

# HIGH RESOLUTION X-RAY IMAGING OBSERVATIONS OF TWO LOW LUMINOSITY SEYFERT GALAXIES

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## ABSTRACT

Results from observations of two *nearby, low X-ray luminosity* Seyfert-type galaxies, namely, NGC 1365, and NGC 4051, using the *ROSAT* High Resolution Imager (HRI) are presented. The observations carried out with the aim of detecting and resolving the extra-nuclear (beyond the central  $5''$ – $10''$ ) X-ray emission show evidence for an extended component of  $\simeq 2$  kpc size in NGC 1365 and NGC 4051. The extended component contains  $56 \pm 8\%$  of the total observed flux in the case of NGC 1365, and  $21\% \pm 6\%$  in the case of NGC 4051. In NGC 1365, the extended X-ray emission shows a component aligned with the inner disk structure, another as wings or ears along the east and west direction aligned with the inner spiral arms, and an elongated edge-brightened structure (“chimney”) breaking out of the disk in the north-west direction. The extended soft X-ray component around the nucleus of NGC 4051 is co-spatial with the disk of the galaxy. It also shows an elongation coincident with a “banana”-like feature in the north-east seen in the 6 cm radio band. Extensions are also seen towards the south and south-east of the nucleus. Starburst activity driving strong winds through the disk of NGC 1365 can account for most of the extended soft X-ray emission in it. In the case of NGC 4051, extended X-ray emission probably owes its origin to both nuclear activity as well as starburst induced activity.

The nuclear component of NGC 4051 shows strong soft X-ray variability with X-ray intensity changing by a factor of 2–3 on a time-scale of a few 100s. The power-spectrum of the variability has been extended to higher frequencies compared to the previous observations, and has now reached the true Poissonian noise level due to the source. At lower frequencies the power spectrum is best characterised by a power-law and a Gaussian. The power-law slope of  $\simeq -1.8$  is consistent with the previous low-energy observations with *EXOSAT*, and the presence of a Gaussian feature signifies the persistence of a quasi-periodic oscillation that was also seen earlier with *EXOSAT*.

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During its low intensity and low variability state, however, the extended component of soft X-ray emission dominates the flux in NGC 4051.

A list of X-ray sources, some of which are new, detected in the field of view of the HRI during the observations, is also presented.

*Subject headings:* galaxies:active – galaxies:nuclei – Seyferts individual (NGC 1365, NGC 4051) – X-rays: galaxies

## 1. INTRODUCTION

X-ray emission from active galaxies is generally dominated by luminous unresolved nuclear sources. In other bands, like radio continuum and optical line emission from ionised gas, extended emission is seen around the nuclei of Seyfert-type galaxies. These extra-nuclear emissions, as distinct from the emission from the disks of galaxies, are quite often anisotropic or collimated in nature suggesting an outflow of gas from the nucleus in the form of jets or starburst-driven superwinds. Since these processes can also lead to X-ray emission, spatially extended circum-nuclear X-ray emission may also be quite common in these galaxies. Observationally, its occurrence in several Seyfert galaxies with good high resolution observations has been pointed out by Elvis et al. (1990) and Wilson (1994), and confirmed in five Seyferts viz., NGC 1068, NGC 1566, NGC 2110, NGC 2992 and NGC 4151 (see Weaver et al. 1995). The extent of the circum-nuclear X-ray emission in these Seyfert ranges from  $\sim 7''$  to  $\sim 30''$ , going up to  $90''$  in NGC 1068 which includes the starburst regions (Wilson et al. 1992). The intensity of the extended circum-nuclear component amounts to  $\sim 10\% - 30\%$  of the total soft X-ray flux in these objects.

In principle, the extended X-ray emission could arise due to a number of reasons. For example, thermal emission from hot interstellar gas, emission from starburst regions, synchrotron radiation or inverse Compton scattering by relativistic electrons, and electron-scattered nuclear radiation all could lead to such an emission. It is, however, believed that the inner extended ( $\sim 10''$ ) X-ray emission is most probably related to the active nucleus because of its abnormal brightness, whereas the emission on the arcmin scale could be due to starburst regions with a large number of binaries and supernova remnants (Elvis et al. 1990; Wilson et al. 1992). Another favoured explanation for the extra-nuclear com-

ponent is thermal emission from hot gas in pressure equilibrium with the optical narrow-line gas, although other possibilities cannot be ruled out at present.

*ROSAT* with its low-scatter mirror and High Resolution Imager (HRI), has the unique capability to resolve extended X-ray components beyond the central  $5''$  of the point-like nucleus of an active galaxy (also known as the active galactic nucleus or AGN) as has been demonstrated in some of the cases mentioned above. Furthermore, the weak extra-nuclear emission is best resolved in nearby and low-luminosity AGN's, where the nuclear component is less dominant and is further suppressed by high absorption intrinsic to the nuclear region of these objects, thus reducing the contribution from the point spread function (PSF) to the extra-nuclear regions. With this consideration in mind I have observed two *low luminosity, nearby (distance  $\leq 20$  Mpc) and hard X-ray selected* Seyfert galaxies, viz., NGC 1365 and NGC 4051 with the *ROSAT* HRI. The Galactic column density due to the interstellar medium towards them is very low, which is also an important consideration while looking for an extended X-ray component.

X-ray variability is another characteristic of an AGN that holds clues to the physics of the central regions. *ROSAT* with its high sensitivity in soft X-rays can probe variations at much smaller time scales than before. Of the two galaxies targeted for observations, NGC 4051 is known to be highly variable on all time scales observed so far. Extending the study of its variability to short time-scales could be very useful, as is indeed found in the present observations.

In this paper, I report *ROSAT* HRI observations of NGC 1365 and NGC 4051 and their spatial and timing analysis. The paper is organized as follows. In §2, I review a few of the basic parameters of the target galaxies, followed by observational details in §3. In §4, I present the results from a detailed spatial analysis of the X-ray images (corrected for the instrumental wobble),

their comparison with other wavebands, and a temporal analysis of short term variability seen in NGC 4051. The results are discussed in §5, followed by conclusions in §6.

## 2. The Sample

Some of the basic parameters of the two Seyfert galaxies are listed in Table 1. These include their distance, B magnitude, hard X-ray luminosity in the 2 - 10 keV band, the  $N_{\text{H}}$  from 21 cm measurements (Elvis, Lockman & Wilkes 1989; Dickey & Lockman 1990), soft X-ray extent, soft X-ray flux and luminosity in the 0.2 - 2.0 keV band from the present observations. Other important characteristics of these galaxies are given below.

