The Astrophysical Journal, 168:L1–L6, 1971 August 15

X-RAY OBSERVATIONS OF VIRGO XR-1

M. Lampton, Stuart Bowyer, J. E. Mack,* and B. Margon
Space Sciences Laboratory and Department of Astronomy, University of California, Berkeley

Received 1971 May 20; revised 1971 June 14

ABSTRACT

Virgo XR-1 was observed on 1969 June 14 with two rocket-borne proportional counters. The 1–10-keV X-ray intensity was $(7 \pm 1) \times 10^{-10}$ ergs cm^{-2} s^{-1}. A photon power-law index of -2.6 ± 0.6 or a bremsstrahlung temperature of $(2 \pm 1) \times 10^7$ °K is consistent with the measured spectrum. Comparisons with other measurements are made, and the question of possible variability is discussed. We conclude that present evidence for variability is not compelling.

On 1969 June 14 at 21$^{\mathrm{h}}$52$^{\mathrm{m}}$UT, an Aerobee 150 rocket was launched from Natal, Brazil. The payload was equipped with argon-methane proportional counters sensitive to X-rays in the 0.2–10-keV band, and with a three-axis inertial attitude control system (ACS). The ACS was programmed to perform several scans of selected portions of the celestial sphere. On one such scan, X-ray fluxes from NGC 5128, 3C 273, and Virgo XR-1 were detected. The observations of NGC 5128 and 3C 273 have been described in a previous letter (Bowyer *et al.* 1970), where complete descriptions of the detectors, collimators, and scan track are given.

Virgo XR-1 was scanned at a speed of $0\overset{\circ}{.}34$ s^{-1} in a south-to-north direction. One detector equipped with a 3° × 12° FWHM fan-beam collimator viewed Virgo XR-1 for a total transit time of 21 s. The other detector was equipped with a narrow pencil-beam ($1\overset{\circ}{.}6$ FWHM) circular-field collimator, and viewed this object for 11.8 s. Care was taken in determining the effective areas and efficiencies of these detectors so that precise intensity and spectrum reductions of data on cosmic X-rays could be performed. The background counting rates were determined during more than 39 s of high-galactic-latitude scans, which excluded all known sources and excluded positions lying within 10° of Virgo XR-1. The corrected peak counting rates in the 0.96–7.1-keV pulse-height band were 0.112 ± 0.015 counts s^{-1} cm^{-2} (fan beam) and 0.109 ± 0.011 counts s^{-1} cm^{-2} (pencil beam).

The X-ray spectrum of Virgo XR-1 was measured by an accumulation of pulse-height spectra recorded during a 6.4-s interval centered on the transit of this object through each detector's field of view. In Figure 1 we illustrate the energy dependence of the X-ray fluxes observed by our detectors. Each point represents the background-corrected counting rate in each analyzer channel, divided by the accumulation time, the time-averaged effective area, the channel energy width, and the detector efficiency. No corrections for energy resolution have been applied to the data in this figure. For comparison, we have also shown the spectra observed by the Leicester group (Adams *et al.* 1969) and the NRL group (Byram, Chubb, and Friedman 1971). The error bars shown are the statistical $\pm 1\ \sigma$ errors.

We have analyzed all available spectral data by comparing them with three model X-ray photon distributions:

$$\text{Bremsstrahlung:} \quad C \exp(-N_{\mathrm{H}}\sigma)\bar{g} \exp(-E/kT)/[E(kT)^{1/2}]\,,$$

$$\text{Power law:} \quad C \exp(-N_{\mathrm{H}}\sigma)E^{n}\,,$$

$$\text{Blackbody:} \quad C \exp(-N_{\mathrm{H}}\sigma)E^{2}/[\exp(E/kT) - 1]\,.$$

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* Present Address: Physics Department, University of Houston, Houston, Texas 77004.

