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EXTENDED SOFT X-RAY EMISSION FROM NGC 4151

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ABSTRACT

An *Einstein* HRI exposure of ~8000 s shows evidence for an extended emission region centered ~5″ to the SW of the nucleus of NGC 4151. This emission accounts for ~15% of the total HRI flux and is equivalent to a luminosity of $\sim 5 \times 10^{40}$ ergs s^{-1}. The X-rays do not appear to come from the radio jet and are more likely to be associated with the large forbidden emission line region.

We consider three possible sources: A hot thermal plasma in pressure equilibrium with the optical line emitting clouds and confining them; shock heating of outflowing forbidden line clouds as they impact on the normal interstellar medium of the galaxy; enhanced star formation, stimulated by shocks originating from outflowing emission line clouds leading to an unusual concentration of SNR and massive X-ray binaries. Of these we find that shock heating is the most plausible explanation, although X-ray binaries are a possible source for the X-rays.

Removal of this extended soft emission from the nuclear spectrum will modify somewhat the conclusions of Holt *et al.* by decreasing the uncovered fraction of the central continuum source. The extended emission that we resolve cannot explain the bulk of the soft excess that they find.

Subject headings: galaxies: individual — galaxies: nuclei — galaxies: Seyfert — radiation mechanisms — shock waves — X-rays: sources

I. INTRODUCTION

Seyfert galaxy nuclei are characterized by bright unresolved sources that are variable on time scales of days in the X-ray (Marshall, Warwick, and Pounds 1980) or weeks to months in the optical (Penston *et al.* 1974) indicating source sizes $\sim 10^6$–10^{18} cm. However, careful optical (Ulrich 1973; Walker 1968) and radio (Wilson 1981) measurements have shown that weak resolved emission can be found associated with the active nuclei in the nearer of these objects on a scale $\sim 10^{21}$ cm. Until recently it had not been possible to look at Seyfert nuclei in the X-ray band with comparable resolution. The launch of the *Einstein Observatory* (Giacconi *et al.* 1979) provided this opportunity. Extended X-ray emission associated with radio and optical jets has been reported in other types of active galaxies: Cen A (Schreier *et al.* 1979), M87 (Schreier, Feigelson, and Gorenstein 1982), and 3C 273 (Henry 1981). The known extended radio and optical features in Seyfert nuclei are much weaker than in the above galaxies. Nevertheless, we undertook a program of long ($\sim 10^4$ s) High Resolution Imager (HRI; see Henry *et al.* 1977 for a detailed description of the HRI) observations of nearby Seyfert galaxies in which resolved radio or optical structure had been seen. Our search was encouraged by the report by Holt *et al.* (1980) that NGC 4151 exhibits an excess of soft (<1 keV) X-rays over that expected from an extrapolation from higher energies.

The low HRI energy range of 0.1–3.0 keV with a peak response at around 0.7 keV (Giacconi *et al.* 1979) makes it more sensitive to extended features in NGC 4151 than in most other Seyfert galaxies since the large, and variable ($N_H \sim 10^{23}$ atoms cm^{-2}; Barr *et al.* 1977) low energy cutoff in the central source produces a factor of ~100 reduction in the expected count rate from the unresolved nucleus (assuming a covering factor of unity). Thus the dynamic range problem of searching for weak features near to a strong source is greatly eased.

Here we report the detection of an extended component to the soft X-ray source in NGC 4151. This is a confirmation of the marginal result mentioned in Johnston *et al.* (1982).

II. OBSERVATIONS AND SEARCH FOR EXTENT

Two observations of NGC 4151 were made with the HRI. Details are given in Table 1. In order to eliminate any possible spurious effects introduced by the aspect solution, we reprocessed the data, allowing only those photons detected when the star trackers were locked on

TABLE 1

EINSTEIN HRI OBSERVATIONS OF NGC 4151

Date	Effective HRI Exposure Time[a] (s)	HRI counts s^{-1}	MPC counts s^{-1}	Seq. No.
1979 May 31............	5169.9	0.067 ± 0.004	4.43 ± 0.06	340
1980 May 20–21........	8289.2	0.055 ± 0.003	5.57 ± 0.06	6395

[a] Includes only "Locked on" data; see text for details.

their chosen guide stars to be placed in the image. All data recorded when the star trackers were scanning over their fields of view to detect whatever stars were available ("MAPMODE") were rejected. Furthermore, the first observation (1979 May 31) was spread over a half-day interval. This forced the choice of guide stars to be changed toward the end of the observation. This occasionally leads to systematic offsets between the two segments of the image. We used only the longer segment in this analysis.