### 2.1. NGC 1365

NGC 1365 is a luminous, dusty, barred spiral galaxy belonging to the Fornax cluster of galaxies. It has been classified as type SBb(s)I (Sandage & Tammann 1981). Measurements of 37 Cepheids in NGC 1365 by Madore et al. (1998) give a distance of  $18.6 \pm 1.9$  Mpc. It has large extinction and several bright  $H\alpha$  spots near its nuclear region. The optical spectrum of its nucleus shows both broad and narrow  $H\alpha$  emission and forbidden narrow-line emission, and therefore, it can be called a Narrow Emission Line Galaxy (NELG) (Veron et al. 1980) or a Seyfert type 1.5, although Veron & Veron (1989) (VV89) list it as a type 1 Seyfert. It shows a small radio jet and a circum-nuclear ring with a number of non-thermal continuum radio sources in it (Sandqvist et al. 1995). A conical outflow of high excitation gas, seen in [O III], has been found aligned with the small radio jet (Kristen et al. 1997). The Galactic  $N_{\text{H}}$  towards this galaxy is  $1.35 \times 10^{20} \text{ cm}^{-2}$  (Dickey & Lockman 1990). In soft and hard X-rays, it is an order of magnitude less luminous than most type 1 Seyferts. NGC 1365 was perhaps the first Seyfert for which an extended soft X-ray emission was suspected (Maccacaro et al. 1982). The X-ray

spectrum of NGC 1365 has been found to contain a hard power-law component and a soft thermal component based on *ROSAT* observations by Turner, Urry, & Mushotzky (1993) and Komossa & Schulz (1998), and *ASCA* observations by Iyomoto et al. (1997). A strong line emission component due to iron is also detected in the *ASCA* observations by Iyomoto et al. An analysis of the *ROSAT* HRI observations of NGC 1365 has been presented by Komossa & Schulz (1998) in which they pointed out the detection of a bright variable source southwest of NGC 1365.

### 2.2. NGC 4051

NGC 4051 is an early type spiral, SB (Paturel et al. 1989). It has an optically bright and active nucleus that shows both broad and narrow permitted line emission and forbidden narrow-line emission. It has been classified as Seyfert type 1.5 by Dahari & De Robertis (1988). The Galactic  $N_{\text{H}}$  towards this galaxy is  $1.3 \times 10^{20} \text{ cm}^{-2}$  (Elvis et al. 1989). Among the nearest (distance = 13.8 Mpc) Seyfert galaxies, it has the lowest X-ray luminosity of all the galaxies of this type. A triangular region of ionised gas seen in [O III] line emission has been detected out to a distance of  $\sim 400$  pc from its centre by Christopoulou et al. (1997). Anisotropic radio emission from this galaxy has been studied by Baum et al. (1993) and Kukula et al. (1995). Three components of radio emission – nuclear, extra-nuclear, and galactic disk have been seen in radio maps of different resolutions in 6cm and 21cm continuum bands (Baum et al. 1993). The [O III] line emission region is co-spatial with the extended radio emission (Christopoulou et al. 1997).

It is a highly variable X-ray source (see Papadakis & Lawrence 1995), and its spectrum has been measured with many instruments – *HEAO-1* (Marshall et al. 1983), *EXOSAT* (Turner & Pounds 1989), *Ginga* (Matsuoka et al. 1990; Nandra & Pounds 1994), *ROSAT* (McHardy et al. 1995; Komossa & Fink 1997), simultaneous *ROSAT* and *Ginga* (Pounds et al. 1994), and

*ASCA* (Mihara et al 1994). Its broad-band X-ray spectrum can be described by a power-law with photon index in the range of 1.6 to 2.3, and modified by the presence of a warm absorber (Pounds et al. 1994; Mihara et al. 1994). The steepness of the power-law is usually positively correlated with the brightness of the X-ray source (Matsuoka et al. 1990). A steeper low energy (<1 keV) spectral component (“soft excess”) due to a black-body or hot thermal gas at a few million degrees K has also been seen in many observations (Pounds et al. 1994; Mihara et al. 1994). The soft excess is, however, usually seen in X-ray high states analysed by Pounds et al. (1994) and Mihara et al. (1994) but not in X-ray low states analysed by McHardy et al. (1995) and Komossa & Fink (1997). However, in a very low X-ray state observation, a steep low energy component with photon index of  $3.0_{-0.3}^{+0.2}$  has been reported by Guianazzi et al. (1998). During this very low state, both the hard X-ray power-law component as well as the soft component were significantly lower than in the previously reported observations.

### 3. OBSERVATIONS

*ROSAT* HRI (Truemper 1983, Pfeffermann et al. 1987) observations of NGC 1365 and NGC 4051 were proposed by me for a total of 20,000s and 10,000s, respectively. These exposure times were realised in observations carried out in 1994 and 1995. NGC 4051 was observed in 1994, whereas the observations of NGC 1365 were split-up over the two years and many satellite orbits. Further details of these observations are given in Table 2. In the case of NGC 1365, data from only two of the longest observations were used for further analysis below. The known positions of the centres of the galaxies were targeted at the on-axis positions of the HRI, and X-ray peaks were detected within 2'' of these positions.

Data were recorded over several satellite orbital intervals (OBIs). X-ray images were made

using data from all the OBIs in the case of NGC 4051, and most of the OBIs in the case of NGC 1365, after correcting for the residual errors from aspect corrections and due to wobble of the satellite. Details of the analysis and results are given in the following section.

## 4. ANALYSIS AND RESULTS

### 4.1. Count Rate and X-ray Flux Measurements

The total counts for the targeted sources were extracted from the X-ray images using a circle of radius 22'' for NGC 1365 and 30'' for NGC 4051, centred on the source. Background counts were obtained from an annulus 50'' wide outside a radius of 80'' from the source centre, and subtracted from the total source counts after scaling the background to the same number of pixels as in the source. The mean count rates thus derived for sources centred on the nuclei of NGC 1365 and NGC 4051 are listed in Table 2.

