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THE X-RAY SPECTRUM OF NGC 5128

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ABSTRACT

The X-ray spectrum of NGC 5128 (Cen A) obtained by sounding rocket and balloon observations is presented in the range 1–180 keV. NGC 5128 may be fitted by a power law with a photon index $-2 \leq n \leq -1.45$. Inverse Compton models are presented, and constraints on their parameters are discussed. In all such models, the electrons and magnetic field have not yet equilibrated. Alternatively, the X-rays may originate in a compact central core source.

I. INTRODUCTION

The observations reported in this Letter were made from an Aerobee 150 rocket launched from Natal, Brazil, on 1969 June 14, and from a balloon launched from Parkes, N. S. W., Australia, on 1970 December 8. The rocket payload contained argon-methane proportional counters equipped with Mylar windows sensitive to X-rays in the 1–10-keV band, and the balloon, an actively collimated phoswich scintillation detector sensitive in the region 20–180 keV.

II. ROCKET DATA

A complete description of the instrumentation and scan track of the rocket flight, together with a report of the detection of X-rays from NGC 5128 and 3C 273, has appeared previously (Bowyer *et al.* 1970). NGC 5128 was viewed for approximately 13 s in a fan-beam detector and 7.3 s in a pencil-beam detector. In the spectral analysis reported here we have utilized only data from the 1°.6 FWHM pencil-beam detector which had a total collecting area of 332 cm^2. The small solid angle of 7×10^{-4} sterad of this detector causes it to be insensitive to the diffuse X-ray background. The chief source of background in this detector is assumed to be the result of unrejected cosmic-ray events and should be random and statistically uniform. The background counting rate was derived from 50 s of high-latitude data, which excluded all known source positions. The statistical uniformity of our background sample was verified numerically by comparing it with five shorter segments of background data using the χ^2 test. The results are consistent with a random distribution of errors between the samples. We therefore conclude that our choice of background has had minimal influence on the derived source spectrum.

The method of spectral data analysis employed is similar to that previously described (Lampton *et al.* 1971). Counts from 13 channels of the on-board pulse-height analyzer obtained during the central 7.3 s of the transit of NGC 5128 through the detector were grouped into six bins. These data, corrected for detector efficiency, background, and resolution, are shown as circles in Figure 1.

The data have been compared with power-law model photon distributions subjected to photoelectric absorption. The results of this analysis appear in Table 1, which gives the best-fit values of the photon power-law index, n, and column density of hydrogen,

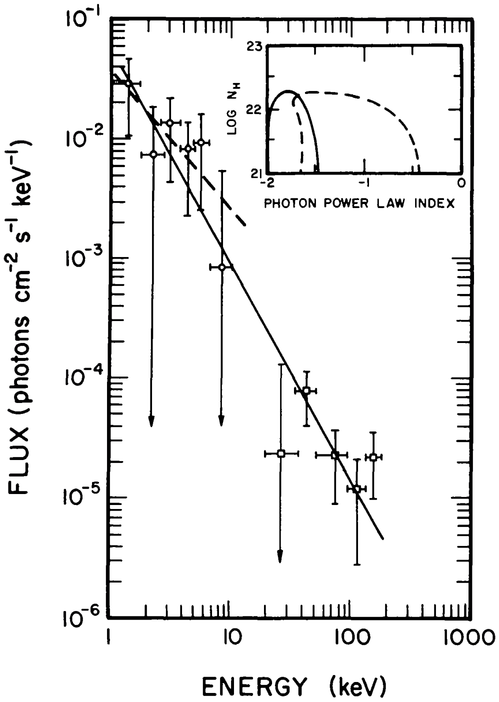

FIG. 1.—Spectrum of NGC 5128. Error bars are ±1 σ statistical errors. *Circles*, rocket data; *squares*, balloon data. *Broken line*, best power-law fit to rocket data only. *Solid line*, best power-law fit to all data. *Inset*, contours of constant probability for these fits.

TABLE 1

SPECTRAL ANALYSIS OF NGC 5128

Data	Photon Power-Law Index (n)	N_H (cm^{-2})	Confidence (%)	Intensity 1–10 keV (keV cm^{-2} s^{-1})
Rocket.............	−1.0	$<10^{21}$	57	0.302
Rocket and balloon..	−1.8	$<10^{21}$	68	0.166

N_H. This best-fit model is shown as a dotted line in Figure 1. The inset to the figure presents a contour of constant probability for the power-law fit. The contour shown is where the confidence of the least-squares fit drops to $e^{-1/2} = 0.607$ of the peak value. Although the error bars on several of the experimental points are large, the probability contour indicates that the range of likely values of the free parameters n and N_H is reasonably well constrained by these observations.