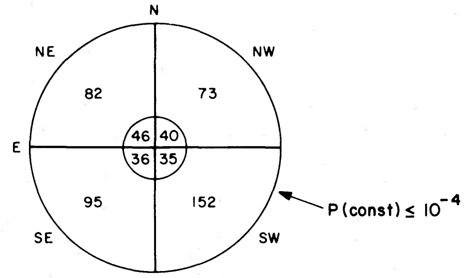
Inspection of the images, including maximum entropy deconvolutions and Gaussian smoothed maps, showed that no gross asymmetries were present. A search for smaller effects close to the nucleus was thus started by binning the data in pie-shaped bins as in Figure 1. A difficulty with this search was the correct choice of center about which binning would be performed. This is important since a small displacement from the point source position will cause photons from the central peak to be counted in outer bins, resulting in an apparent asymmetry. Therefore, we could not simply use the centroid determined from the standard production processing since it uses a 12″ × 12″ bin size. Any real asymmetry would bias that position toward itself and tend to mask its existence. We could not use the accurate optical or radio positions either, because of residual uncertainties in the absolute pointing position of the satellite.

We chose the following method. A circle of 5 pixels (2″.5) radius was placed on the image from the longer observation (1980 May). This small size was chosen to maximize the importance of the central point source. This circle was then divided into four quadrants about the north-south and east-west lines. The circle was then moved over a grid of pixels. The χ^2 for a fit to constant counts in each quadrant at each center was noted. The χ^2 grid was well behaved and defined a clear minimum at ($Y = 2029$, $Z = 2045$). The 90% error ($\chi^2 + 4.61$; Avni 1976) on this position is approximately ±1 pixel (±0″.5) in both coordinates. The centroid found by the standard processing is ($Y = 2029$, $Z = 2046$). The χ^2 at this position is 7.0, just outside the 90% contour, so no significant error is produced from the standard processing.

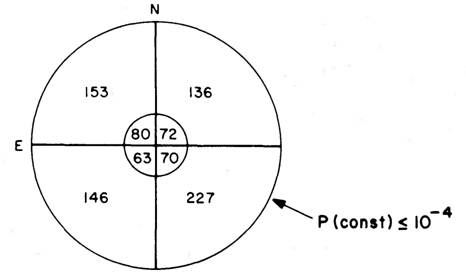
The standard processing position in celestial coordinates is R.A. = $12^{\rm h}08^{\rm m}01^{\rm s}.17$, decl. = $+39°41'02''.7$, (1950.0 coordinates; ±4″, 90% confidence, in both coordinates). This agrees with the accurate optical (Clements 1981) and radio (VLA; Johnston *et al.* 1982) positions to better than 2″.

With the center determined by the χ^2 grid we then chose a larger radius and looked for asymmetries between the different quadrants outside the 2″.5 core. In order to obtain a reasonable number of counts, a fairly large radius is needed; however, a radius which is too large introduces significant numbers of background counts. A good compromise is a 10″ (20 pixel) radius.

a. 1980 NGC4151 HRI data



b. Sum of 1979 and 1980 NGC4151 HRI data



c. 3C273 HRI data

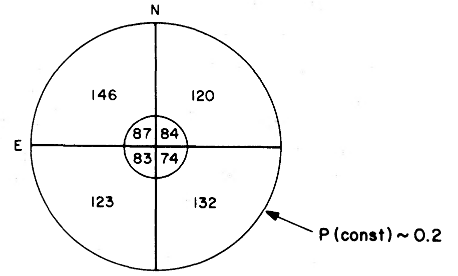


FIG. 1.—Pie diagrams centered on the central nuclear X-ray source in NGC 4151 (*a*, *b*) and 3C 273. Construction of the diagrams is described in § II. There is an excess of counts in the SW quadrant in the NGC 4151 diagrams. The probability that the counts in the outer quadrant are independent of azimuth, *P*(const), is given for each diagram.

