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NEW X-RAY AND RADIO OBSERVATIONS OF THE GALAXY CLUSTER A2319

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ABSTRACT

A significantly improved position for the X-ray source 3U 1921+43 has been obtained by ANS and *Uhuru*. The combined ANS–*Uhuru* error box is only ~7′ × 7′ and is centered on the cD galaxy in the galaxy cluster Abell 2319. New radio observations of this galaxy cluster were obtained at Westerbork. The emission at 610 MHz includes several discrete sources and a weak extended component. This strengthens the general association between extended radio halos and X-ray emission from galaxy clusters. The radio halo fills the X-ray error box and is consistent with the new limits reported for the angular size of the X-ray source.

Subject headings: galaxies: clusters of — X-rays: sources

I. INTRODUCTION

The X-ray source 3U 1921+43 was identified as probably within the radius of the galaxy cluster A2319 ($D = 3$, $R = 1$) by Giacconi *et al.* (1974), although the cluster center was significantly outside the 0.2 deg^2 (90% confidence level) 3U error box. We report a significantly improved X-ray source position and upper limit for source extension obtained by the X-ray detectors on the Astronomical Netherlands Satellite (ANS) and *Uhuru*. We also present preliminary results of high-resolution radio observations of A2319 made with the Westerbork Synthesis Radio Telescope. The new error box (~0.014 deg^2) is centered on an extended radio halo source that surrounds the prominent cD galaxy at the center (Bahcall 1974) of the cluster. The galaxy cluster A2319 has been recently studied by Faber and Dressler (1976), who find that both the velocity dispersion and spatial distribution of the galaxies indicate (~99% confidence level) there are in fact two clusters. One (cluster A) is centered on the cD galaxy and, we shall demonstrate, is associated with 3U 1921+43; the other (cluster B) is centered ~8′ to the NW. In this binary (?) cluster, the X-ray cluster is the richer cluster with the central massive galaxy and surrounding extended radio source. Our data would allow an arbitrarily large fraction of the X-ray luminosity ($L_x \sim 10^{45}$ ergs s^{-1}) to arise in a point-source component, presumably the cD galaxy (then interesting in its own right). This could then enable a better fit to the (cluster luminosity, velocity dispersion)-relation than found by Faber and Dressler (1976).

II. X-RAY AND RADIO OBSERVATIONS

In an effort to improve the position of 3U 1921+43, we observed the field around A2319 with the X-ray detectors on ANS during ~3 day intervals in 1974 November, 1975 May, and 1975 November. The detectors used included the two ~1.5–28 keV hard X-ray (HXX) counters with 10′ × 3° (FWHM) fields of view offset by 3′.7 (Gursky, Parsignault, and Schnopper 1975) and the ~1–8 keV soft X-ray (SXX) detector with ~38′ × 75′ (FWHM) field of view (Brinkman, Heise, and de Jager 1974). The SXX and HXX experiments have comparable sensitivities in the ~1.3–7 keV range such that 1 count s^{-1} ≈ 15 *Uhuru* counts s^{-1} for a Crab-type spectrum. All ANS observations reported here were conducted in the offset pointing mode with 64 s integrations alternating between source and background. The total exposure on source for each observing period was typically ~1 hr, and the pointing stability was ±0′.5. In the 1974 November and 1975 May observations, the "source" direction used was the center of the 3U error box (Giacconi *et al.* 1974), and background was taken 40′ south. No difference in count rate was observed between these two regions, giving an upper limit (3 σ) of 0.2 counts s^{-1} (≈3 *Uhuru* counts s^{-1}) for X-ray emission from the original 3U *Uhuru* position. Since this upper limit is a factor of ~2 below the reported *Uhuru* flux, it was obvious that either the source was variable or the true source position was significantly north of the *Uhuru* error box.

Accordingly, after one of us (J. E. G.) learned of recent radio observations (at 610 MHz) of the field from Westerbork, we planned our final ANS observations to observe several prominent radio features. We chose a "source" position to be 28′ north (in ecliptic latitude) and 14′ west (in ecliptic longitude) of the *Uhuru* position, since that was the approximate location of an extended radio halo source surrounding several relatively bright discrete sources (see discussion below).

this position is also very nearly that of the bright cD galaxy noted by Bahcall (1974) as near the center of A2319. By analogy to other X-ray clusters, the presence of a cD galaxy may be a probable indicator of (and center for) X-ray emission. The "background" position used was 14′ south (in ecliptic latitude) of the 3U position where the radio observations showed both a source associated with NGC 6792 (a 13.5 mag spiral galaxy) and another complex source identified with a more distant E galaxy.