The conversion of the observed count rate to the X-ray flux requires the knowledge of the X-ray spectrum and the characteristics of the telescope and detector. For NGC 1365, spectral measurements have been provided by Turner et al. 1993 using the *ROSAT* Position Sensitive Proportional Counter (PSPC), and by Iyomoto et al (1997) using the *ASCA* Solid-State Imaging Spectrometer (SIS). The *ROSAT* PSPC measurements over the 0.1–2.0 keV energy range suggest the presence of a power-law with energy index ( $\alpha$ ) of 1.22 and a thermal component (Raymond-Smith plasma model) with  $kT=0.55$  keV (Turner et al. 1993) with the two components being equally strong at 1 keV (ratio of about 1:0.90). Using this spectral model and the *ROSAT* HRI characteristics I estimated the X-ray flux in the *ROSAT* HRI band of 0.1–2.0 keV using the ‘hxflux’ program in the PROS software package. The absorption in the line of sight to the source was kept fixed at the 21-cm value of  $1.35 \times 10^{20} \text{ cm}^{-2}$  and the abundances used were

as given by Morrison & McCammon (1983). The unabsorbed X-ray flux from NGC 1365 thus obtained is  $1.08 \times 10^{-12}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$ , with the corresponding X-ray luminosity being  $4.5 \times 10^{40}$  ergs  $\text{s}^{-1}$ . These values are given in Table 1. (A similar result is obtained by using the spectral model of Komossa & Schulz (1998).) The *ASCA* SIS measurements over the 0.6–7.0 keV band also suggest the presence of both a power-law and a thermal component, as well as a strong line emission due to iron (Iyomoto et al. 1997). The energy index of the power-law in these measurements is, however, very flat (-0.2), and the temperature of the Raymond-Smith plasma model is 0.85 keV with the abundance being only 20% of the solar value. Use of this spectral model for the present *ROSAT* HRI observations gives a flux that is  $\sim 24\%$  less than the value given above in the 0.1–2.0 keV energy range.

There have been many spectral measurements of the highly variable X-ray source in NGC 4051 as mentioned in §2.2. The spectral parameters can vary quite rapidly in response to the intensity variations, making the task of converting total HRI count rate to flux rather difficult. Presently, it is not clear what spectral parameters can be attributed to the extended soft X-ray component in NGC 4051. However, for the purpose of estimating the flux associated with such a component, I assume that the total soft X-ray flux can be characterised as a power-law with  $\alpha$  assumed to lie in the range of 0.6 to 2.0, as indicated by the various measurements. The absorption in the line of sight to the source was kept fixed at the 21-cm value of  $1.3 \times 10^{20}$   $\text{cm}^{-2}$  with the elemental abundances as given by Morrison & McCammon (1983). The total count rate corresponds to the observed (absorbed) flux of  $\simeq 3.20 \times 10^{-11}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$  for  $\alpha = 0.6$ – $1.0$  in the 0.1–2.0 keV energy range. For  $\alpha = 1.5, 2.0$  the corresponding flux values are 3.0,  $2.8 \times 10^{-11}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$ , respectively. The unabsorbed source flux in the same energy is, however, very susceptible to the value of  $\alpha$ ; the total flux values being 4.3, 4.75,

5.74 or  $7.2 \times 10^{-11}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$  corresponding to  $\alpha=0.6, 1.0, 1.5,$  or  $2.0$  respectively. Adopting a value of 1 for  $\alpha$ , the X-ray luminosity of the source is  $1.08 \times 10^{42}$  ergs  $\text{s}^{-1}$ .

#### 4.2. Other X-ray Sources in the Field of View

X-ray emission was also detected from several new objects. These sources are listed in Table 3. These sources were found using the source detection programs in the XIMAGE and PROS software packages. Only sources  $\geq 3\sigma$  above background noise are shown, along with the count rates determined from a box size of  $8'' \times 8''$  around the source. Background was determined from a box size of  $32'' \times 32''$ , but excluding the central source box and has been subtracted from the count rates shown in Table 3. Many of these sources are variable. Even though the exposure times in 1994 and 1995 were almost equal, some of these were detected either in 1994 or in 1995, but not in both years, and therefore termed as transients. This information is provided against each source in Table 3.

In a previous study based on PSPC observations in 1991-92, Turner et al. (1993) had detected a number of sources in the field surrounding NGC 1365. Two of those sources have been detected in the present observations, and one of them has been resolved into two separate sources (source numbers 1,2,3 in Table 3). Sources 5 and 6 are coincident with a strong source detected with the Einstein Observatory. Source number 7 is coincident with a clusters of galaxies. Because of the better position determination in the present observations compared to that given in Turner et al. (1993), I have looked for the optical counterparts of these sources using the Digitised Sky Survey data and the USNO catalogue provided on-line by ESO via Skycat. Based on this, I provide the information about the possible optical counterparts of these sources in Table 3.

### 4.3. Resolving the Spatial Components

The knowledge of the pointing position of the telescope as a function of time is required to be known to a very high accuracy ( $< 4''$ ) to be able to fully exploit the intrinsic spatial resolution ( $4'' - 5''$  FWHM) of the *ROSAT* HRI for detecting extended X-ray emission within  $10'' - 20''$  of bright, unresolved point sources (David et al. 1993). The errors in determining the pointing position (aspect errors) can arise from either the *ROSAT* wobble (introduced to protect the HRI and reduce shadows due to mechanical structures) or errors in the re-acquisition of the guide stars. Aspect errors can lead to artificial elongated structures around point sources or blurring on the scale of  $10''$  (David et al. 1993). Corrections for these errors have been provided by the analysis of Morse (1994). Recently, Harris et al. (1998) have provided a set of scripts under the IRAF/PROS package to minimise these effects. These routines correct the aspect for a) residual errors induced by the wobble of the satellite, and b) errors due to re-acquisition of the guide stars at the start of each OBI in a multi-OBI observations. Errors due to wobbling are corrected for by dividing the data in different phase bins of the wobble period of 402s. Harris et al. (1998) give examples showing the improvement in the HRI images after applying the above corrections to aspect, which can vary from observation to observation.

Observations of NGC 4051 were done in 2 OBIs, whereas the observations of NGC 1365 in 6 OBIs in 1994 and 5 OBIs in 1995. The effect of aspect errors could be seen easily in the case of the strong source in NGC 4051 resulting in displaced images in different OBIs. I have used the routines provided by Harris et al. (1998) to find the aspect solutions, and restacked the images for each OBI to produce the corrected image for each source using all available data. In the case of NGC 4051, I was able to divide the data in 10 phase bins for finding the centroid of the image for each phase bin of the wobble period in

an OBI while using an aperture factor of just 3 times the  $\sigma$  of the PSF of the HRI for accepting the source photons, and then restacking the images at a position closest to the optical position of the source. The centroids of the images in different phase bins were found to wander around by as much as  $11''$  in the y-axis (declination) and  $\simeq 3''$  in the x-axis. The entire data were used and corrected for errors due to wobble as well as due to the re-acquisition of the guide stars. The resulting X-ray image of NGC 4051 is shown in Figure 1(a) after using Gaussian smoothing with  $\sigma=2''$ , and in Figure 1(b) after using Gaussian smoothing with  $\sigma=5''$  to show both the small scale and larger scale structures in X-ray emission. The *uncorrected* image, after using Gaussian smoothing with  $\sigma=2''$ , is shown in Figure 1(c) for comparison with Fig. 1(a). An elongation of the inner contours (radius  $\leq 10''$ ) along the south easterly direction can be seen in Fig 1(c), and is mostly due to the aspect errors in the data. The peak brightness is  $\sim 12\%$  lower than that in Fig. 1(a). These images (Figs. 1(a),(b),(c)) of surface brightness have been shown as contour plots with contours plotted at 0.1, 0.15, 0.2, 0.3, 0.5, 1, 2, 5, 10, 20, 30, 50, 70, 90 and 95% of the peak brightness level. The mean background level in Fig.1(a) is  $\sim 0.015 \pm 0.003$  counts/pixel and that in Fig.1(b) is  $\sim 0.005 \pm 0.001$  counts/pixel. The lowest contour plotted in the figures 1(a) and 1(b) is of  $\geq 2\sigma$  significance above background. A number of anisotropically extended components can be seen in these contour maps towards the north-east, south and south-west of the nucleus.

