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Presented at the 12th ESLAB Symposium, "Recent Advances in Gamma-Ray Astronomy," Frascati, Italy, 1977 May 24-27

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

High-energy x-ray spectra of the Crab Nebula, Cyg XR-1, and Cen A have been determined from observations with the scintillation spectrometer on board the OSO-8 satellite, launched in June, 1975. Each of these sources was observed over two periods of 8 days or more, enabling a search for day-to-day and year-to-year variations in the spectral and temporal characteristics of the x-ray emission. No variation in the light curve of the Crab pulsar has been found from observations which span a 15-day period in March 1976, with demonstrable phase stability. Transitions associated with the binary phase of Cyg XR-1 and a large change in the emission from Cen A are reported.

Keywords: X-Rays, Pulsar, X-Ray Binary, Galaxy, Astrophysics

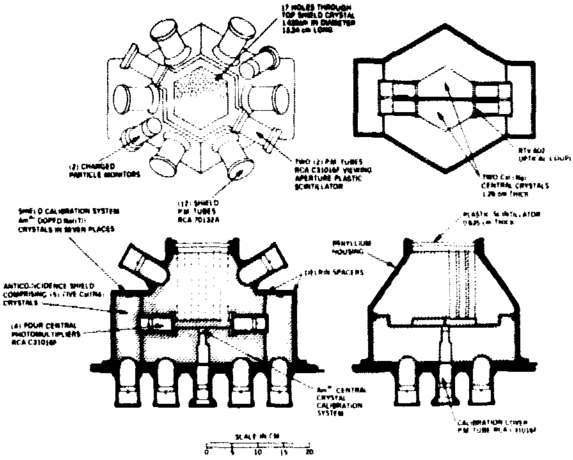

Figure 1. The OSO 8 high-energy scintillation spectrometer. The detector has a sensitive area of 27.5 cm^2, a circular aperature of 5.1° FWHM, and a sensitive area x solid angle factor of 0.25 cm^2 sr.

1. INTRODUCTION

High-energy x-ray observations are probes of that portion of the electromagnetic spectrum in which the source emission mechanisms change from predominantly thermal processes to magneto-bremsstrahlung, nuclear reactions, and other high-energy processes. Because this is also the energy range in which the interaction mechanisms undergo transition, detector techniques must be uniquely suited to achieve the wide dynamic range and high sensitivities required. The high-energy detector on board OSO 8 is an actively shielded scintillation spectrometer of the type originally designed by Frost et al. (1966). The center of the detector consists of two optically isolated CsI(Na) crystals each 1.27 cm thick. These are shielded by an active CsI(Na) collimator, as shown in Figure 1. Seventeen parallel holes, drilled through the top shield crystal to one of the two central crystals, allow the unimpeded passage of a fraction of x-rays from the forward direction. X-rays from all other directions are attenuated by a shield thickness of at least 5 cm. This configuration provides a total sensitive area of 27.5 cm^2 and an aperture with a circular FWHM of 5.1°. The second completely shielded central crystal serves to monitor the internal background of the instrument. The choice of electronic gains available on command from the ground allows the analysis of incident spectra between photon energies of 20 keV and 3 MeV. The measured energy resolution of the detector is given by $\mathrm{FWHM} = 1.45\, E^{0.7}$ keV, where FWHM is the full width at half-maximum, in keV, of a monochromatic line at E keV. This gives an energy resolution (FWHM/E) of 21% at 662 keV, and 36% at 100 keV.

The instrument is mounted with the axis of its field of view offset by 5° from the negative spin axis of the rotating wheel as indicated in Figure 2. Once every 10 seconds, the wheel rotation period, a source positioned 5° from the spin axis will pass through the center of the field of view. The time resolution of the instrument is 0.3 ms. Because of the pointing requirements of the spacecraft, the spin axis is constrained to precess around the sky once every year, always lying within 4° of a great circle, one pole of which is the direction to the sun. The resultant geometry allow observations of any source near the ecliptic for a maximum duration of 18 days. This detector provides the highest duty factor and the finest time resolution of any of its kind for observations over such extended periods. For a complete description of the instrument and its

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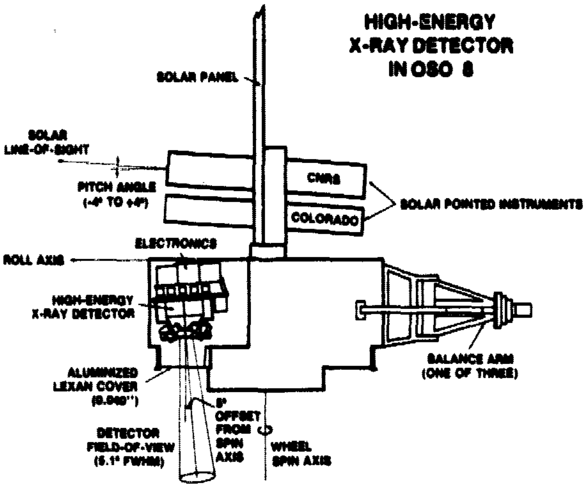

Figure 2. A schematic outline of the experiments on board the OSO-8 spacecraft. The high-energy x-ray spectrometer is mounted in the wheel with the axis of its field of view offset by 5° from the negative spin axis.

operation on board the spacecraft, see Dennis et al. (1977).