Both the HXX and SXX detectors recorded a significant excess count rate $F(\sim 1.3\text{–}7 \text{ keV}) = 0.35 \pm 0.06$ counts s^{-1} from the source position. This corresponds very closely to the 6.5 ± 0.5 counts s^{-1} flux recorded by *Uhuru* (Giacconi *et al.* 1974) and indicates that the source 3U 1921+43 was well centered in the ANS collimators. Given the detector fields of view, this restricts the source to be within $\pm 5'$ in ecliptic latitude and $\pm 37'$ in ecliptic longitude of the cD galaxy. These limits (HXX and SXX, respectively) are shown in Figure 1 (the cD galaxy is marked by a cross), where we also show the 3U and revised (described below) *Uhuru* positions. In actual fact, the (SXX) limit on the source longitude uncertainty is $\sim \pm 15'$ since three observations were conducted with the "source" position displaced by 20′ in longitude and the apparent (SXX) flux was reduced to 0.14 ± 0.10 counts s^{-1}. The limits given here have referred to the position of either a point source or the centroid of an extended source. However, from the ratio of ANS to *Uhuru* apparent flux, we can (assuming a constant source with uniform brightness distribution) limit the angular size of the source to be less than the positional uncertainties given above (i.e., $\lesssim 10' \times 30'$ in diameter). The limit on source extension in latitude (for uniform brightness) can be further reduced to less than $\pm 4'$ (from the cD galaxy) by comparing the apparent fluxes recorded by HXX and SXX on ANS.

The *Uhuru* position of 3U 1921+43 has itself been improved significantly with the analysis of considerably more data than included in the 3U catalog (Giacconi *et al.* 1974). The new *Uhuru* position for this source is one of a number of improved positions for possible cluster sources (Jones and Forman 1977); the error box (90% confidence level) is shown ("U") in Figure 1. It is significant that this position intersects the ANS–HXX band in a $\sim 7' \times 7'$ square nearly centered on the cD galaxy. Thus, the new *Uhuru* position primarily restricts the source right ascension whereas the declination is comparably limited by ANS. If the source angular diameter is not greater in right ascension than the limit (in ecliptic latitude) given above, we obtain $\theta_{\text{radius}} \lesssim 7'$ for an isothermal sphere distribution (Kellogg and Murray 1974 obtained $\theta_{\text{radius}} < 14'$). Any extended X-ray source is therefore not appreciably larger than the radio halo. The limit on the linear size of the extended X-ray emission is $r_{\text{core}} < 0.7$ Mpc using the velocity measurement of Faber and Dressler (1976). The limiting X-ray core radius is comparable to those found (e.g., Kellogg and Murray 1974) for other clusters but is apparently smaller than the ANS limit (Brinkman *et al.* 1977) found [$\theta_{\text{radius}} > 6'$ (uniform brightness) or $> 10'$ (isothermal sphere)] for the cluster near Cyg A, which is at nearly the same distance.

The low source flux results in only a poor determination of the continuum X-ray spectrum. Best-fit spectra for the ANS (SXX) data yielded parameters (for a power law fit) $\alpha \approx 0.8$ $(+3, -0.6)$ and $n_{\text{H}} < 3 \times 10^{22}$ cm^{-2} for the energy spectral index and low-energy absorption column density. An exponential spectrum fit was equally acceptable with $kT \approx 8 \pm 7$ keV and $n_{\text{H}} < 3 \times 10^{22}$ cm^{-2}. Although these parameters are consistent with other clusters, the limited statistics precluded searching for iron line emission as has been found from other cluster sources (Serlemitsos *et al.* 1977).

The radio observations were obtained at 610 and 1415 MHz with the Westerbork Synthesis Radio Telescope and will be presented in more detail at a later date (Harris and Miley, in preparation). A complex of radio sources in a common halo was found at the center of the cluster and this section of the map is shown in Figure 1. None of the bright cluster galaxies coincides with the centroids of the radio positions for the components within the halo (note that the cross marking the optical position of the cD galaxy is slightly north of one of the ratio source components). However, the whole complex of source components and halo surrounds the cD galaxy at the cluster center, and from an examination of the 1415 MHz data it appears likely that the easternmost component and the component to the south of the cluster center are both tailed radio galaxies (TRGs).

