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A HIGH RESOLUTION SURVEY OF THE DISK OF M31

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Final Report

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1 Introduction

This report describes research activities funded for SAO Proposal P3481-5-95, "Monitoring the Center of M31", under contract NAG5-3210. Related activities for SAO Proposal P3486-5-95, "A High-Resolution Survey of the Disk of M31" (see Primini 1998) are also described. The research involved the data analysis and interpretation of eleven separate ROSAT HRI observations of the center and inner disk of M31, obtained between July, 1990 and January, 1997. A log of the individual data sets is given in Table 1. All proposed observations were successfully carried out by the ROSAT Observatory, and standard data products were successfully generated for each observation.

There were two basic thrusts to the research. First, we wished to monitor the x-ray source nearest the nucleus of M31, to search for anti-correlated radio/x-ray variability predicted by theoretical models for the source (Melia 1992). We would also be able to assess the degree and range of variability of other x-ray sources in the central bulge of M31 and to estimate rates of transients. Secondly, we wished to survey the entire inner disk of M31, and in particular the region covered by the recent MIT wide-band and narrow-band surveys (Magnier et al. 1992,1993,1995; Haiman et al. 1994), to identify x-ray counterparts to supernova remnants, OB associations, and young blue stars, in areas in which the ROSAT PSPC survey (Supper et al. 1997) was confused.

Results of each research project are summarized below. Papers describing the results in more detail are in preparation.

Table 1: **Log of ROSAT HRI Observations**

Observation	Dates	Exposure (kiloseconds)	Target Coordinates
150006n00	July 25-28, 1990	30.6	00:42:46 41:16:12
600474n00	July 7-8, 1994	18.6	00:42:43 41:16:12
600475n00	July 21-22, 1994	26.8	00:42:43 41:16:12
600674n00	July 17-Aug. 6, 1995	3.8	00:42:43 41:16:12
600675n00	July 16-Aug. 7, 1995	5.2	00:42:43 41:16:12
400780n00	Jan. 2-7, 1996	84.5	00:42:48 41:16:12
600813n00	Jan. 21-Feb. 5, 1996	70.8	00:44:12 41:30:00
600813a01	Jul. 7-Aug. 1, 1996	164.6	00:44:12 41:30:00
600931n00	Jan. 4-Feb. 3, 1997	167.6	00:41:24 41:00:00
600932n00	Jan. 5-Feb. 3, 1997	131.7	00:40:22 40:30:00
600932a01	Dec. 31, 1997 - Jan. 2, 1998	31.8	00:40:22 40:30:00

2 Monitoring the Center of M31

2.1 The Nuclear Source

The detection of a variable, unresolved radio source coindcident with the dynamical nucleus of M31 (Crane et al. 1992, 1993), known to contain a central dark object of $\sim 10^7\ M_\odot$ (Kormendy 1995 and references therein), led Melia (1992) to propose a model for a supermassive black hole in M31, powered by accretion from the stellar winds of nearby stars. A central feature of the model was a prediction for anticorrelated x-ray and radio flux variability.

In 1994 we began a campaign of coordinated VLA 3.6 cm and ROSAT HRI observations of the nucleus of M31, in collaboration with Crane et al., to test this prediction. We have compiled a set of 4 coincident x-ray and radio fluxes from 1994-1996. Because of the difficulty in scheduling for both the VLA and ROSAT, the x-ray and radio observations were not simultaneous, but typically occurred within a few days of each other. In addition, our original ROSAT HRI observation of M31 (Primini, Forman & Jones 1993) occurred approximately 1 month after the VLA discovery observation of Crane et al. (1992). A preliminary report of the 1990 and 1994 results was presented in Primini et al. (1994). The fluxes for all observations available to date are tabulated in Table 2, and shown in Figure 1. There are no correlations apparent in the data.

Table 2: **Coordinated X-ray and Radio Flux Measurements of the Nucleus of M31.**

Date	ROSAT HRI Count Rate (counts ksec^{-1})	VLA 3.6 cm Flux Density (μJy)
June/July 1990	4.9 ± 0.7	28 ± 5
July 7-8, 1994	4.6 ± 0.9	< 21 (3σ)
July 21-22, 1994	3.8 ± 0.6	34 ± 8
July/Aug. 1995	3.4 ± 1.2	< 27 (3σ)
Jan. 1996	6.5 ± 0.4	Not yet available

As part of this research, we examined in detail the question of whether the x-ray source nearest the nucleus could indeed be identified with it. Using all Einsten and ROSAT HRI observations, we determined the average position and 90% error radius of the nuclear x-ray source, using x-ray detected Globular Clusters as reference stars for the astrometric solutions. Our results were presented in Primini, Magnier & Hasinger (1997). We concluded that the radio source was at the edge of the x-ray error circle but that the probability of chance coincidence was low ($\sim$few percent).