III. BALLOON DATA

The balloon-borne instrumentation consisted of a NaI(Tl) scintillation crystal 0.64 cm thick surrounded by an anticoincidence shield of CsI. An array of cylindrical holes in the shield gave the detector an effective area of 60 cm² and an angular width of 4°6 FWHM. This detector was placed in an equatorial mount which allowed any source within about 60° of the zenith to be tracked continuously. Pointing corrections and changes between source and background runs were made from the ground through a radio command system. The height of all main detector pulses accepted by the logic, as well as considerable housekeeping data, were transmitted as 8-bit words on a PCM-FM telemetry system. A more complete description of this apparatus has been given by Hurley (1972).

A float altitude of approximately 130,000 feet (39,624 m) (3.0 mb) was maintained for 8.5 hours. The data from the first half of the flight pertained to NGC 5128 and are reported here. The observation procedure consisted of 0.5-hour accumulations alternating between the source and background. Background accumulations were made by tracking a region of the sky 7°.5 E of NGC 5128 where there are no reported X-ray sources. This procedure minimized any zenith- or azimuthal-angle background dependence, since both angles were the same for a given source run and the preceding background runs. In-flight calibrations were made every hour with a radioactive source containing ^{241}Am and ^{57}Co. During the entire time NGC 5128 was observed, the gain of the system changed less than 1 percent.

The data for NGC 5128 comprise 96 minutes of source observations and 126 minutes of associated background accumulations. The excess of total signal above background during this time is 2.8 σ. The data were accumulated in a pulse-height analyzer and then grouped into five bins. To estimate the incident flux above the atmosphere, the background-subtracted counting rate for each bin was corrected for atmospheric absorption and detector efficiency. No corrections were applied for the position of the source in the field of view of the detector. The average pointing error during the source observations was less than 0°.5; however, the initial pointing uncertainty could have been as large as 1°. Given the most unfavorable combination of pointing errors, the intensities reported here could be low by $\sim$25 percent.

The resulting data on NGC 5128 are shown in Figure 1 as square symbols. The figure also gives the probability contour for the best-fit power law to the combined rocket and balloon data. Table 1 gives the details of this fit.

IV. DISCUSSION

The results summarized in Table 1 indicate that the power-law model photon distribution provides acceptable confidence fits to the data from NGC 5128. The difference in power-law indices derived from the rocket data alone and from the combined rocket and balloon data suggest a break or steepening in the spectrum somewhere in the region 10–50 keV. A test of this hypothesis was made by comparing the probability contour for the rocket data with a contour for the balloon data alone. Since the two contours intersect, an acceptable interpretation of the data is that a single power law is appropriate over the entire energy range 1–180 keV. In either interpretation it is assumed that there was no change in the intensity or spectral shape of the source in the 18 months between the rocket and the balloon experiments. We consider such a change particularly unlikely in view of the close agreement of our data with the *Uhuru* satellite observations (Kellogg *et al.* 1971), which were obtained at approximately the same time as the balloon flight. The *Uhuru* intensity determination of $(8 \pm 2.4) \times 10^{-11}$ ergs cm^{-2} s^{-1} in the 2.4–6.9-keV band agrees well with our value of $(13 \pm 4) \times 10^{-11}$ ergs cm^{-2} s^{-1} for the same interval.

We have also fitted a mechanism of thermal-bremsstrahlung emission to the combined rocket and balloon data at an acceptable confidence level. In these models, all temperatures $T \geq 4 \times 10^8$ ° K are consistent with the data at the 1 σ level.

Four other extragalactic X-ray spectra have been reported. In two of these cases, Coma X-1 (Gursky *et al.* 1971; Meekins *et al.* 1971) and the Magellanic Clouds (Price *et al.* 1971; Leong *et al.* 1971), the sources are reported to be diffuse or may consist of a superposition of weaker, unresolved sources. The two remaining cases involve galaxies in which violent events are occurring. Spectral observations of Vir XR-1 (M87) have been summarized by Lampton *et al.* (1971), who find that a photon power-law index of $n = -2.6 \pm 0.6$ is consistent with existing data. There is evidence that Vir XR-1 may be a composite source (Kellogg *et al.* 1971), but ~75 percent of the flux appears to emanate from M87. The spectrum of Per XR-1 (NGC 1275) has been reported as compatible with $n = -3.0$ (Fritz *et al.* 1971). The data reported here indicate that NGC 5128 is a significantly harder source, with $n \leq -2$ excluded by these observations.

The radio source Cen A is well known to be nonthermal, with a power-law radio spectrum with photon index −1.61 (Kellermann 1964) and high polarization (Bracewell, Cooper, and Cousins 1962). The present observations suggest that the X-ray emission is also nonthermal; it is thus natural to suspect that the sources of radio and X-ray emission are strongly related. It has been established (Bowyer *et al.* 1970; Kellogg *et al.* 1971) that the X-rays originate close to or coincident with the galaxy; thus the outer radio halo is not the principal X-ray source. Since the X-ray intensity is a factor ~100 below the extrapolated intensity of the central radio source (Bowyer *et al.* 1970), and since the X-ray spectral index is approximately the same as the radio index, the two spectra cannot be joined with a break due to an energy-loss mechanism. Thus, a simple model where the same pool of relativistic electrons generates both radio and X-ray emission by the synchrotron process appears to be ruled out.