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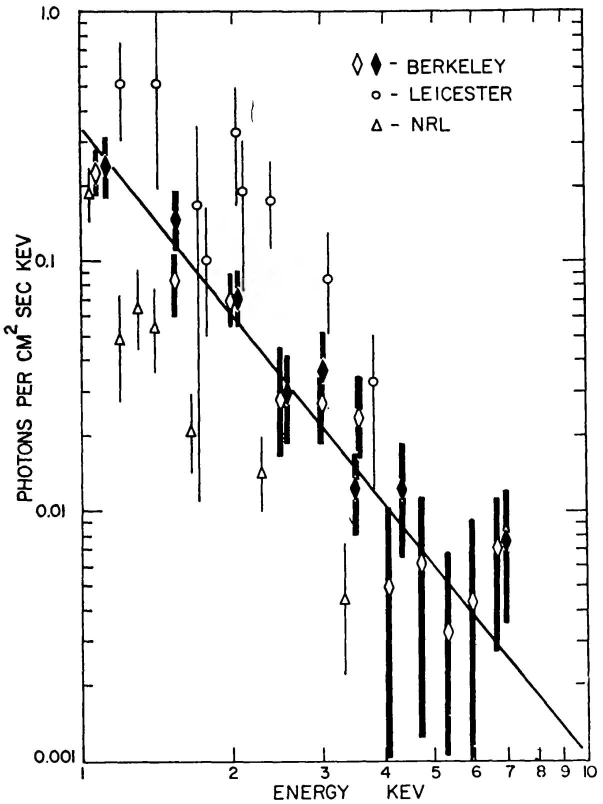

FIG. 1.—Photon distributions derived from the Leicester, NRL, and UCB rocket measurements of the X-ray emission from Virgo XR-1. *Filled diamonds*, data from the fan-beam detector; *open diamonds*, data from the pencil-beam detector. Error bars shown are the ±1 σ statistical errors.

In these expressions, N_H represents the line-of-sight column density of hydrogen and σ is the cross-section for X-ray attenuation of the interstellar medium, taken from Brown and Gould (1970). The exact Born approximation Gaunt factor has been employed: $\bar{g} = (3^{1/2}/\pi) \exp (E/2kT)\, K_0(E/2kT)$ from Greene (1959). In our model spectra, the quantities C, N_H, and n or T were adjustable parameters and were fitted to the observations by a minimum χ^2 technique, which incorporates the detector efficiency and a Poisson energy resolution kernel. The fitting method will be detailed in a forthcoming publication.

In Table 1 we list the characteristics of the models that best fit our data. Here, the errors quoted for the coefficients C have been derived by finding the change in C at which the χ^2 confidence is reduced by a factor of $e^{-1/2} = 0.606$. In this table we also list

TABLE 1

SUMMARY OF BEST-FITTING SPECTRA

Model	Detector	C	N_H	T or n*	Confidence (percent)	Ergs (cm² s)⁻¹ (1–10 keV)
Bremsstrahlung	Pencil beam	0.57 ± 0.06	$<10^{21}$	2.5×10^7	33	$(6.61 \pm 0.7) \times 10^{-10}$
	Fan beam	1.16 ± 0.15	10^{21}	1.6×10^7	16	$(6.95 \pm 0.9) \times 10^{-10}$
Power law	Pencil beam	0.34 ± 0.035	$<10^{21}$	-2.5	44	$(7.42 \pm 0.8) \times 10^{-10}$
	Fan beam	0.91 ± 0.12	4×10^{21}	-3.4	14	$(7.45 \pm 1.0) \times 10^{-10}$
Blackbody	Pencil beam	0.79 ± 0.08	$<10^{21}$	6.3×10^6	2.3	$(6.0 \pm 0.6) \times 10^{-10}$
	Fan beam	2.31 ± 0.3	$<10^{21}$	5×10^6	0.4	$(6.2 \pm 0.8) \times 10^{-10}$

* As used in this paper, n is the exponent describing the photon distribution. The power flux index is $n + 1$.