In the case of the much weaker source in NGC 1365, the aperture factor had to be increased to  $10\sigma$ . Besides, the 1995 data were not divided into any phase bins and the different OBIs were corrected for errors associated with the re-acquisition of guide stars only. The 1994 data of NGC 1365 did, however, require division of the data into 2 phase bins to get rid of the residual wobble effects as well as errors due to the re-acquisition of guide stars. This resulted

in some loss of data, and the effective exposure time for the 1994 data used for analysis was thus reduced to 5904.4s. The resulting images from 1994 and 1995 data were then added to produce the final X-ray images of NGC 1365 shown in Figures 2(a) and 2(b). As in Figures 1(a) & (b), Gaussian smoothing with  $\sigma=2''$  has been used in Fig. 2(a) and with  $\sigma=5''$  in Fig. 2(b). The effective exposure time for the images shown in Figs. 2(a) and 2(b) is 15666.4s. Contours are shown plotted at 5, 8, 12, 20, 30, 50, 70, 90 and 95% of the peak brightness level in Fig 2(a), and 4, 6, 10, 20, 30, 50, 70, 90 and 95% of the peak brightness level in Fig 2(b). The mean background level in Fig.2(a) is  $\sim 0.008\pm 0.007$  counts/pixel and that in Fig.2(b) is  $\sim 0.005\pm 0.002$  counts/pixel. The lowest contour plotted in the figures 2(a) and 2(b) is of  $\simeq 2\sigma$  significance above background. Several anisotropically extended components can be seen around the central amorphously extended emission, particularly in the east-west directions.

The azimuthally averaged radial brightness distributions of the X-ray sources in the galaxies were extracted from the corrected images and are shown in Figures 3 and 4, respectively for NGC 1365 and NGC 4051. The azimuthally averaged point source radial profile given by David et al. (1993) was computed and scaled to match the inner region ( $\leq 5''$ ) of each X-ray source, and is shown as a solid curve in Figs. 3 and 4. Excess X-ray emission is seen clearly in the two sources at extents between  $6''$  and  $20''$ . A circularly symmetric point spread function (PSF) image was also created using the azimuthally averaged point source radial profile given by David et al. (1993). The excess due to the extended emission component was determined by binning the source and the scaled PSF images radially over identical regions and then subtracting the contributions from the PSF. The extended emission component found thus in the case of NGC 4051 is  $0.229\pm 0.014$  counts  $s^{-1}$ , amounting to  $21\%\pm 6\%$  of the total observed count rate and extending

to a radius of  $\simeq 30''$ . About 68% of this extended component is in the radial bins from  $6''$  to  $20''$ . In the case of NGC 1365, the excess over the PSF or the extended component was determined similarly from the re-stacked images from 1994 and 1995 observations. The total average count rate for the source was found to be  $0.022\pm 0.0013$  counts  $s^{-1}$ , of which  $0.0126\pm 0.0007$  counts  $s^{-1}$  were due to the extended component in the region encompassed by radii of  $6''$  to  $22''$  centred on the source. This amounts to  $56\pm 8\%$  of the total observed X-ray count rate (not corrected for absorption) being in the circum-nuclear component of NGC 1365.

#### 4.4. Comparison with Optical and Radio Emission

Anisotropic emission from circum-nuclear regions of these galaxies has also been seen at other wavebands, e.g., radio continuum and [O III]  $5007\text{\AA}$  line emission. A comparison of these extended emissions in various wavebands is presented below.

##### 4.4.1. Extended Components in NGC 1365

High quality optical images of NGC 1365 in the B-band and [O III] have been published by Kristen et al. (1997) (see their Figs. 1 and 2(b)) and were obtained from them. Using positions of stars (or star-like objects) in the field from Sky-cat program, I created the co-ordinate reference system for their B-band image and overlaid the X-ray contours from Fig. 2(a) on the B-band image after resampling the X-ray image. This overlay is shown in Figure 5. The same co-ordinate system was also used for the [O III] line image and a similar comparison was carried out.

From Fig. 5 one can see that the extended X-ray emission shows the following different features – (a) a component aligned with the inner disk structure along the north-east to the south-west directions, (b) wings or ears along the east and west direction aligned with the inner spiral arm structures, and (c) an elongated



structure (chimney) in the north-west direction that appears to protrude through the disk of the galaxy. This structure shows an edge brightening towards its northern end, and is aligned with a channel through the disk as seen in the blue colour image in that direction. No X-ray features seem to be related to the [O III] conical feature or the small radio jet reported in the literature. The component (a) above is also aligned with the circum-nuclear elliptical ring seen in the radio continuum by Sandqvist et al. (1995), and is of similar extent ( $\sim 45''$ ). The radio ring has a channel of low intensity, just like in the optical, along the component (c) in X-rays.

#### 4.4.2. *Extended Components in NGC 4051*

Good quality images of NGC 4051 in the continuum of V-band and pure [O III] line emission published by Christophoulou et al. (1997) (see their Fig. 1) were obtained from them. Because of the lack of any stars in the field, the optical images were re-scaled, shifted, and trimmed to align the nuclear region with the X-ray image as well as possible. A residual mis-alignment of  $\sim 2''$  could have remained, however. An overlay of the X-ray contours from Fig. 1(a) on the V-band image of is shown in Figure 6. We have also created an X-ray image of the anisotropic X-ray component by subtracting a model image of the point spread function scaled to the central (inner to  $4''$ ) intensity of NGC 4051. X-ray intensity contours from this image have also been overlaid on the V-band image and this is shown in Figure 7. Similarly, an overlay of the X-ray contours from Fig. 1(a) on [O III] line emission regions is shown in Figure 8.