The similarity of the X-ray and radio spectral indices suggests that the inverse Compton mechanism may be the source of the observed X-rays. Felton and Morrison (1966) have shown for inverse Compton scattering that the ratio of the intensity coefficient of the radio spectrum K_s to that of the X-ray spectrum K_c is given by

$$\frac{K_s}{K_c} = \frac{B^2/8\pi}{U}\left(\frac{2 \times 10^4\, T}{B}\right)^{(3-m)/2},$$

where B is the magnetic field strength in gauss, U is the energy density in the photon field in ergs cm^{-3}, T is the temperature characterizing the photon field, and m is the electron power-law exponent. Employing the data of Shain (1958), Sheridan (1958), and Cooper, Price, and Cole (1965), we adopt $m = 2.22$. The X-ray measurement reported here, $F(10^{18}\ \mathrm{Hz}) = 1.24 \times 10^{-28}$ ergs $cm^{-2}\ s^{-1}\ Hz^{-1}$, combined with the flux from the inner radio source, $F(10^8\ \mathrm{Hz}) = 1.8 \times 10^{-23}$ W $m^{-2}\ Hz^{-1}$ (Ginzburg and Syrovatskii 1964), yields $K_s/K_c = 110$. For a given value of T, all quantities in the above equation except U and B are now determined.

We have examined the effect of inverse Compton scattering of relativistic electrons in the inner radio lobes from microwave, infrared, and optical radiation fields, for a range of energy densities. Figure 2 shows the observational constraints placed upon values of the magnetic field and photon energy densities for each of these radiation fields. The solid lines present the loci of consistent models for photon fields with thermal distributions peaked at $\lambda = 1$ mm, $10\,\mu$, and $1\,\mu$. A magnetic field of at least $B = 2 \times 10^{-7}$ gauss is required since the cosmic microwave background contains at least $U = 0.25$ eV cm^{-3} and at this field strength sufficient X-rays are produced to explain the observations. Some emission from the microwave background is present in the optical and infrared models as well, and this radiation will be the dominant source of X-rays at low field strength. This accounts for the curvature in the lines of allowable optical and infrared models at low B. Also shown in Figure 2 is the energy density of the magnetic field and that of the relativistic electrons in the inner radio lobes, assuming a containment volume of 10^{65} cm^3. The intersection of these two lines gives the electron equipartition field strength, 8×10^{-5} gauss. Finally, the figure also indicates the locus where the Compton loss time of the most energetic synchrotron electrons observed becomes less than 10^4 years, which is the lower limit on the source age dictated by the lobe spacing. This line constrains $B < 10^{-4}$ gauss for all models.

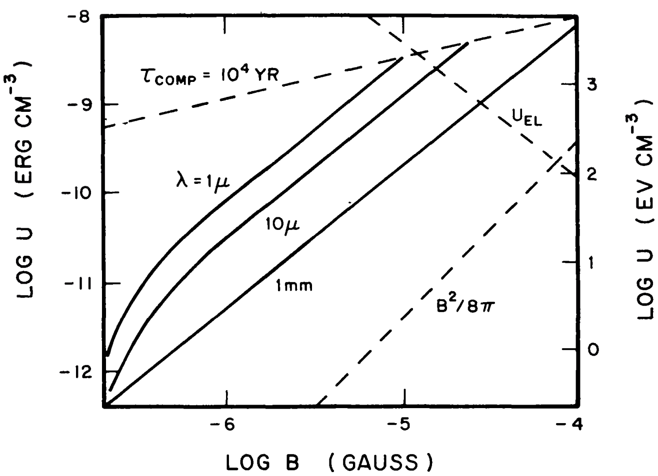

FIG. 2.—Consistent models for X-ray production by inverse Compton scattering from inner radio lobes of Cen A.

From the information provided in Figure 2 we conclude that, if the inverse Compton mechanism is responsible for X-ray generation in NGC 5128, the magnetic field in the inner radio lobes must be considerably weaker than the equipartition value, even if the energy density in one of the photon fields is enhanced many orders of magnitude above normal values. A lack of equipartition may not be surprising in an object that has obviously undergone a recent violent event.

Another mechanism consistent with the present observations involves X-ray generation by synchrotron emission from relativistic electrons in the center of the galaxy rather than those in the inner radio lobes. The resulting radiation could extend uninterrupted from radio to X-ray wavelengths. Interferometric studies (Wade *et al.* 1971) in fact show evidence of a compact radio source located near the center of the galaxy at an intensity compatible with an extrapolation of the X-ray spectrum reported here.

It should be possible to distinguish the alternative models discussed here by obtaining better positional data for the X-ray source. If the X-ray and inner-lobe radio sources are shown to be spatially coincident, this would be strong evidence for the inverse Compton mechanism. However, if the X-ray emission is found to coincide with the compact central radio source, then the X-rays are likely to be synchrotron radiation. This measurement, requiring spatial resolution of a few arc minutes, is within current experimental capabilities.

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