III. DISCUSSION

Although the suggested identification of 3U 1919+43 with A2319 has generally been accepted, it must now be considered certain. The X-ray and radio properties of this cluster are similar in some respects to other X-ray clusters (e.g., Coma and Perseus) and enable further development of models. The observations described in this paper contain three new data: (1) the X-ray source, which may be extended, lies at the cluster center; (2) a radio halo has been detected which coincides with the X-ray error box; (3) two *probable* tailed radio galaxies have been found within the radio halo.

Rather than review the various arguments for and against the inverse-Comption (IC) model or the thermal bremsstrahlung (TB) model, we will simply point out that our new data provide circumstantial evidence which supports both models. It is possible that both processes may contribute to the observed X-ray flux from a given cluster.

The presence of tailed radio galaxies in A2319 is indirect evidence of a containing medium which, if it is hot enough and dense enough, will produce the observed X-rays by thermal bremsstrahlung emission. Our upper limit on source size would imply densities at least that of Perseus, which also contains TRGs. Gull and Northover (1976) have obtained marginal evidence for a reduction in the 3 K radiation flux from A2319 as well as several other X-ray clusters which, if confirmed, would also support the hot-gas interpretation.

On the other hand, the presence of a radio halo is direct evidence for a population of relativistic electrons. If the electron spectrum extrapolates to a large reservoir at low energies, the observed X-rays can be produced by inverse-Compton radiation. The required electron energy density would restrict the average magnetic field strength to be $\sim 3 \times 10^{-8}$ gauss (compared with the approximate equipartition field strength of 6×10^{-7} gauss). Both of these values are very close to those which were derived for the IC model of the Coma cluster (Harris and Romanishin 1974). Extended low-brightness radio emission has been positively detected in only a few clusters: the Coma Cluster (Jaffe, Perola, and Valentijn 1976); Abell 2256 (Bridle and Fomalont