The results reported here are based on the first 18 months of observations with the OSO-8 satellite. These include observations of the Crab Nebula and the associated pulsar NP0532 in March 1976, observations of Cyg XR-1 in November 1975 and during October and November 1976, and observations of Cen A during July and August of 1975 and 1976.

2. OBSERVATIONS OF THE CRAB NEBULA

The x-ray spectrum of the Crab Nebula has been measured many times in the past 12 years and considerable evidence has been accumulated indicating that the intensity has not changed significantly during that time (Toor and Seward 1974). The spectrum is well represented by a single power law over a wide energy range. However, there still exists some uncertainty about the constancy of the source and the exact shape of the spectrum at higher energies (greater than 20 keV). In the past, most of the observations at these higher energies have been made from balloon-borne instruments. Systematic uncertainties associated with calculations of the absorption by the overlying atmosphere have left the measured spectrum open to question. With the OSO-8 high-energy spectrometer, the energy spectrum of the Crab Nebula has been determined with a precision not previously possible up to 500 keV.

The Crab Nebula and its associated pulsar, NP0532, were observed between 1976 March 9 and 23. The data reduction and analysis procedures employed in this work are described by Dolan et al. (1977b). The spectrum derived from these observations is presented in Figure 3. The photon spectrum is well represented by a power law of the form $dN/dE = C(E/E_0)^{-\alpha}$ photons cm^{-2} s^{-1} keV^{-1} with $C = (4.19 \pm 0.14) \times 10^{-3}$ photons cm^{-2} s^{-1} keV^{-1}, $E_0 = 39.1$ keV, and $\alpha = 2.00 \pm 0.06$. Comparison of the spectra derived from individual, one-day observations with the average spectrum shown in Figure 3 reveals no evidence for day-to-day variations in the spectrum of the source.

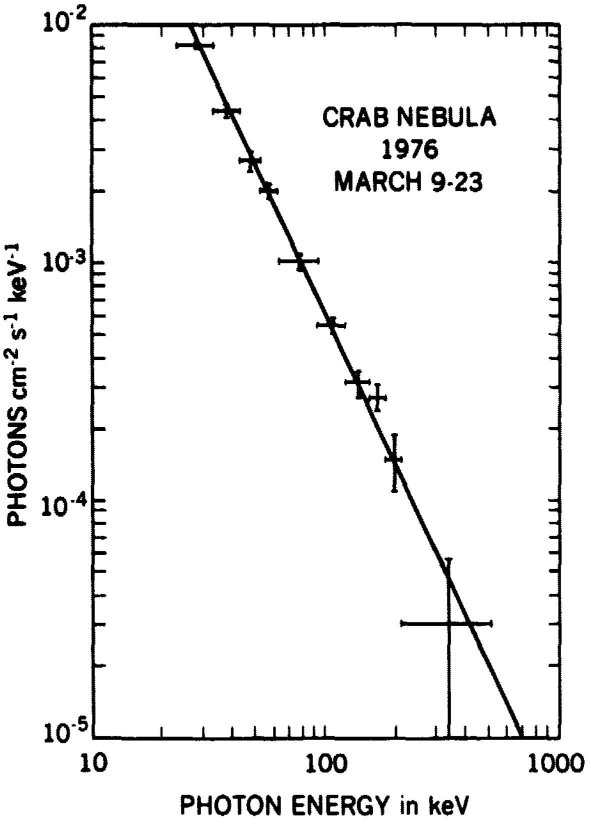

Figure 3. The photon spectrum of the Crab Nebula observed between 1976 March 9 and 23. The error bars on each point are ± one standard deviation in the measured flux as propagated through the reduction procedure. The straight line is the power law spectrum suggested by Toor and Seward (1974) between 2 and 100 keV, with $C = 9.5(\pm 1.0)$ photons cm^{-2} s^{-1} keV^{-1} and $\alpha = 2.08$ (± 0.05) for $E_0 = 1$ keV.

