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THE NUCLEAR X-RAY SOURCE IN NGC 3628: A STRANGE ACTIVE GALACTIC NUCLEUS OR THE MOST LUMINOUS HIGH-MASS X-RAY BINARY KNOWN?

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ABSTRACT

After 12 years, during which its unabsorbed soft X-ray flux in the 0.1–2.0 keV band was almost constant at about $f_x \sim 10^{-12}$ ergs s^{-1} cm^{-2}, the compact nuclear source in NGC 3628 was not detected in one of our *ROSAT* observations, with a limiting sensitivity of $f_x \simeq 5 \times 10^{-14}$ ergs s^{-1} cm^{-2}. Our data can be explained in two ways. The source is either the most massive X-ray binary known so far, with a $\gtrsim 75\ M_\odot$ black hole, or an unusual low-luminosity AGN. The X-ray spectrum is typical of a high-mass X-ray binary, while the luminosity of the source of $L_x \simeq 10^{40}$ ergs s^{-1} is more similar to those of low-luminosity AGNs. If it is an AGN, variable obscuration might explain the observed light curve.

Subject headings: binaries: general — galaxies: individual (NGC 3628) — galaxies: Seyfert — galaxies: starburst — X-rays: galaxies

1. INTRODUCTION

One of the most interesting and controversial topics in extragalactic astronomy concerns the relationship between massive stars and nuclear activity in galaxies. Some (cf. Terlevich & Boyle 1993) have argued that massive stars are the fundamental energy source in all types of active nuclei. Others (e.g., Weedman 1983; Sanders et al. 1988; Norman & Scoville 1988) have argued that compact nuclear starbursts are the evolutionary progenitors of classical active nuclei like quasars. On a basic taxonomical level, there is still great difficulty in determining whether typical infrared-bright galaxies are powered by dust-shrouded AGNs or starbursts (cf. Heckman 1991 and references therein). X-ray observations are potentially important in resolving these issues, since strong X-ray emission is a characteristic signature of most types of classical AGNs.

In this paper we report new X-ray observations of the galaxy NGC 3628. NGC 3628 is a member of the Leo Triplet of galaxies, for which we will adopt a distance of 10 Mpc. It is a spiral viewed at an inclination angle of ~80°, i.e. nearly edge-on (Wilding, Alexander, & Green 1993) and is classified as a starburst galaxy on the basis of its relatively strong, warm far-infrared emission (Rice et al. 1988). In the optical domain, the nucleus is heavily obscured and cannot be classified as either a starburst or AGN (Véron-Cetty & Véron 1986). However, the radio maps of Carral, Turner, & Ho (1990) show no sign of an unresolved (<0″.2) radio source that could be plausibly associated with an AGN.

The nucleus of NGC 3628 has long been known to harbor a bright, hard X-ray source (Fabbiano, Heckman, & Keel 1990, hereafter FHK). Our new *ROSAT* soft X-ray observations, taken together with the *Einstein* data by FHK, and the new *ASCA* data of Yaqoob et al. (1995) reveal several very peculiar properties of this source, raising the question as to what kind of object it is.

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2. X-RAY OBSERVATIONS AND RESULTS

We observed NGC 3628 with both the *ROSAT* PSPC and HRI at various epochs. The basic observing parameters are collected in Table 1. We also list the old *Einstein* IPC observations of NGC 3628 (FHK) and new *ASCA* observations by Yaqoob et al. (1995), thus comparing all currently existing data in the 0.1–5 keV energy range. The data analysis was carried out using XSPEC and IRAF/PROS.

2.1. *Flux Measurements from X-ray Spectra*

Reliable flux measurements of X-ray sources can only be obtained if their spectral characteristics in the observed passband are known. In Table 2 we list three observations with X-ray spectrometers which lead to independent flux measurements of NGC 3628.