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Figure 1*a* shows the result for the longer observation (1980 May). A χ^2 fit gives a probability $P(\text{const}) < 10^{-4}$ that the four outer quadrants are consistent with constant counts in each. Removing the most discrepant quadrant (SW) brings $P(\text{const})$ to ~ 0.1. The excess of 69 counts in the SW over the mean of the other three quadrants is significant at the 5.1 σ level.

Although unexpected, a poor or unstable aspect solution could smear counts from the central point source to the SW. A signature of such a situation would be a bunching of photons in time of arrival in the SW quadrant. During such an occurrence, the instantaneous count rate to the SW would appear to be increased by a factor of 10. We have looked for such an effect and do not find it. According to a χ^2 test, the distribution of the number of counts in 30 second bins is consistent with Poisson noise about a uniform mean arrival rate at the 6% confidence level. We thus conclude that the excess to the SW is not caused by poor aspect.

Repeating this analysis for the shorter HRI observation of NGC 4151 (1979 May) gives a $P(\text{const}) \sim 0.05$ for the four outer quadrants. However, two factors render the 1979 data less likely to exhibit the excess seen in 1980 May at a statistically significant level. First, there are a smaller number of counts in the shorter 1979 image so that, in fact, the two observations are consistent. Second, the count *rate* in the 1979 data is $\sim 20\%$ (2.4 σ) higher than in the 1980 data. This is presumably due to a brighter central source which would tend to mask out the excess to the SW.

Combining the two data sets gives the pie diagram shown in Figure 1*b*. Using the outer three quadrants to define a mean of 145 counts gives an excess of 82 counts or 15.3×10^{-3} counts s^{-1} in the SW when corrected for the 60% of the flux scattered outside the $\sim 4''$ radius of the SW quadrant. This amounts to $\sim 15\%$ of the total counts in the entire emitting region source, again allowing for the point spread function of the HRI mirror system for which 32% of the flux lies outside a $10''$ radius. The total number of background counts expected within this area is only about 5 and is neglected throughout. The excess flux from the SW quadrant in the 0.5–4.5 keV band, assuming a cutoff due only to our Galaxy (2×10^{20}; Heiles 1975) and thermal spectra of $kT = 1$ keV and 10 keV, lies in the range 6.5×10^{-13} ergs cm^{-2} s^{-1} to 1.3×10^{-12} ergs cm^{-2} s^{-1}, respectively. At an assumed distance to NGC 4151 of 20 Mpc, these fluxes give luminosities of 3.1×10^{40} ergs s^{-1} and 6.2×10^{40} ergs s^{-1}.

This level of asymmetry is not a normal feature of HRI images. For a comparison we performed the same analysis on a segment of data on 3C 273 (Seq 569) containing a similar number of counts (Fig. 1*c*). In this case the counts are consistent with constant counts in each quadrant [$P(\text{const}) \sim 0.2$].

In order to estimate the position angle of the excess we have rotated the pie bins in Figure 1*b* in 22°5 steps and performed a χ^2 fit as described previously. The peak in the χ^2 occurs at the initial binning chosen so that our best estimate of the position angle of the emission is 225° ± 15° (Fig. 2). We find no evidence for emission at the position angle of the radio jets (80° and 260°; Johnston *et al.* 1982; Booler, Pedlar, and Davies 1982).

We have subtracted the mean surface brightness distribution of the other three quadrants from that at position angle 225° to produce the radial profile of the excess shown in Figure 3. This can be compared with the [O III] $\lambda 5007$ profile of Heckman and Balick (1983).