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the integrated X-ray power flux corresponding to each model. It is seen that while considerable uncertainty is associated with the spectral indices or temperatures, the inferred power flux is rather strongly constrained at $(7 \pm 1) \times 10^{-10}$ ergs cm^{-2} s^{-1}. The spectral intensity at 4 keV (approximately 10^{18} Hz) is 0.036 ± 0.007 keV $(\text{cm}^2 \text{ s keV})^{-1}$, or $(2.4 \pm 0.5) \times 10^{-28}$ ergs cm^{-2} Hz^{-1}.

In Figures 2 and 3 we show spectral parameter contours having constant χ^2 for the power-law and bremsstrahlung models. The particular contour we have chosen to display is the one whose χ^2 confidence is $e^{-1/2} = 0.606$ times the confidence of the best-fitting point on the grid. This contour is analogous to the standard deviation of a Gaussian variate.

We have performed a similar analysis of the spectra obtained and published by the Leicester and NRL groups. The χ^2 contours were calculated from the observed intensities and their variances as obtained from the published spectra. The spectral parameter contours for these measurements are shown in Figures 2 and 3. Again, the particular contour graphed for each case is the one whose confidence is $e^{-1/2}$ of the best-value confidence.

We have carried out several checks to establish that the intensities derived from our experiment were, in fact, free from systematic errors. The close agreement of the corrected peak 1–7-keV counting rates for our two detectors (fan beam, 0.112 ± 0.015 counts s^{-1} cm^{-2}; narrow beam, 0.109 ± 0.011 counts s^{-1} cm^{-2}) indicates that our scan path passed within 0°2 of the X-ray centroid of Virgo XR-1. Confirmation that the absolute intensities derived from our detectors are correct is provided by a scan of several previously measured, well-isolated galactic sources later in the flight. For example, the intensity at 4 keV observed from GX−10.7 is within 10 percent of the mean of the values reported by Fisher *et al.* (1967), Gorenstein, Giacconi, and Gursky (1967), and MacGregor, Seward, and Turiel (1970). Consequently, we believe that the Virgo XR-1 determinations obtained in this experiment are correct for the epoch at which the measurements were performed.