However, recent Chandra observations indicate that the nucleus is more complex than the ROSAT observations indicated. The ROSAT HRI nuclear x-ray source is, in fact, resolved by Chandra into 5 separate sources, one of which, on the basis of position and spectrum, is the real x-ray nucleus (Murray et al. 1999). The ROSAT nuclear fluxes are therefore seriously contaminated by the other nearby sources, and no conclusions can be drawn at present about anti-correlated radio and x-ray variability. Further Chandra/VLA observations are needed for a more reliable variability study.

2.2 Other Sources Near the Center of M31

In addition to the nuclear x-ray source, other discrete sources within $\sim 20'$ of the nucleus were monitored from 1990-1996. A preliminary report of the 1990 and 1994 results was presented in Primini et al. (1994). Source detections were accomplished using both standard IRAF/PROS detection software and, more recently, using more sophisticated wavelet

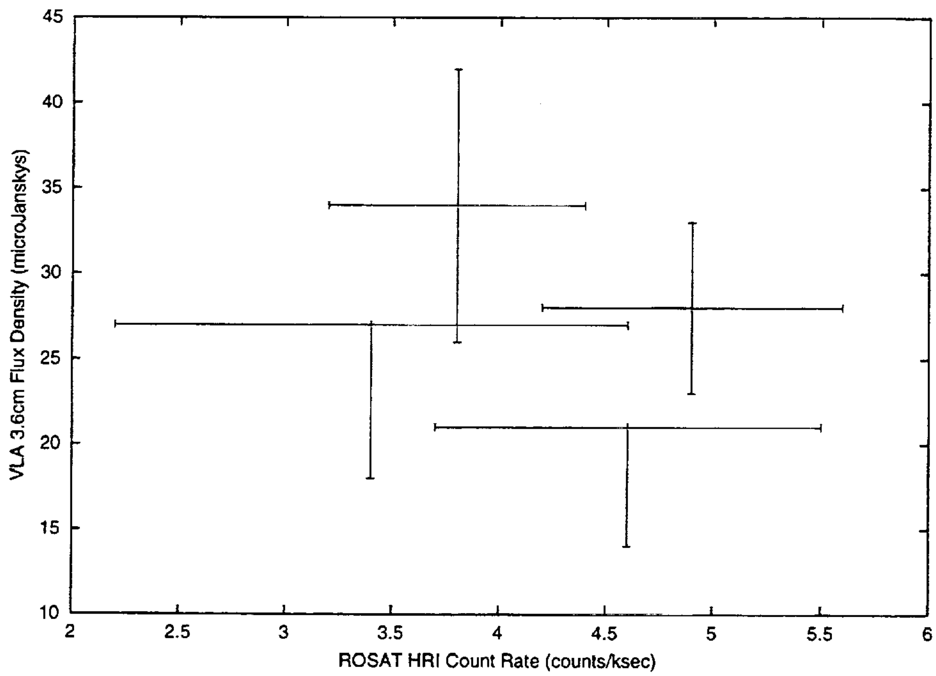

Figure 1: *Coordinated X-ray and Radio Flux Measurements of the Nucleus of M31.*

decomposition techniques (Vikhlinin et al. 1998). Background-subtracted count-rate images using the latter technique are shown in Figure 2.

3 The ROSAT HRI Disk Survey

In addition to the observations discussed above, 5 observations covering the inner disk of M31 were also performed. The purpose of the disk survey was to identify x-ray counterparts to supernova remnants, OB associations, and young blue stars. Although the ROSAT PSPC survey had also covered this region and reported many identifications (Supper et al. 1997), in a number of cases the x-ray sources had multiple optical candidates, due to the poor spatial resolution of the PSPC. The HRI survey attempted to resolve those ambiguities.

Preliminary results from one field in the survey were reported in Magnier et al. (1997). All proposed fields have now been observed and the data analysed. Typical exposures per field are $\gtrsim$ 160 ksec. Proper efficiency- and vignetting-corrected exposure maps for each field have been generated, using software provided by the US ROSAT Science Data Center (Snowden & Kuntz 1998), and an exposure-corrected mosaic of the entire survey field is shown in Figure 3.

Each of the eleven fields listed in Table 1 was analysed separately for point sources and the results were cross-matched with counterparts from a number of catalogs. In Tables 3 and 4, we list the identifications with the MIT catalogs of SNR's (Magnier et al. 1995) and OB Associations (Magnier et al. 1993).