The extended component of X-ray emission (Figs. 6 & 7) appears to be associated with the disk of the galaxy and coincident with it. X-ray emission also shows an elongation along the banana-like feature in the north-east seen in the 6 cm radio band (Baum et al. 1993; Kukula et al. 1995) which is also aligned with the [O III] emission cone (Fig. 8). Extended X-ray com-

ponents are also seen (a) towards the south-east of the nucleus, and (b) towards the south. The component towards the south appears stronger in the high resolution X-ray maps (Figs. 1(a) & 6), whereas the component towards the south-east is stronger in the low resolution X-ray map of Fig 1(b).

#### 4.5. **Variability and Power Spectrum of NGC 4051**

X-ray source counts from a region (radius =  $1'$ ) centred on the source peak were extracted and examined for source variability. An X-ray intensity curve was derived after binning the data every 32 s, and is shown in Figure 9 as a function of time. The source strength varies from  $\sim 0.5$  counts  $s^{-1}$  to about 1.8 counts  $s^{-1}$ , with the average intensity being around 1 count  $s^{-1}$ . The time-scale for this variation seems to be as small as 200s, and is significantly smaller than the previous time-scales observed with the less sensitive low energy experiment aboard *EXOSAT*. The observed source intensity in soft X-rays indicates that the source was in a high state during these observations in 1994. To estimate the power spectrum of this light curve, I created two light curves: (a) using data binned every 16s, and (b) using data binned every 32s. We used the 'powerspec' program in FTOOLS to estimate the fractional power as a function of frequency. The power spectra were estimated for 128 bins per interval for both light curves, and then averaged. The averaged power spectra thus obtained are plotted in units of  $(\text{rms})^2 \text{ Hz}^{-1}$  in Figure 10. The power spectrum based on finer binning of 16s shown in the upper panel extends to the highest frequency observed so far. The constancy of the spectrum for frequencies higher than 0.005 Hz shows the onset of the Poisson noise in the source. The spectral power increases towards lower frequencies, between 0.005 and 0.0005 Hz. A constant plus a power-law fitted to the power spectrum shown in the upper panel in Figure 10 gives a power-law index =  $-2.1 \pm 0.4$ . The power

spectrum based on time binning of 32s, shown in the lower panel of Fig.10, is more sensitive to the lower frequencies and is used to further investigate the nature of excess power at low frequencies. A constant plus a power-law fitted to the power spectrum shown in the lower panel in Figure 10 gives a power-law index =  $-1.8 \pm 0.3$ . This model is shown as a dotted line in the lower panel of Fig.10 and has  $\chi^2 = 52.45$  (for 29 degrees of freedom (dof)). An excess power above the dotted line can be seen at frequencies lower than 0.002 Hz. We, therefore, fitted the power spectrum with a constant+power-law+Gaussian model. The best fit model has  $\chi^2 = 45.06$  (for 26 dof) and is shown as a solid line in the lower panel. Based on the F-statistics the improvement in the fit is significant at more than 99% confidence level. The power-law index is now  $-1.8 \pm 0.5$ , and the Gaussian is centred at  $0.0011 \pm 0.0004$  Hz and has a width of  $0.00042 \pm 0.00022$  Hz.

## 5. DISCUSSION

Based on high resolution X-ray observations with the *ROSAT* HRI, extended and anisotropic soft X-ray emission components have been detected around the nucleus of both NGC 1365 and NGC 4051. Although the presence of a soft extended component in NGC 1365 had previously been indicated by IPC observations, the PSF of the IPC was, however, not best suited for this problem. In addition, the presence of several nearby sources detected with the *ROSAT* PSPC (Turner et al. 1993), some of them variable, might have significantly confused the IPC measurements. The origin of this extended emission and its relation to other wavebands is discussed below, and is followed by a discussion of rapid X-ray variability in NGC 4051.

### 5.1. Extra-nuclear X-ray Emission

The circum-nuclear X-ray emission, over and above the strong nuclear component, is found to

extend to a radius of  $\sim 2$  kpc in both NGC 1365 and NGC 4051. The extent of this extra-nuclear X-ray emission is much larger than the extent of emission line gas in these galaxies. In NGC 1365, none of the extended features is coincident with the emission line gas. The X-ray extent is, however, consistent with the size of the radio disk, and also with the starburst regions in the optical disk. Similarly, the X-ray extent in NGC 4051 is also consistent with the size of its radio disk. An extended X-ray emission feature in NGC 4051 appears related to the jet-like feature seen in radio. A region of X-ray emission resembling a ‘‘chimney’’ and suggesting a breakout of superwind from the starburst regions in the disk is clearly visible in NGC 1365. The bulk of the extended X-ray emission is, therefore, very likely to come from these starburst regions.

The detection threshold, corresponding to signal-to-noise ratio of 2.5 for a point source in the present observations, is  $\sim 4 \times 10^{39}$  ergs  $s^{-1}$  in the case of NGC 1365, and  $\sim 2.2 \times 10^{39}$  ergs  $s^{-1}$  in the case of NGC 4051. This threshold is above the luminosity of most of the known types of individual sources (for example, X-ray binaries, supernova remnants etc.) in Local Group galaxies, although a few sources have been reported to come close to this limit or even exceed it, as for example in NGC 1365 itself (Iyomoto et al. 1997). X-ray sources which are below the detection threshold, and thus could not be detected individually, can collectively contribute to the extended emission. The X-ray luminosity of  $2.5 \times 10^{40}$  ergs  $s^{-1}$  for the extended component in NGC 1365 is comparable to that seen in NGC 253 and other starburst galaxies (Fabbiano 1988). Thus, about 1000 luminous ( $L_x = 10^{37}$  ergs  $s^{-1}$ ) X-ray binaries and a similar number of supernova remnants can account for the extended X-ray emission in the disk of NGC 1365. This is not unreasonable for a supernova rate of  $\geq 0.1$   $yr^{-1}$ , seen in starburst galaxies, over  $10^7$ - $10^8$  years of a starburst age and a lifetime of  $10^3$ - $10^4$  years for the bright phase of X-ray emis-