2.1.1. *The ROSAT PSPC Spectrum*

The spectral resolution of the *ROSAT* PSPC is relatively poor, $(\Delta E/E) \simeq 0.4$ at 1 keV. Thus, only a low-resolution spectrum could be obtained. We extracted the spectrum of the central source from a circle with a diameter of 100″, centered on the position of the nucleus of NGC 3628, at α, δ(2000) = $11^{\rm h}20^{\rm m}16^{\rm s}.98$, 13°35′19″.9 (Condon et al. 1982), and the background spectrum was determined in an area with a diameter of 3′, ~5′ SE of the nucleus. *ROSAT* imaging (Dahlem et al. 1995) shows that no X-ray source is detected in this area. The best fit, assuming a power-law spectrum, as indicated by the *ASCA* data (see below), yields the parameters shown in Table 2. Although (within the 1 σ uncertainties) compatible with the Galactic foreground column density of $N({\rm H})_{\rm Gal} = 1.98 \times 10^{20}$ cm^{-2} (Hartmann & Burton 1995), the best fit for the absorbing column density, N(H), is considerably higher than this value, indicating intrinsic absorption within NGC 3628. This suggests that the X-ray source either resides deep in the disk or is itself embedded in absorbing gas as, e.g., found in X-ray

TABLE 1

X-Ray Observations of NGC 3628

Date	Satellite	Detector	Integration Time (ks)	Bandpass (keV)
1979 Dec 6	*Einstein*	IPC	12.68	0.4–4.5
1991 Nov 23–26	*ROSAT*	PSPC	13.77	0.1–2.0
1991 Dec 7–10	*ROSAT*	HRI	13.57	0.1–2.0
1993 Dec 12	*ASCA*	SIS + GIS	~30	0.5–10.0
1994 May 23–24	*ROSAT*	HRI	5.31	0.1–2.0

binaries. For more details on the *ROSAT* observations see Dahlem et al. (1995).

2.1.2. *Reanalysis of the Einstein Data*

Because of low signal-to-noise, FHK fixed the temperature in their fit of a thermal bremsstrahlung spectrum to the *Einstein* IPC data to $kT = 5$ keV. Based on this, they find $N(\mathrm{H}) = 6 \times 10^{21}$ cm^{-2}. Such a spectrum, however, can be ruled out on the basis of the *ASCA* data by Yaqoob et al. (1995). A reanalysis of the *Einstein* spectrum, using photons from a circular area of 3′ diameter, shows that the data can also be well fitted by a power-law model with the spectral parameters derived from the *ASCA* data by Yaqoob et al. (1995) (see Table 2).

2.1.3. *The ASCA SIS + GIS spectrum*

Currently, *ASCA* is the satellite with the best spectral resolution in the X-ray regime. Thus, it provides us with the most detailed spectral information on NGC 3628. Yaqoob et al. (1995) find that the spectrum is best fitted by a power-law model with the parameters listed in Table 2. The best-fitting absorbing H I column density is $N(\mathrm{H}) = 1.2 \times 10^{21}$ cm^{-2}, in agreement with the *Einstein* and *ROSAT* observations. Note that the flux value for the *ASCA* observations has been extrapolated into the *ROSAT* passband (cf. Table 1). The error margins in Table 2 represent the 1 σ (67%) confidence levels. Given these uncertainties, the (model-dependent) fluxes, f_x, derived from the fits have to be considered uncertain by a factor of ~ 1.3.

2.2. *ROSAT HRI Imaging*

Two additional flux measurements can be gathered from our *ROSAT* HRI images. Due to the lack of spectral resolution of the HRI, however, one has to adopt a shape for the photon spectrum. For this purpose we use the observed PSPC spectrum because of the best compatibility in both spectral range and observing dates with the HRI pointings. This yields the soft X-ray flux values listed in Table 2. One can see very clearly that the flux of the central source in NGC 3628 stayed almost constant from 1979 to 1991, varying by only a factor of ~ 1.5, and then dropped drastically, by a factor greater than 27, between 1991 December and 1994 May (and by a factor of > 12 from 1993 December to 1994 May).

This fading of the source is shown in Figure 1, where we plot our first HRI image (1991 December; left), the second image (1994 May; center), and the difference map (right). In 1994 May the central source in NGC 3628 has vanished below the detection limit of the *ROSAT* HRI after an integration time of 5.3 ks. Since part of the other sources in the field of view do not vary, the possibility of a calibration error can be excluded.

2.3. *Timing Analysis and the Light Curve of the Central Source in NGC 3628 over 15 Years*

For those observing runs of *ROSAT* during which the nuclear source in NGC 3628 was detected, a timing analysis was performed in order to search for variability on short and intermediate timescales. Due to the low count rates reliable results could only be obtained by binning the photons into 500–1500 s time intervals. In Figure 2, the light curves for 1000 s binning are displayed. No variability on timescales of hours to days is recognizable, corroborating the numerical results of a Fourier timing analysis. However, within the error bars, the data are consistent with flux variations of up to a factor of 2–3.