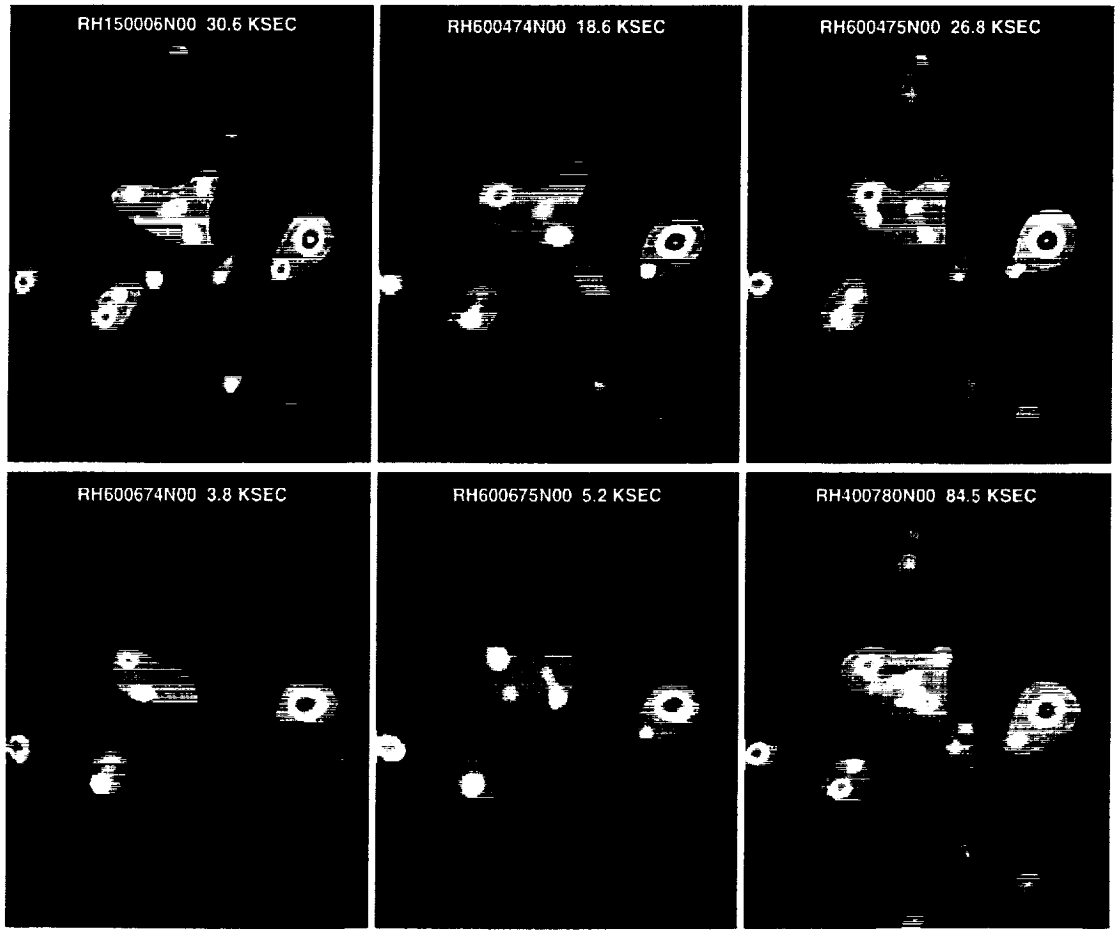

Figure 2: *Background-subtracted count-rate images of the Center of M31. Panels are in time order from left to right and top to bottom. All images have the same intensity scale applied.*

Table 3: **SNR Candidates identified with survey sources.**

HRI Source	SNR	RA	Dec.
rh600813a01-09-01	2-033	0:43:28.10	41:18:25.20
rh600813a01-09-20	3-059	0:43:39.46	41:26:48.84
rh600813n00-09-05	3-082	0:44:24.14	41:21:46.44
rh600813a01-24-73	2-048	0:45:14.26	41:36:11.87

Table 4: **OB Associations identified with survey sources.**

HRI Source	OB Assoc.	RA	Dec.
rh600931n00-24-80	[MBL93] 27	0:40:48.21	41:04:14.9
rh600813a01-12-23	[MBL93] 74	0:43:43.34	41:23:34.9
rh600813a01-09-07	[MBL93] 69	0:44:30.33	41:21:33.0
rh600813n00-09-18	[MBL93] 103	0:44:56.85	41:31:43.1

