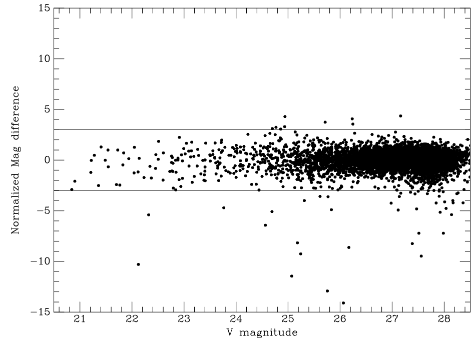

Fig. 2. The magnitude difference for galaxies in the GSS normalized by the photometric error as a function of nuclear magnitude. Solid lines represent the 3σ significance level for variability.

5. Variable Galaxies in the Groth-Westphal Survey Strip

A very similar approach to that described for the HDF-N for detecting nuclear variability has been adopted for the GSS. Charge transfer efficiency effects were determined and corrected for each WFC in each of the 17 GSS fields for which 2 epochs of data were available. A characterization of the photometric error as a function of magnitude was also determined and applied to the data. The results for the 5936 galaxies in the GSS data analyzed to date are shown in Figure 2, which is similar to Figure 1b for the HDF-N.

¿From these preliminary results, we find that ∼2% of galaxies above V=26.5 display

[2] A 14th source is detected but lies too close to the edge of one of the HDF-N CCDs to do nuclear photometry in both epochs.

nuclear variability over the 7 year period with greater than 3σ significance. As in the HDF-N, we find that these galaxies represent a variety of morphologies and luminosities.

We are currently carrying out a spectroscopic survey of the GSS as part of the DEEP (Koo et al. 1996) collaboration. Several hundred galaxy spectra obtained at the 10-meter Keck telescope are currently in hand and being analyzed to identify AGN through their spectroscopic signatures (see Sarajedini et al. 2002). Two objects in the present variability sample have revealed broad emission lines indicative of QSOs/Seyfert 1 galaxies, both of which appear as significant variables in our survey.

We also find some overlap between our variable galaxies and X-ray sources in the field. A recent deep XMM survey of a portion of the GSS (Miyaji et al. 2002) has revealed several X-ray sources. Of the 7 in the GSS overlapping the variability survey, two have been detected as significant variables.

6. Conclusions

We present results from two recent surveys to isolate and measure nuclear variability in z$\simeq$1 galaxies to identify AGN candidates. Nuclear photometry was performed for 990 galaxies in the HDF-N separated by 5 years and 5936 galaxies in the GSS separated by 7 years. We find that approximately 2% of the galaxies above V=29.5 in the HDF-N and V=26.5 in the GSS appear to have significantly variable nuclei.

There is supporting evidence for the AGN nature of many of these sources based on correlations with X-ray, radio, mid-IR and optical spectroscopic surveys. In the HDF-N, 35% of the variable galaxies are also X-ray sources and 47% are associated with sources detected in the mid-IR. In the GSS, we find that 29% of those covered by the recent XMM survey are detected in the X-ray band and all of the broad-line AGNs are detected as variable. Further analysis of these results and discussions concerning the nature of the sources are being prepared for future publication.

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