3. DISCUSSION: (IM)POSSIBLE EXPLANATIONS

Several of the observed properties of the nuclear source in NGC 3628 are unprecedented, thus not fitting into the standard pictures of different classes of currently known X-ray emitters.

Although naturally associated with a starburst, one type of object, namely a luminous supernova (SN) or SN remnant (SNR), can be excluded because of the observed light curve, which does not exhibit the sharp rise and slow exponential decay over years or tens of years that is typical for them. Also the X-ray spectrum of the source in NGC 3628 is much harder than those of known luminous SNe/SNRs (e.g., Schlegel 1993). This leaves us with two possible interpretations: high-mass X-ray binary (HMXRB) or low-luminosity AGN.

3.1. *An "Ultraluminous" High-Mass X-Ray Binary?*

Like SNRs, one also expects to find HMXRBs in starbursts. An HMXRB (cf. White, Nagase, & Parmar 1993), which might have been observed in the projected direction toward the center of NGC 3628, could explain the high-amplitude varia-

TABLE 2

Best Power-Law Fits to the Spectrum of the Central Source in NGC 3628

Date	Photon Index Γ	N(H) (10^{20} cm^{-2})	f_x(0.1–2.0 keV) (10^{-13} ergs s^{-1} cm^{-2})	L_x(0.1–2.0 keV)[a] (10^{40} ergs s^{-1})
1979 Dec 6	1.16[b]	12[b]	8.0	1.0
1991 Nov 23–26	0.27 ± 0.72	18.9 ± 18.4	9.3	1.1
1991 Dec 7–10	0.27[c]	18.9[c]	14.2	1.7
1993 Dec 12[d]	$1.16^{+0.24}_{-0.21}$	12^{+19}_{-12}	2.3–3.0	0.72
1994 May 23–24	0.27[c]	18.9[c]	<0.53	<0.06

[a] For $D = 10.0$ Mpc.
[b] Adopted from the *ASCA* SIS + GIS spectral fit.
[c] Adopted from the *ROSAT* PSPC spectral fit.
[d] Data by Yaqoob et al. 1995.

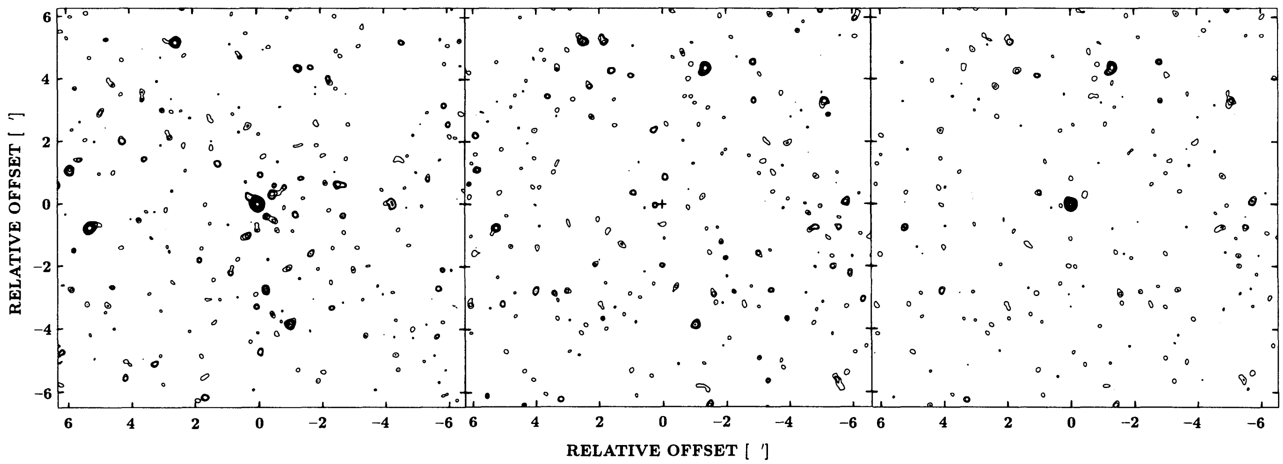

FIG. 1.—*ROSAT* HRI observations of NGC 3628. *Left:* data taken on 1991 December 7–10; *middle:* 1994 May 23–24 data; *right:* difference map. All images are normalized to counts s^{-1}, the first contour in each case represents the 3 σ significance level. The contour spacings are semilogarithmic ($2^{n/2}$ steps).