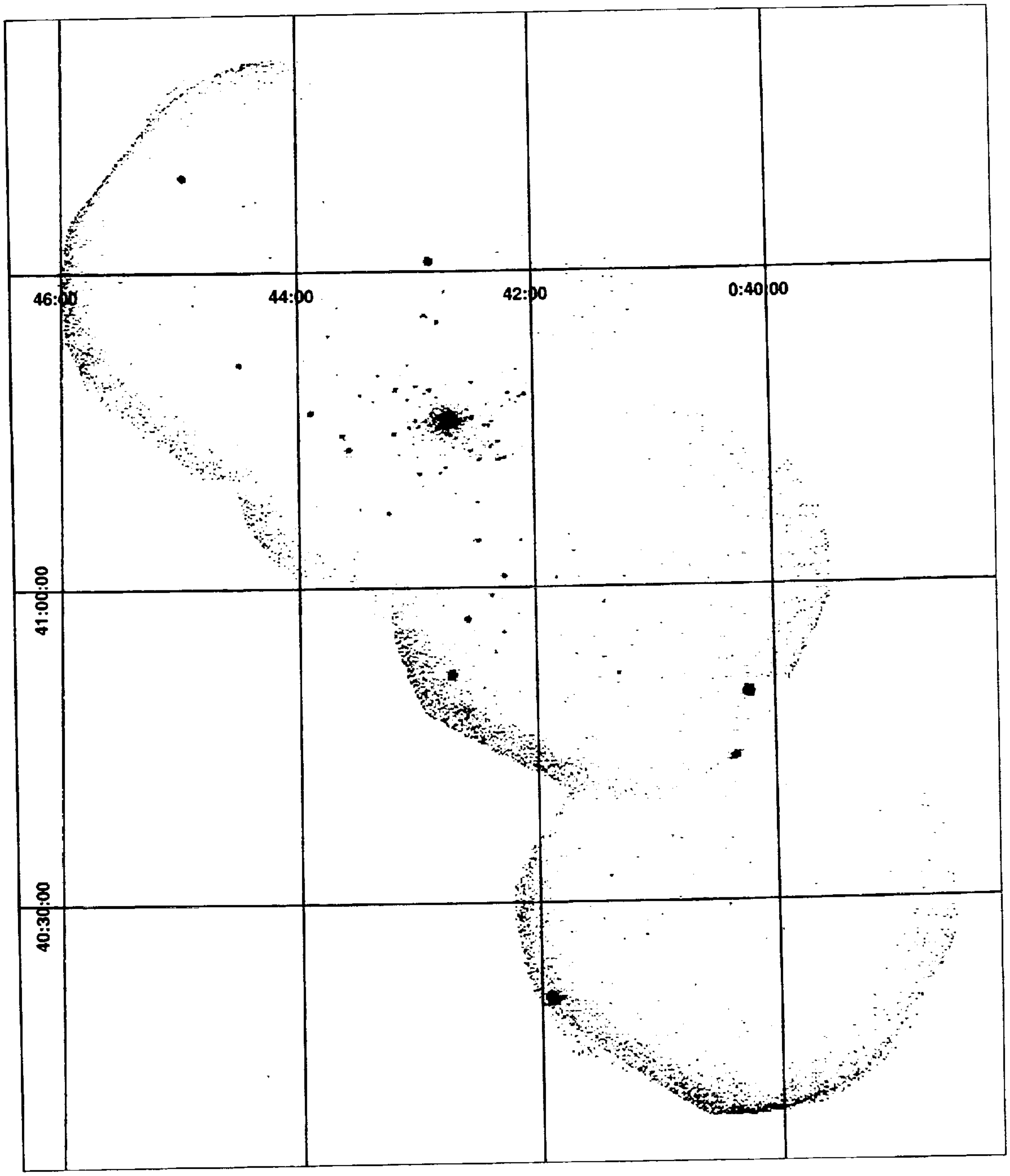

Figure 3: *Exposure-corrected mosaic image of HRI survey fields. Pixel values are counts* $ksec^{-1}$.

4 Supporting Work

In the process of conducting our research, we developed solutions to some technical problems that were of general interest to the community.

We developed scripts for the ROSAT Guest Observer Facility to correct HRI event positions for sequences in which event times had been incorrectly calculated. These incorrect times had led to residual aspect errors and subsequent image blurring in many ROSAT HRI observations (David et al. 1999).

We also collected a number of catalogs of interesting objects in M31 and inserted them into a STARBASE ASCII relational database (Roll 1996). The database and UNIX scripts for cross-referencing them to x-ray source lists were turned over to the Chandra GTO M31 team.

Finally, we developed a technique for reducing the bias in parameter estimation for observations with few counts (Kearns, Primini & Alexander, 1995), which has been incorporated into the Chandra CIAO data analysis software suite.

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