From observations of the Crab Nebula prior to 1973, Toor and Seward (1974) conclude that the total emission between 2 and 100 keV is steady over a time scale of years and that the spectrum of the Crab Nebula is a power law with $\alpha = 2.08 \pm 0.05$. The results presented here are consistent with their conclusions and provide further evidence for the single power law character of the spectrum out to at least 200 keV and probably to as high an energy as 500 keV.

The reported variations in the spectrum of the Crab Nebula from balloon-borne observations emphasize the importance of measurements from satellites, where the problem of correcting for the absorption in the overlying atmosphere is not present. The only other satellite measurements at energies of 60 keV and above were reported by Schwartz (1969) and Carpenter et al.

(1976). Their observed spectra are in agreement with ours.

If a single power law spectrum with an index of -2.0 to -2.1 is assumed for the Crab Nebula up to energies on the order of 500 keV, then significant changes must be made in various models of the Nebula. Cocke (1975) assumes a power law index of -2.3 at energies above 0.1 keV. He concludes from the extrapolation of this spectrum to lower energies and from the radio, infrared, and ultraviolet observations that there must be two breaks in the electromagnetic spectrum - one at 3 x 10^{14}Hz and a second at 3 x 10^{16}Hz. The x-ray spectrum with a slope of -2.08 extrapolated back in frequency shows that only one break is needed, at $\approx 10^{14}$ Hz. This break is usually interpreted as resulting from the transition between synchrotron losses at low energies and electron escape from the Nebula at high energies. The break at 10^{14} Hz also means that the electron injection energy for the pulsar into the Nebula can be characterized by a Lorentz factor $\gamma = 7 \times 10^5$, in agreement with analytical calculations cited by Cocke.

We conclude, with Toor and Seward, that the total emission of the Crab Nebula x-ray source shows no long-term variability and that the x-ray spectrum itself can be described by a single power law out to energies of at least 500 keV.

The x-ray light curve of the Crab pulsar and the pulsed fraction of emission have been determined from the OSO-8 observations for the energy range 23 to 393 keV. The existence of permanent or transient structure, in addition to the well-known double peaked structure of the pulsar light curve, has been suggested by several observers (cf. Helmken 1975). Observations of such structure have been made by balloon-borne instruments and have, therefore, been limited to time scales on the order of minutes or hours. The observations reported here are the first made with a single detector to look for variations in structure on a time scale of days. For a more complete discussion, see Maurer et al. (1977).

The light curve for the energy range 23 to 103 keV, shown in Figure 4, resembles the light curve observed at lower energies with little distinct structure in the interpulse region. The data in this energy range were used to search for day-to-day variations in the structure of the pulsed emission. The light curve for each day was compared to the light curve obtained from the sum of all accumulated data, using the chi-squared test. No statistically significant variations were found.

The pulsed fraction of emission is shown in Figure 5. The calculation of the pulsed fraction of emission as a means of characterizing the spectral properties of the pulsed emission is both convenient and useful. Because it is a ratio of fluxes at the same photon energy, this parameter is independent of problems associated with interstellar scattering and absorption, absorption in overlying atmosphere, and detector response. It therefore facilitates the comparison of spectral information obtained from different experiments. Although some deviation from the fit of Thomas and Fenton (1975) is observed above 103 keV, the data from 23 to 103 keV

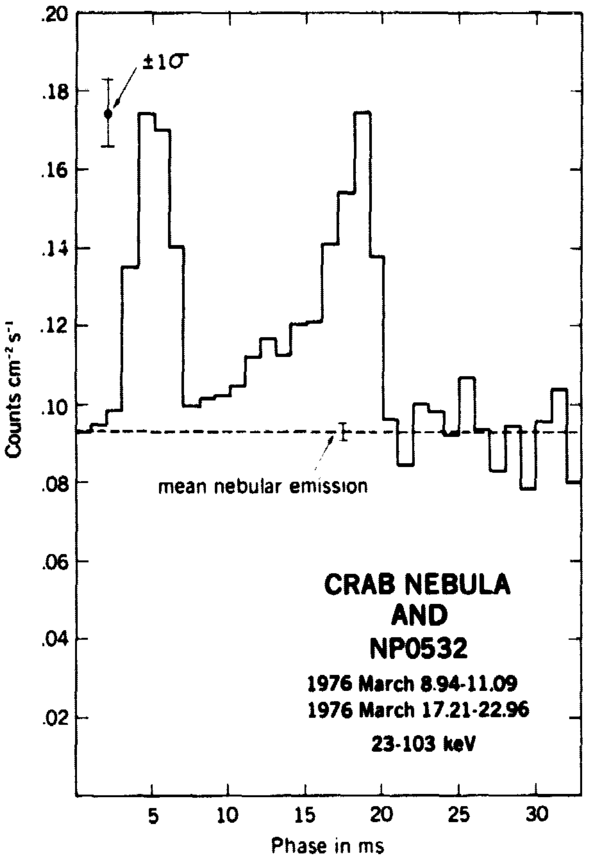

Figure 4. Light curve of the Crab Nebula and the associated pulsar NP0532.