tions in the source flux. The very hard slope of the X-ray spectrum (Table 2) is compatible with that of an HMXRB, too (Nagase 1989). We note that a similar source in M82 with $L_x = 1.4 \times 10^{39}$ ergs s^{-1} and a flux variability of a factor greater than 17 was interpreted as an HMXRB by Collura et al. (1994). These authors also detect variability of about a factor of 2 in the nuclear X-ray source of M82 ($L_x \simeq 6 \times 10^{39}$ ergs s^{-1}), which they also attribute to an ultraluminous X-ray binary.

The observed luminosity of $L_x \sim 1 \times 10^{40}$ ergs s^{-1} of the source in NGC 3628 (Table 2) would correspond to the Eddington luminosity of an accreting $\sim 75\ M_\odot$ black hole. Such a supermassive system has not been detected before. $L_x \lesssim 10^{39}$ ergs s^{-1} for HMXRBs, typically (Nagase 1989). Thus, if it were an HMXRB, the source in the center of NGC 3628 would be extraordinarily massive, indicating a stellar progenitor with a mass exceeding 100 $M_\odot$. Very luminous unresolved X-ray sources have been reported in other galaxies and could be similarly explicable with massive black holes (e.g., Fabbiano 1988). Light curves similar to that of the source in NGC 3628 have been reported for X-ray binaries, e.g., Tananbaum & Tucker (1974).

3.2. *An Unusual X-Ray Variable AGN?*

The location of the source—within the pointing accuracy in the galaxy center—and its compactness favor an interpretation in terms of a low-luminosity AGN. However, this also faces some problems with the observed source properties.

The spectrum (Table 2) is unusually hard and does not fit the spectral slopes of "normal" AGNs (e.g., Walter & Fink 1993). One might speculate that low-luminosity AGNs show a different behavior than the more luminous ones, but Koratkar et al. (1994) and Trinchieri, Fabbiano, & Peres (1988) find that such low-luminosity cores show similar spectra to more luminous AGNs, with photon spectral indices, Γ, in the range from 2 to 3 in the *ROSAT* band. The "mini-Seyfert" nucleus of M81, which is of comparable luminosity to NGC 3628, has a fairly steep spectrum in the *Einstein* IPC (Fabbiano 1988).

Many Seyfert galaxies are known to have variable X-ray fluxes. Most of them, however, have lower amplitudes in their long-term variations than NGC 3628 (see, e.g., the review by Mushotzky, Done, & Pounds 1993, and references therein). For NGC 3516, Giommi (1994, private communication) reports long-term variability of the Seyfert nucleus by a factor of $\simeq 40$ over 15 years. Its light curve, however, like those of other AGNs reported in the literature (e.g., Mushotzky et al. 1993), is very different from that of NGC 3628. While the X-ray source in NGC 3628 was observed in a "high-flux" state before fading recently, the nuclei of other galaxies are in "low-flux" states most of the time and flare only occasionally. The unusual light curve of NGC 3628 can be explained, if one considers variable obscuration of the nucleus.