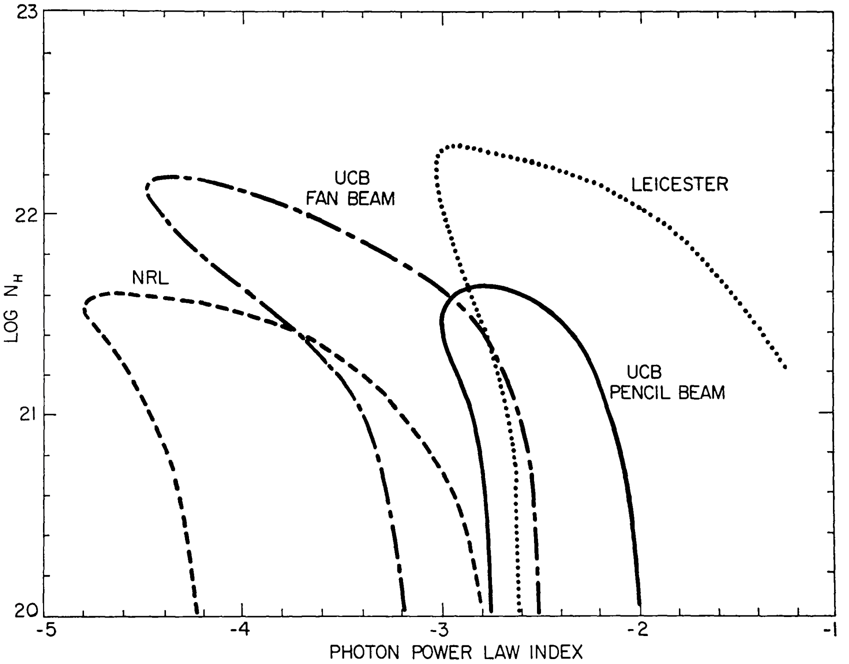

FIG. 2.—Contours of constant χ^2 for power-law models, for the data indicated

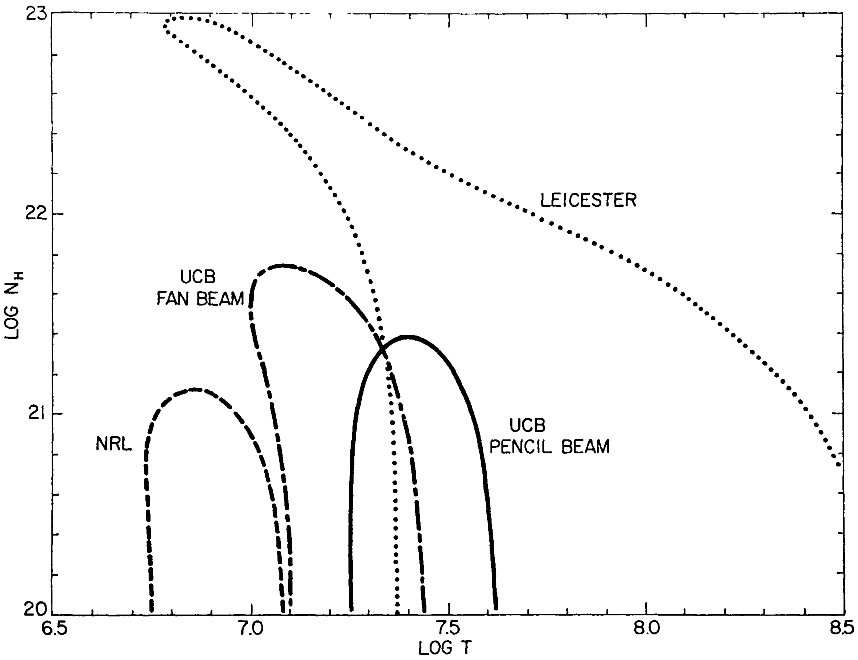

FIG. 3.—Contours of constant χ^2 for bremsstrahlung models, for the data indicated

Arguments for variability in the X-ray emission from M87 have been advanced (Byram, Chubb, and Friedman 1971; Janes *et al.* 1971) which cite differences in spectral shape and absolute intensity as measured by various investigators. We have listed all the available experimental data in Table 2. We first consider the question of variability of spectral shape. Insufficient data were obtained in the first three experiments listed to provide a reliable estimate of this quantity. The more complete Leicester, NRL, and UCB data are most easily compared by referring to Figures 2 and 3. The spectra derived from our data are compatible with the Leicester data at the 1 σ confidence level but are in disagreement with the NRL data at this level. However, even the considerable disparity between the NRL and Leicester determinations noted by Byram *et al.* (1971) occurs only at the 1 σ confidence level, and considerable regions of the (N_H, n)- and (N_H, T)-planes overlap for these measurements at the 2 σ level. We therefore conclude that no serious disagreement exists among the spectra reported for Virgo XR-1.

TABLE 2

X-RAY OBSERVATIONS OF VIRGO XR-1

Group (1)	Date (2)	Energy Flux (10^{-10} ergs cm^{-2} s^{-1}) (3)	Range (keV) (4)	Photon Index (5)	Intensity at 4 keV (keV[cm^2 s keV]$^{-1}$)* (6)
NRL............	1965	20±10	1–10	...	0.11 ±0.054
NRL............	1967	8.7±2	1–10	...	0.047±0.011
MIT............	1967 July 7	5±2	1.5–6	...	0.046±0.018
Leicester.........	1968	15±3	1.5–5	−1.8	0.151±0.030
NRL............	1969 Mar. 28	3.1±0.3†	0.8–4	−3.3	0.018±0.002
UCB............	1969 June 14	7±1	1–10	−2.6±0.6	0.036±0.005
Leicester.........	1970 Nov. 20	8.6±3	0.8–5.0	−2.5	0.046±0.014
AS&E...........	1970 Dec.–1971 Jan.	1.8±0.5	2.4–6.9	...	0.026±0.007

* Assumes a power-law spectrum whose photon index = −2.6.