III. DISCUSSION

Could this excess be due to a single point source? If it were a source unassociated with NGC 4151, then, *a posteriori*, we can say that the probability of finding a source of this flux in any given $10''$ radius circle is $\sim 10^{-5}$ using the log N/log S of Maccacaro *et al.* (1982). We used here the lower of the above fluxes to give the greatest number of possible chance coincidences. On the other hand, a single point source with a luminosity $\sim 5 \times 10^{40}$ ergs s^{-1} in a galaxy would be remarkable although nuclear sources at this luminosity are known (Elvis and Van Speybroeck 1982). Nonnuclear point sources at luminosities $\sim 10^{39}$ ergs s^{-1} may have been seen in some galaxies (Long and Van Speybroeck 1982), although the reality of the association has not been established. The possibility of our having detected a single high-luminosity point source in NGC 4151 near to its nucleus remains open. However, more plausibly we are seeing extended emission at a position angle of about 225° with a maximum approximately $5''$ from the nucleus.

What is the origin of this excess emission, assuming it to be extended? It does not appear to be associated

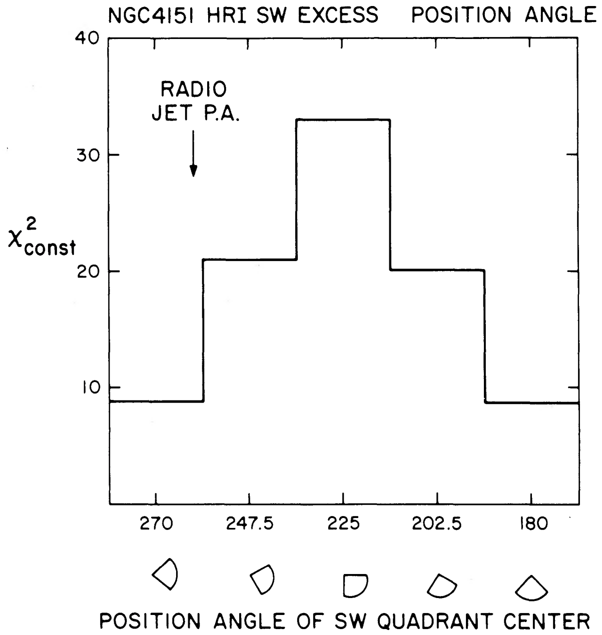

FIG. 2.—Change in χ^2 fit of Fig. 1 for outer quadrants as the bins are rotated through 22°5 steps. The χ^2 peaks at the position angle of Fig. 1 and is clearly lower at the position angle of the radio jet (Booler, Pedlar, and Davies 1982; Johnston *et al.* 1982).

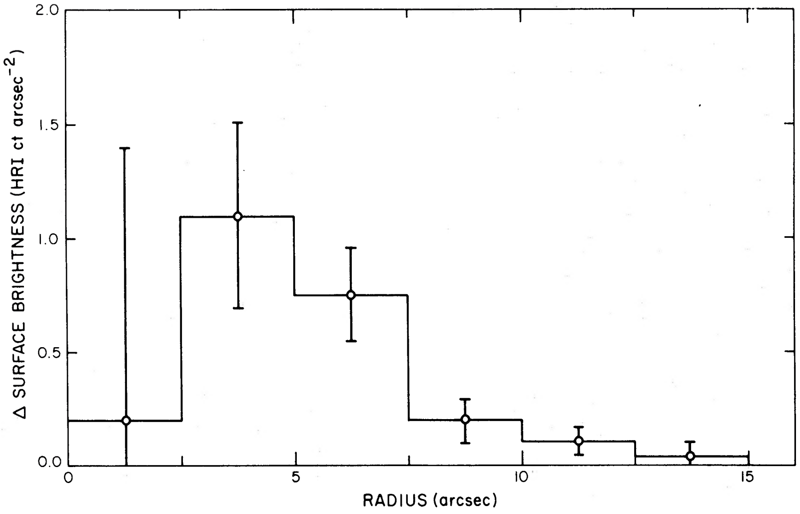

FIG. 3.—Radial surface brightness distribution of the SW excess obtained from the sum of the two observations of NGC 4151. The first bin is constrained to be close to zero by the fitting procedure (see § II).

with the radio jet. Figure 4 shows the positions of the radio components detected in the VLA maps of Johnston *et al.* (1982). The radio jet is at a different position angle from the X-ray emission. In the case of NGC 4151 we are clearly not seeing the jet as we are in Cen A, M87, and 3C 273.