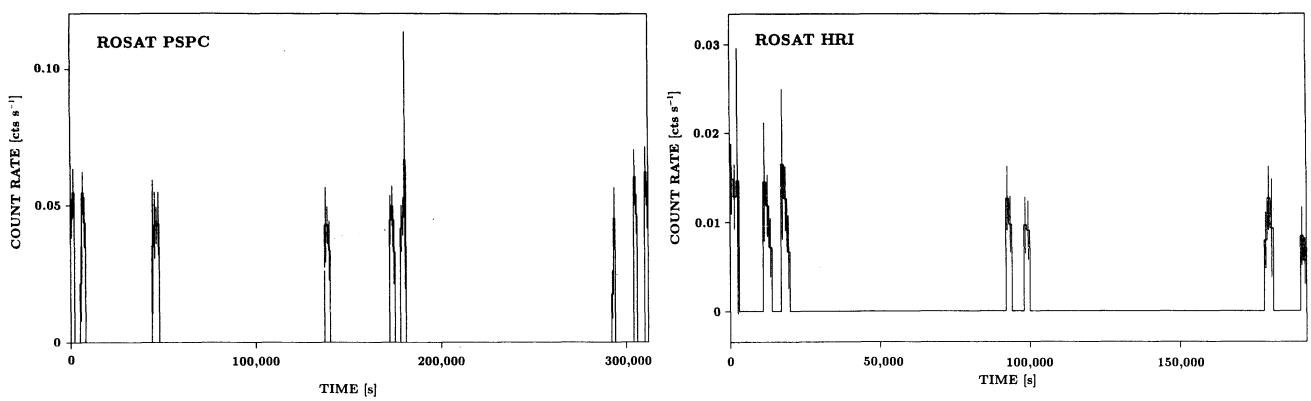

FIG. 2.—Light curve of the nuclear source in NGC 3628 during our *ROSAT* observations. *Left:* 1991 November 23–26 period (PSPC); *right:* 1991 December 7–10 observing run (HRI). We present observed count rates, averaged over 1000 s time intervals.

Schmelz, Baan, & Haschick (1987a, b) detected very massive and compact gas clouds in the central rotating disk or ring in NGC 3628, with column densities of order 10^{22} cm^{-2} and total masses in the range of 10^5 $M_\odot$. Using the observed PSPC spectrum and fixing the spectral index and the flux normalization, we find by varying the absorbing column density that a cloud with N(H) = 4.75 × 10^{22} cm^{-2} *can* shield a 10^{40} ergs s^{-1} source so that its observed flux would drop by a factor of 27 and would thus not be observable in our second HRI pointing. Similar changes in N(H) on timescales of months have been observed in the X-ray regime in a few AGNs (e.g., ESO 103-G35; Warwick, Pounds, & Turner 1988).

From the observed behavior we can deduce the following constraints on the properties of the absorber: The absorbing column density has to be high ($\sim 5 \times 10^{22}$cm^{-2}), which is similar to the observed values of the circumnuclear molecular clouds (Schmelz et al. 1987a, b; Reuter et al. 1991). The observed velocity gradient of the circumnuclear gas disk or ring of 32.7 km s^{-1} arcsec^{-1} leads to a rotational velocity of 100 km s^{-1} at 3″ (140 pc) from the center. On the line of sight to the nucleus this motion is in the tangential plane, leading to a displacement of the source by $\sim 10^{14}$ cm over 5 months. This size scale and N(H) $\sim 5 \times 10^{22}$ cm^{-2} implies a gas density of order 10^8 cm^{-3}, which is very high compared to mean H_2 densities in galactic nuclei of order 10^4–10^5 cm^{-3} (e.g., Henkel, Baan, & Mauersberger 1991). This and the observed widths of the H I and OH absorption lines of ~ 50 km s^{-1} (Schmelz et al. 1987a, b) implies that the absorber is one compact core of a molecular cloud—within an ensemble of clouds—with a column density that is several times higher than the above average values derived from the radio measurements. The X-ray source must also be compact (10^{14} cm) in order to account for the fast fading of the emission.

Alternatively, the fading of the nuclear source might result from a decrease in the ionization state of the absorbing material rather than a change in column density. There is evidence that partially ionized absorbers are present in at least some AGNs (e.g., Fiore et al. 1994). If there is a partially ionized absorber in NGC 3268 that is ionized by an AGN, then—if the AGN fades enough to allow the ionization state of the absorber to drop—the opacity of the absorber to soft X-rays can go up dramatically. Thus, a relatively small change in the intrinsic luminosity of the AGN could result in a significantly bigger drop in the observed (unabsorbed) soft X-ray flux, even if the total column density of the absorber remained unchanged. This effect can be clearly seen in Figure 4 of Krolik & Kallman (1984).

4. CONCLUSION

Despite the wealth of new data, the nature of the compact and strongly variable X-ray source in the center of NGC 3628 remains unclear. It might either be an extremely massive X-ray binary with a $\gtrsim 75$ $M_\odot$ black hole or an unusual low-luminosity AGN. If it is a binary, it would be the most massive system known so far. In an AGN scenario it is probable that variable obscuration leads to the observed light curve.

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