sion from supernova remnants. The “chimney” seen in NGC 1365, however, suggests a superwind activity from starburst driven hot winds, pointing to disk-halo interaction in NGC 1365 and the presence of a diffuse X-ray component. Superwind models of Suchkov et al. (1994) predict the formation of such “chimney” like structures with edge-brightening due to shocked gas at the top heated by superwinds from starbursts in the disks. An edge-brightened feature is indeed present in the “chimney” feature in NGC 1365. A thermal component with the temperature of a few million degrees K as predicted in the simulations of Suchkov et al. also appears to be present in the spectrum of NGC 1365 (see §4.1) and could in fact be associated with the extended soft X-ray emission observed. A detailed discussion of the contribution of starburst driven superwinds to the X-ray luminosity of NGC 1365 has been given by Komossa & Schulz (1998). They have pointed out that the extremely large infra-red (IR) luminosity,  $\log L(25\text{--}60\mu\text{m})=44.87$ , of NGC 1365 measured with *IRAS*, is in considerable excess of what can be expected from a pure AGN based on correlations between hard X-ray and infra-red luminosities (Ward et al 1988), and could plausibly arise in star formation. Such large IR luminosity if assumed to come from a starburst would predict a supernova rate of between 0.01 and  $1\text{ yr}^{-1}$  depending on the initial mass function of the starburst and the upper and lower mass limits in the starburst models of Gehrz et al. (1983). They conclude that a supernova rate of  $0.015\text{ yr}^{-1}$  is consistent both with starburst models of Gehrz et al. (1983) and with the observed soft X-ray luminosity of NGC 1365. Their scenario also requires that 90% to 99% of the  $\text{H}\alpha$  emitting gas in the starburst region be obscured.

The extended X-ray emission component in NGC 4051 is an order of magnitude more luminous than in NGC 1365, but comparable to a similar component seen in NGC 1808 – a superwind powered starburst (Dahlem, Hartner, & Junkes 1994). It is, therefore, more difficult to

explain by invoking unresolved X-ray emission from discrete X-ray sources alone. If powered by superwinds from a starburst, then the starburst is required to be much stronger than in the case of NGC 1365 to explain this emission. However, unlike in NGC 1808, there is no clear evidence for a strong starburst activity in the circumnuclear region of NGC 4051, although observations of: (a) widespread diffuse  $\text{H}\alpha$  emission within  $15''$  radius from the nucleus, and compact HII regions just beyond that, reported by Evans et al. (1996); (b) strong “bar” strength (see Martinet & Friedli 1997, however), and (c) extended feature in radio (“disk” component reported by Baum et al. and attributed by them to superwind from a circumnuclear starburst) and X-ray emission being co-spatial, indicate the presence of a starburst-like activity in NGC 4051 at some level. Therefore, some contribution to the extended X-ray emission from starburst related activity can not be ruled out, although it may be difficult to quantify at the moment. The shape and extent of [O III] emission line gas and the asymmetric profile of the [O III] 5007 Å line in and around the nucleus of NGC 4051 favour models with centrally driven radial outflow of gas (Christopoulou et al. 1997; Veilleux 1991), thus indicating nuclear activity as possible contributor to the extended X-ray region in NGC 4051. There is, however, a lack of detailed spatial correlation of extended X-ray emission with the [O III] emission line gas in both galaxies which argues against the the extra-nuclear soft X-ray component being thermal emission from hot gas in pressure equilibrium with the optical narrow-line gas. The origin of the extended X-ray emission in NGC 4051 is, therefore, not very clear, and could be due both to nuclear activity as well as starburst induced activity.

In NGC 4051, the unabsorbed soft (0.1–2.0 keV) X-ray flux from the extended component ( $21\%\pm 6\%$  of the total count rate) corresponds to a value of  $(0.7 - 1.0)\times 10^{-11}\text{ ergs cm}^{-2}\text{ s}^{-1}$ . This is not inconsistent with the value of (0.4–

$1.0 \times 10^{-11}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$  observed by *BeppoSAX* recently when NGC 4051 presumably went into its lowest observed state (see upper panel of Fig. 2 in Guainazzi et al. 1998). The spectral index at low energies ( $< 4$  keV) measured by Guainazzi et al. is very steep ( $\alpha = 2.0$ ) and a thermal origin has been suggested by Guainazzi et al. In such cases, the exact matching of soft X-ray fluxes is critically dependent on the spectral parameter characterisation and the intensity level, however, based on the present comparison, it is quite possible that the *BeppoSAX* soft X-ray measurements indeed saw mostly the extended disk component. This is further corroborated by the near absence of soft X-ray variability when the source exhibits the lowest count rate in the present observations (see the left side of the lowest panel in Fig. 9). During this stage the extended component is nearly 50% of the total count rate.

## 5.2. Rapid X-ray Variability of NGC 4051

In an AGN the X-ray source is powered by accretion onto a putative supermassive black hole (SMBH). If the highly variable component of the X-ray emission in NGC 4051 comes from outside 3 Schwarzschild radii of the SMBH, then the shortest observed variability time scale of 200s implies an upper limit of  $4.4 \times 10^6 M_{\odot}$  for the mass of the black-hole. A similar upper limit on the mass of the black hole was given by Mihara et al. (1994).

The knowledge of the form of the power-spectrum of variability can help us investigate physical models of X-ray emission in the source. In a detailed study of soft and hard X-ray variability in NGC 4051 based on long *EXOSAT* observations, Papadakis & Lawrence (1995) found that at lower energies ( $< 2$  keV) the power spectrum is steeper than at higher energies (2 – 10 keV) i.e., power-law slope = -1.85 versus -1.46 in the frequency range of  $10^{-5}$  Hz to  $10^{-3}$  Hz, and constant at higher frequencies. It should be noted, however that *EXOSAT* was sensitive mostly to the low-frequencies (with bin time=300s)

and covered the frequency range between  $10^{-5}$  Hz and  $4 \times 10^{-3}$  Hz. Subsequent to *EXOSAT* observations, hard X-ray observations by Matsuoka et al. (1990) using *Ginga* showed that in hard X-rays the variability time scale can be as short as 200s, thus extending the power spectrum to higher frequencies without any noticeable flattening upto 0.005 Hz. The present soft X-ray observations with *ROSAT* are more sensitive than the previous low-energy observations, and show that the variability time scale is indeed as short as a few hundred seconds even in the soft X-rays. As a result the power spectrum of soft X-rays is now extended to higher frequencies between 0.03 Hz and 0.005 Hz. The present observations also appeared to have reached the true Poisson level of fluctuations in the source.

The slope of the power-spectrum observed in the present observations is consistent with that observed at low energies with *EXOSAT*. Based on *EXOSAT* low energy observations Papadakis & Lawrence (1995) had also reported the presence of an excess in the power spectrum near 0.0004 Hz and modelled it as a broad Gaussian component in the power spectrum. This broad component indicated the presence of *quasi-periodic oscillation (QPO)* in the source. A broad feature of excess power can also be seen in the present observations (Fig. 10 lower panel) between 0.0006 Hz and 0.0018 Hz, and has also been modelled by adding a Gaussian (centred at  $0.0011 \pm 0.0004$  Hz) to the power-law. The addition of a Gaussian did not change the slope of the power-law and led to an improvement in the fit to the power spectrum. The QPO frequency is 1.75 to 3.75 times higher than that observed with *EXOSAT*. However, since the dynamic range of low frequencies in the present observations is smaller than that of the *EXOSAT* observations, the QPO frequency is not well determined.