More promising is an association with the forbidden line emitting gas. The outer dotted area in Figure 4 shows the extent of [O III] λ5007 seen by Fricke and Reinhardt (1974). The position angle (~225°) and general extent are compatible with the extended X-ray emission given that lower surface brightness features would be lost to the HRI. The NE-SW symmetry of the outer [O III] emission poses a difficulty however since it is not mirrored in the X-rays. The new Heckman and Balick (1983) data remove this problem by showing that,

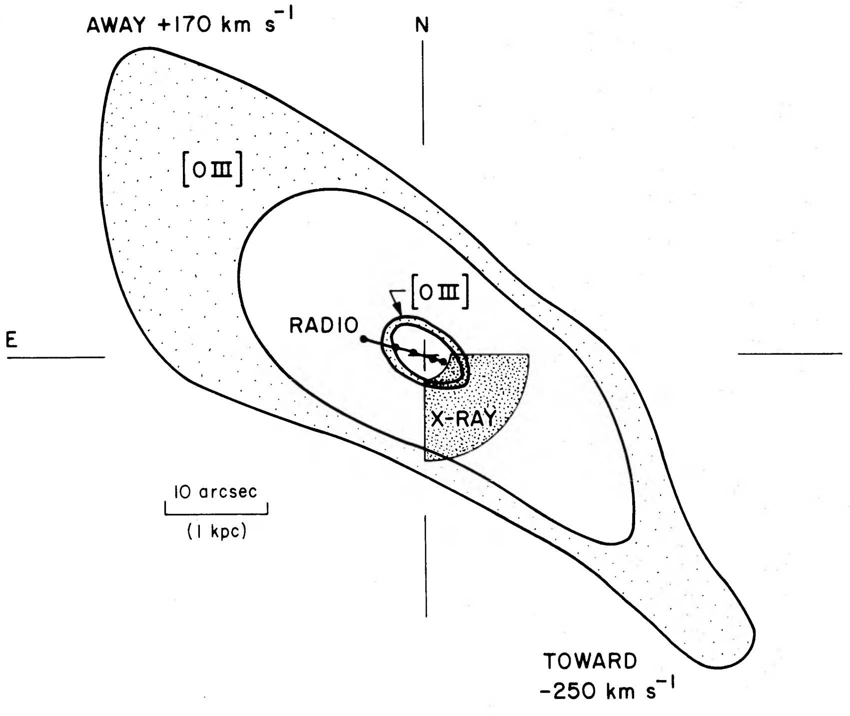

FIG. 4.—Composite of extended optical (*dotted areas*; outer from Fricke and Reinhardt 1974; inner from Ulrich 1973), radio (*line of dots*; from VLA map of Johnston *et al.* 1982) and X-ray (*shaded area* to SW; this paper). The optical data come from deep (outer) and short (inner) long slit, image tube spectra at various position angles. For each area the inner contour shows the saturation level, and the outer shows the detection limit. Also shown are the velocities of the [O III] lines in the NE and SW quadrants relative to the nucleus.

on the scale of the extended X-ray source, the [O III] emission is also asymmetric to the SW.

Assuming then that the X-ray emission is associated with the extended forbidden line emitting region we can discuss possible mechanisms for producing it. We consider three possibilities: thermal emission from a hot medium confining the forbidden emission line clouds; shock heated gas arising from the impact of outflowing forbidden emission line clouds on the normal interstellar medium of the galaxy; and the shocks caused by the outflowing clouds giving rise to enhanced star formation and hence an excess of supernova remnants and massive X-ray binaries.

It has been proposed that the broad emission line clouds in AGN are confined in pressure balance with a hotter medium (Krolik, McKee, and Tarter 1981). One might assume that a similar situation exists for the narrow line emitting clouds. The product $n_e T$ for narrow line clouds measured for NGC 4151 (Boksenberg *et al.* 1975) and other Seyfert galaxies (Koski 1978) lies in the range 10^7–10^9 cm^{-3}. These values are from *nuclear* spectra and cover only the clouds in the central 2″ or so of each galaxy. Physical conditions in the region of the extended X-ray emission are not known. Within this limitation we can see whether an X-ray hot medium at 10^6–10^7 K with a corresponding confinement density of 10^1–10^3 could produce the observed X-ray emission by bremsstrahlung. If we approximate the X-ray emitting region as a sphere of radius 0.5 kpc, then the luminosity of the proposed confining gas is far larger than observed (e.g., $n_e = 10^3$, $T = 10^6$ gives $L_x \sim 10^{46}$ ergs s^{-1}; $n_e = 10^2$, $T = 10^7$ gives $L_x \sim 10^{45}$ ergs s^{-1}, Tucker 1975). This explanation thus seems implausible.