† Revised from earlier value of 1.9 ± 0.2 (H. Friedman, private communication).

A comparison of the integrated X-ray intensities for Virgo XR-1 is complicated by the differing energy bandpasses employed by various investigators. In an attempt to facilitate a comparison among the various experiments, we show in column (6) of Table 2 the intensity at 4 keV computed with the assumption of a photon index of -2.6. These values were obtained from a 4-keV evaluation of the spectrum whose coefficient leads to the correct integrated X-ray power as quoted by each group. Regarding the AS&E data, we have summed their flux for M87 and M84, since it is the summed flux which must be compared with the other measurements.

Six of the eight 4-keV intensities listed in Table 2 lie within two standard deviations of their weighted mean value of 0.0353 keV $\text{cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1}$: NRL (Byram *et al.* 1966), NRL (Friedman and Byram 1967), MIT (Bradt *et al.* 1967), UCB (present work), Leicester (Janes *et al.* 1971), and AS&E (Kellogg *et al.* 1971). These six data span 4 years. The (revised) NRL measurement (Byram *et al.* 1971) is below the mean intensity by many times the reported errors in the measurement. We note that the flux from both Virgo XR-1 and 3C 273 were independently measured by NRL on their flight. On our flight, we also measured the flux from these two sources. The NRL measurements of 3C 273 and Virgo XR-1 (Byram *et al.* 1971) were both a factor of 3–5 smaller than our measurements of these objects. It follows that in the 3 months between these observations, either both Virgo XR-1 and 3C 273 brightened by a factor of roughly 4, or one of the measurements is suspect.

The earlier Leicester measurement (Adams *et al.* 1969) appears to be substantially greater than the other determinations. Their datum was derived from two rocket flights, of which one employed an attitude control system and stellar aspect camera, while the other was unstabilized. We note that a best-fit spectrum of their attitude-controlled flight data alone gives a 4-keV intensity of 0.03 keV $\text{cm}^{-2}\ \text{s}^{-1}\ \text{keV}^{-1}$—in excellent agreement with the other groups' determinations.

We conclude that the existing intensity data may well be consistent with a constant flux, when possible systematic errors are allowed for. While we intuitively believe that, at some level, Virgo XR-1 exhibits X-ray variability, it is our opinion that the present evidence for such variability is not compelling.

Figure 3 indicates that the UCB observations of Virgo XR-1 are consistent at the 1 σ level with bremsstrahlung source models with temperatures as high as 4×10^{7} ° K. Our analysis also indicates that the Leicester observations are compatible with temperatures in excess of 10^{8} °. The NRL observation 1 σ upper limit on bremsstrahlung temperature is about 10^{7} ° K, but the 2 σ limit encompasses temperatures well above this. Preliminary observations from the *Uhuru* satellite (Kellogg *et al.* 1971) are reported as compatible with T greater than 2×10^{7} ° K.

The fact that the data are compatible with a thermal emission mechanism at a relatively high temperature has important implications for theoretical models of the structure of the M87 jet. Felten, Arp, and Lynds (1970) consider several different models for the jet but assume an upper limit of 2×10^{7} ° K for its temperature, based on early X-ray observations. This assumption, together with that of secondary-particle production, introduces difficulties that lead to severe restrictions on the physical parameters within the jet.

However, a higher-temperature jet would be consistent with both the X-ray data and the existing optical data. Thus, higher-temperature, secondary production models of the jet must be explored to see if they are free of the difficulties outlined by Felten *et al.* (1970). It should be noted that jet temperatures greater than 2×10^{7} ° K are not demanded by the observations, since it is possible that it is the nucleus rather than the jet that is the site of the X-ray production in M87.

This work was supported by NASA grant NGR 05-003-278.

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