Two models that can lead to a power-law shape of the power spectrum and which were widely discussed by Papadakis & Lawrence (1995) are – a) shot-noise model and b) hot-spot model.

In a shot-noise model superposition of flares with the right shape can produce a power-law shape of the spectrum. In a variation of this model by Begelman & de Kool (1991), known as the ‘reservoir model’, a power-law shape with an index of -1.5 results from exponentially decaying flares having a decay-time proportional to their amplitude, and their occurrence time is proportional to the amplitude of the previous flare. The resulting slope of the power-law is much flatter than the observed index in soft X-rays. In a shot-noise model (Abramowicz et al. 1991; Bao & Ostgaard 1994; 1995) the innermost parts of the accretion disk can develop orbiting hot-spots or clumps due to various thermal and viscous instabilities which modulate the intensity. Bao & Ostgaard (1995) have investigated power spectra of variability produced by orbiting blobs around black-holes using full relativistic details. They have studied the effects of intrinsic luminosity of the blobs, their orbital radii, their number distribution, the inclination of the accretion disk, and the properties of the accretion disk – optically thick or thin. The power-spectrum in every case is characterised by a power-law shape (index -0.6 to -1.5) which flattens at the low frequency end and drops rapidly at the high frequency end. The spectral slope is most sensitive to the number distribution of blobs as a function of radius. It is also sensitive to the inclination of the disk due to gravitational lensing effect – flattening at very high inclinations ( $\geq 70^\circ$ ). None of the slopes is, however, as steep as found in the present *ROSAT* observations or the previous *EXOSAT* observations. A finer tuning of the blob models of Bao & Ostgaard (1995) for the innermost regions of the accretion disk that are responsible for the shape of the power-spectrum at the high frequency end might help in explaining the results.

A QPO-like feature has also been predicted by Bao & Ostergaard (1994) due to rotating spots in the accretion disk closest to the central object and when such a disk is viewed at moderate an-

gles. They predict the centroid frequency of the QPO to be  $\sim 4 \times 10^{-3} (R/R_s)^{-1.5} (M/10^6 M_\odot)^{-1}$  Hz, where  $R$  is the distance of the innermost spots from the SMBH,  $R_s$  is the Schwarzschild radius, and  $M$  is the mass of the SMBH. If the X-ray QPO emission comes from outside  $3R_s$ , then the mass of the SMBH should be in the range of  $5\text{--}11 \times 10^5 M_\odot$ , which is a few times smaller than that implied by the fastest observed variability. QPOs have earlier been observed in many observations of an AGN in NGC 5548 (centroid frequency=0.002 Hz; Papadakis & Lawrence 1993), and in several galactic black-hole candidates.

## 6. CONCLUSIONS

- (i) Extended X-ray emission has been detected in the disks of NGC 1365 and NGC 4051, out to a radius of 2 kpc from their centres, and is much larger in extent than the emission line gas.
- (ii) The extended X-ray emission in NGC 1365 appears to be co-spatial with the starburst regions. An elongated structure of X-ray emission breaking out of the disk in NGC 1365 suggests the presence of superwinds from a starburst as partly responsible for the extended emission in this galaxy.
- (iii) The extended component of soft X-ray emission seems to dominate the flux in NGC 4051 during its low intensity and low variability state. Nuclear activity as well as starburst induced activity could be responsible for this component.
- (iv) The power spectrum of the rapid soft X-ray variability in NGC 4051 has been extended to higher frequencies than before. It is best characterised by a constant + power-law + a Gaussian. The power-law slope is consistent with previous low-energy observations with *EXOSAT*. The presence of a Gaussian feature signifies the persistence of a QPO seen earlier with *EXOSAT*.

Spatially resolved spectral observations with *AXAF* would be required to fully understand the extended emission in these galaxies.

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Fig. 1(a).— The corrected X-ray image of NGC 4051 as observed with the *ROSAT* HRI and smoothed with a Gaussian ( $\sigma=2''$ ). Contours are plotted at 0.1, 0.15, 0.2, 0.3, 0.5, 1, 2, 5, 10, 20, 30, 50, 70, 90 and 95% of the peak brightness of 30.8 counts pixel<sup>-1</sup>. (1 pixel =  $0.5'' \times 0.5''$  and  $1''=66.9$  pc)

Fig. 1(b).— The corrected X-ray image of NGC 4051 as observed with the *ROSAT* HRI and smoothed with a Gaussian ( $\sigma=5''$ ). Contours are plotted at 0.1, 0.15, 0.2, 0.3, 0.5, 1, 2, 5, 10, 20, 30, 50, 70, 90 and 95% of the peak brightness of 11.6 counts pixel<sup>-1</sup>. (1 pixel =  $0.5'' \times 0.5''$  and  $1''=66.9$  pc)

Fig. 1(c).— The *uncorrected* X-ray image of NGC 4051 as observed with the *ROSAT* HRI and smoothed with a Gaussian ( $\sigma=2''$ ). Contours are plotted at 0.1, 0.15, 0.2, 0.3, 0.5, 1, 2, 5, 10, 20, 30, 50, 70, 90 and 95% of the peak brightness of 27.2 counts pixel<sup>-1</sup>. (1 pixel =  $0.5'' \times 0.5''$  and  $1''=66.9$  pc)

Fig. 2(a).— The corrected X-ray image of NGC 1365 as observed with the *ROSAT* HRI and smoothed with a Gaussian ( $\sigma=2''$ ). Contours are plotted at 5, 8, 12, 20, 30, 50, 70, 90 and 95% of the peak brightness of 0.462 counts pixel<sup>-1</sup>. (1 pixel =  $0.5'' \times 0.5''$  and  $1''=90.2$  pc)

Fig. 2(b).— The corrected X-ray image of NGC 1365 as observed with the *ROSAT* HRI and smoothed with a Gaussian ( $\sigma=5''$ ). Contours are plotted at 4, 6, 10, 20, 30, 50, 70, 90 and 95% of the peak brightness of 0.221 counts pixel<sup>-1</sup>. (1 pixel =  $0.5'' \times 0.5''$  and  $1''=90.2$  pc)

Fig. 3.— The azimuthally averaged radial brightness distribution of the nuclear X-ray source in NGC 1365 extracted from the corrected image shown in Fig.1. The fit with the *ROSAT* PSF is shown as a solid curve.