The second possibility is that as the narrow line clouds are ejected from the nucleus, possibly by interaction with the radio jet (Wilson 1980), they should cause shocks in the normal interstellar medium of the galaxy. A velocity of 200 km s^{-1} similar to those measured by Fricke and Reinhardt (1974), would produce a temperature of $\sim 2 \times 10^6$ K or ~ 0.2 keV. This is a low temperature by normal X-ray astronomy standards but is near to the peak of the HRI response (Giacconi *et al.* 1979). Also, the true outflow velocity will be somewhat larger than the measured line of sight. Assuming $n_e \sim 1$, the emitting volume needed to give the observed luminosity corresponds to a sphere of radius 500 pc ($\sim 5''$) similar to the observed size.

A factor of 2 lower outflow velocity would yield no X-ray emission but could lead to an increase in star formation as in galactic spiral arms. Galaxies which are sites of recent star formation show enhanced X-ray emission from extended regions (Fabbiano, Feigelson, and Zamorani 1982; Fabbiano and Trinchieri 1983). They explain this by the presence of a large number of short-lived, massive stars which give both an enhanced supernova rate and a greater number of X-ray binaries. Both SNR and massive binaries have short lives as X-ray emitters and so would remain aligned with the outflow directions. To explain the luminosity we see would require $\sim 5 \times 10^4$ SNR (at 10^{36} ergs s^{-1} each), ~ 5000 normal X-ray binaries (at 10^{37} ergs s^{-1}), or ~ 500 luminous, SMC-X-1–like, binaries (at 10^{38} ergs s^{-1} each). This mechanism has been suggested to explain the X-ray flux from NGC 7714 (Weedman *et al.* 1981). A test for a "starburst" hypothesis would be to search for the strong UV flux expected from the $\sim 10^5$ O and B stars in the burst as seen in NGC 5204 (Fabbiano and Panagia 1983). A preliminary examination of short *U* band photographs of NGC 4151 shows no clumping to indicate the presence of large numbers of H II regions (M. Malkan 1982, private communication).

We prefer shock heating of the normal interstellar medium of NGC 4151 by the outflowing forbidden line emitting clouds since these shocks must occur anyways and our simple numerical estimates give reasonable, consistent results.

Finally, we should consider whether this soft X-ray emission to the SW of the nucleus of NGC 4151 can explain the soft component seen in the *Einstein* SSS spectra (Holt *et al.* 1980). The total NGC 4151 count rate that we see (10.3×10^{-2} counts s^{-1}) is 8.6×10^{-2} counts s^{-1} in excess of that expected from extrapolating the higher energy *Einstein* Monitor Proportional Counter (Gindlay *et al.* 1980; Halpern 1982) spectrum measured simultaneously. However, our total flux is very similar to that expected on the basis of the Holt *et al.* (1980) spectrum. If the HRI flux is produced only by the extrapolation of the hard spectrum plus the soft component observed by Holt *et al.* (1980), then the extended emission that we can resolve to the SW is only about 20% of the soft component.

IV. CONCLUSIONS

We have detected extended soft X-ray emission centered $\sim 5''$ SW of the nucleus of NGC 4151 with a luminosity of $\sim 5 \times 10^{40}$ ergs s^{-1}. Three possible causes were considered. The observations favor shock heating of the interstellar medium by the ejected narrow lined clouds.

The resolved X-ray emission does not explain all of the soft excess in the spectrum of NGC 4151 reported by Holt *et al.* (1980) but does make less ad hoc the possibility that more extended emission exists which is either of too low surface brightness or is too compact to be distinguished by the 4″ beam of the *Einstein* HRI.

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