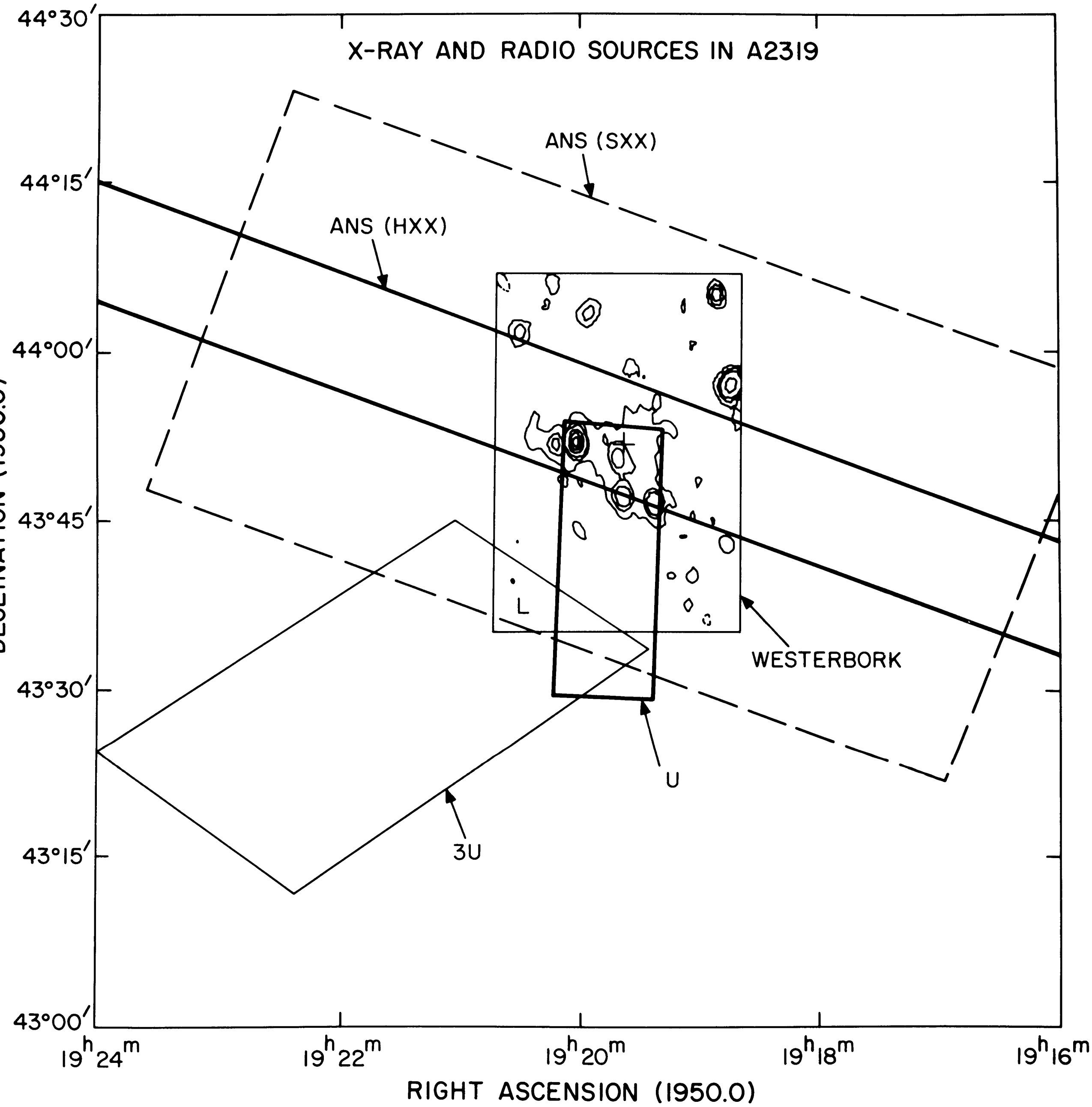

FIG. 1.—ANS position (HXX and SXX 90% confidence level limits) and *Uhuru* error boxes for the X-ray source 3U 1921+43, confirming the association with the galaxy cluster A2319. The new *Uhuru* position (Jones and Forman 1977) is designated by the U. A new high-resolution radio map (610 MHz) from Westerbork is shown by the contours which are 5, 15, 25, 75, 125, and 175 mJy per synthesized beam. The radio map reveals an extended halo component which fills the combined ($\sim 7' \times 7'$) ANS-*Uhuru* error box. The central cD galaxy position is marked by the cross, and the scale ($1' \approx 90$ kpc at the distance of A2319 for $H_0 = 50$ km s^{-1} Mpc^{-1}) is given by the sides of the L at the lower left of the Westerbork map.

1976); Abell 2142 (Bahcall, Harris, and Strom 1976); and Abell 754 (Wielebinski *et al.* 1977). All of the known halo sources occur in X-ray clusters. In view of the difficulty of detecting radio halos, it is entirely possible that all X-ray clusters contain low-surface-brightness, steep-spectra extended radio components.

Higher spatial and spectral resolution (through $\sim$80 keV) observations of A2319 are needed to evaluate the total contributions of IC and/or TB processes. The following observations would further determine physical conditions in the cluster: (*a*) High resolution (better than 10″) radio observations are needed to confirm the presence of two TRGs. (*b*) Low frequency ($<$600 MHz) observations with 1′ resolution are needed to determine the spectrum of the halo so that more accurate IC model calculations can be made. (*c*) High resolution (1′) X-ray data are needed to determine if there are any discrete X-ray sources such as the cD galaxy or one of the discrete radio sources; this would also serve to determine if the luminosity of the extended X-ray emission is significantly less than that indicated by the total *Uhuru* count rate, thereby allowing a better fit to the ($\log L_x$, $\log \Delta V$)-relation than that found by Faber and Dressler (1976). (*d*) High-resolution X-ray spectral data will be needed to compare with the radio data and to determine if an iron emission line is present in any diffuse versus point source component.

The fact that the point source contribution is still not determined is significant. If, by analogy with the Perseus cluster, $\sim$15% of the total X-ray luminosity $L_x \approx 1 \times 10^{45}$ ergs s^{-1} originates in the cD galaxy, this object would be of intrinsic interest for its very high X-ray luminosity. This would suggest that cD galaxies are themselves a luminous class of object worthy of further X-ray observations.

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