Fig. 4.— The azimuthally averaged radial brightness distribution of the nuclear X-ray source in NGC 4051 extracted from the corrected image shown in Fig.2. The fit with the *ROSAT* PSF is shown as a solid curve.

Fig. 5.— Contours of the X-ray source from Fig. 2(a) overlaid on the B-band image (gray scale) of NGC 1365 obtained from Kristen et al. (1997).

Fig. 6.— Contours of the X-ray source from Fig. 1(a) overlaid on the V-band image of NGC 4051 obtained from Christopoulou et al. (1997).

Fig. 7.— Contours of the extended component of X-ray source, obtained by subtracting a model image of a point source and smoothed with a Gaussian ( $\sigma=2''$ ), overlaid on the V-band image of NGC 4051 obtained from Christopoulou et al. (1997). The contour values are 0.1, 0.2, 0.5, 1, 2, 5, 10% of the peak brightness shown in Fig. 1(a).

Fig. 8.— Contours of the X-ray source Fig. 1(a) overlaid on the [O III] image of NGC 4051 obtained from Christopoulou et al. (1997).

Fig. 9.— *ROSAT* HRI light curve of NGC 4051.

Fig. 10.— Power spectral density of the short-term variability in NGC 4051. The upper panel shows the power spectrum based on data binned every 16s. The best fit constant+power-law model is shown as a solid curve. The lower panel shows the power spectrum based on data binned every 32s. The best fit constant+power-law model is shown as a dotted curve, and the best fit constant+power-law+Gaussian model is shown as a solid curve.



TABLE 1  
BASIC PARAMETERS OF THE TWO SEYFERTS

Name	Distance Mpc	Magnitude B	Log $L_{\text{Hx}}$ ergs $\text{s}^{-1}$	X-ray Size arcsecs	$N_{\text{H}}$ $10^{20}\text{cm}^{-2}$	$F_{\text{Sx}}^a$ $10^{-11}\text{ergs cm}^{-2}\text{s}^{-1}$	Log $L_{\text{Sx}}^b$ ergs $\text{s}^{-1}$
NGC 1365	$18.6\pm 1.9$	9.45	$40.6^c$	6–22	1.35	0.11	40.65
NGC 4051	$13.8^d$	10.6	$41.2\text{--}41.9^e$	6–38	1.3	4.75	42.03

<sup>a</sup>Unabsorbed total source flux in the *ROSAT* HRI band of 0.1–2.0 keV; present work (§4.1).

<sup>b</sup>Total source luminosity in the 0.1–2.0 keV energy band; present work. (§4.1)

<sup>c</sup>2–10 keV luminosity from *ASCA* measurements by Iyomoto et al. 1997.

<sup>d</sup>Redshift=0.0023; Hubble constant= 50  $\text{km s}^{-1}\text{Mpc}^{-1}$ .

<sup>e</sup>2–10 keV luminosity from *Ginga* measurements by Matsuoka et al. 1990.

TABLE 2  
DETAILS OF ROSAT HRI OBSERVATIONS

Name	Sequence No.	Start Time Y, M, D, UT	End Time Y, M, D, UT	Effective Exposure Time (s)	Mean Count Rate <sup>a</sup> counts $\text{s}^{-1}$
NGC 1365	rh701297n00	1994 07 20 21:15:21	1994 08 04 18:15:36	9826	$0.023\pm 0.002$
NGC 1365	rh701297a01	1994 08 23 12:43:48	1994 08 23 12:49:42	346	$0.018\pm 0.009$
NGC 1365	rh701297a02	1995 07 03 17:39:20	1995 07 04 19:25:12	9762	$0.022\pm 0.002$
NGC 4051	rh701298n00	1994 05 21 07:04:57	1994 05 22 15:16:20	10478	$1.08\pm 0.01$

<sup>a</sup>Mean count rates are after background subtraction and integrated over the full extent of the source: point source + extended component.

TABLE 3  
NEW X-RAY SOURCES DETECTED WITH THE ROSAT HRI

S. No.	R.A. (2000) H M S	Dec. (2000) D M S	Count Rate <sup>a</sup>	SNR <sup>b</sup>	Years of Detection	ID <sup>c</sup>
1.	03 33 34.4	-36 09 36.2	2.94±0.66	4.48	1994	A Transient in inner arm of NGC 1365
2.	03 33 11.4	-36 11 34.6	2.54±0.60	4.26	1994, 1995	2 objects (B>22, B=20.8) within 6''
3.	03 33 12.8	-36 11 51.7	2.12±0.55	3.85	1994, 1995	B=19.8 mag object within 2.6''
4.	03 32 53.3	-36 06 44.4	1.66±0.49	3.39	1994	B=22.9 mag object within 7''
5 <sup>d</sup> .	03 33 12.1	-36 19 43.4	18.5±1.50	12.3	1994, 1995	1E0331.3-3629, B=20.4 object within 4.5''
6 <sup>d</sup> .	03 33 10.8	-36 19 50.5	13.0±1.30	10.1	1994, 1995	1E0331.3-3629, B≥23.5 object within 4''
7.	03 34 07.6	-36 03 59.3	3.44±0.67	5.12	1994, 1995	EQ0332-3614, B≥24.0 object within 5''
8.	03 32 36.7	-36 11 11.9	2.0±0.90	2.5	1994	B=23.5 object within 12''
9.	03 33 15.9	-36 18 13.0	2.70±0.90	3.0	1995	B=20.9 object within 5''
10.	03 33 40.2	-36 13 38.0	1.80±0.60	3.0	1995	No visible counterpart within 20''
11.	03 33 41.9	-36 07 33.0	2.00±0.60	3.5	1995	Big bright patch in NGC 1365 H II region or a cluster
12 <sup>e</sup> .	03 32 22.6	-36 06 33.0	4.00±1.00	4.0	1994	B=23 mag object 31''away
13 <sup>e</sup> .	03 33 48.1	-36 25 18.0	7.00±2.00	3.5	1995	B=19.3 mag object within 11''
14.	12 03 58.9	+44 37 23.9	1.69±0.57	3.0	1994	B=20 mag object within 9''
15.	12 02 32.4	+44 39 45.0	2.90±0.80	3.5	1994	no visible counterpart within 35''
16.	12 04 13.8	+44 31 52.0	2.20±0.90	2.5	1994	B=19.8 mag object within 5''

<sup>a</sup>in units of  $10^{-3} \text{ s}^{-1}$ .

<sup>b</sup>SNR: Signal-to-Noise Ratio.

<sup>c</sup>B magnitudes and distances of candidate objects from source position are given; EQ refers to clusters of galaxies.

<sup>d</sup>Source Numbers 5 and 6 may be part of one extended source.

<sup>e</sup>Close to the edge of the HRI field of view.

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