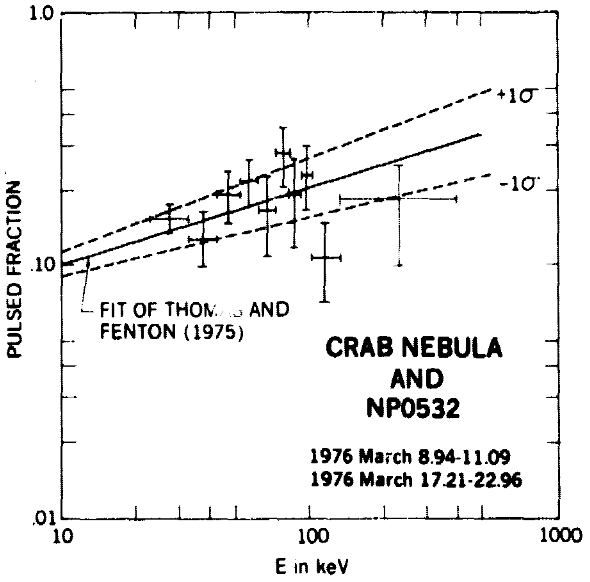

Figure 5. Pulsed fraction of emission from the Crab Nebula observed with the high-energy scintillation spectrometer on board OSO 8.

are in excellent agreement with their previously reported fit.

The Crab Nebula and its associated pulsar were observed a second time in March 1977. The data from these more recent observations will be analyzed in the same fashion as the results presented here. A measure of the year-to-year variability will be obtained. If no indication of variability is found, the data from both sets of observations will be combined to enable more statistically significant analysis of the spectral characteristics of the steady and the pulsed emission.

3. CYGNUS XR-1

The high-energy x-ray source, Cyg XR-1 was observed in 1975 from November 11 to 19 and again in 1976 from October 27 to November 15, excluding the period from November 1 to 7. In the energy range 3 to 6 keV, this source has been reported by many authors to exhibit a variable intensity between states which differ in flux by a factor of 3 (cf. Holt et al. 1976). Although the transitions between these "high" and "low" flux states occur at irregular intervals, the transition itself usually takes no more than one day in either direction. We report here an observation of such a transition at energies above 20 keV which shows that the spectrum of Cyg XR-1 exhibits the pivoting effect during intensity transitions expected from two-temperature accretion disk models of the x-ray emitting region (Shapiro et al. 1976, Eardley and Lightman 1976).

The raw counting rates during the 1975 observations in the interval 23 to 153 keV are shown in Figure 6. Data are grouped in intervals of 0.55995 days, or a phase interval of one-tenth the period of the HDE 226868 binary system. A decrease in counting rate of $\sim 40\%$ was observed to occur on November 16 with the source remaining at a significantly lower counting rate after the transition than before it. Comparison with 3 to 6 keV proportional counter data reported by Holt et al. (1976) reveals a simultaneous rise in the lower-energy counting rate.

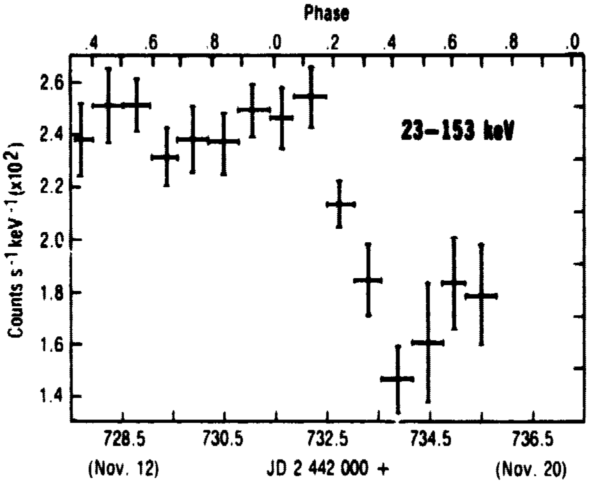

Figure 6. The counting rate observed from Cyg XR-1 in the energy range 23 to 153 keV during 1975 as a function of the binary phase of the system.

Our observations for 1976 are shown in Figure 7. The 23 to 153 keV intensity was higher than that observed in 1975, indicating that a reverse transition must have occurred between the two observations, in agreement with the report of such a transition in February 1976 by Holt et al. (1976). The decrease observed by us to occur on November 14 probably does not correspond to a change in intensity state at low energies; the 23 to

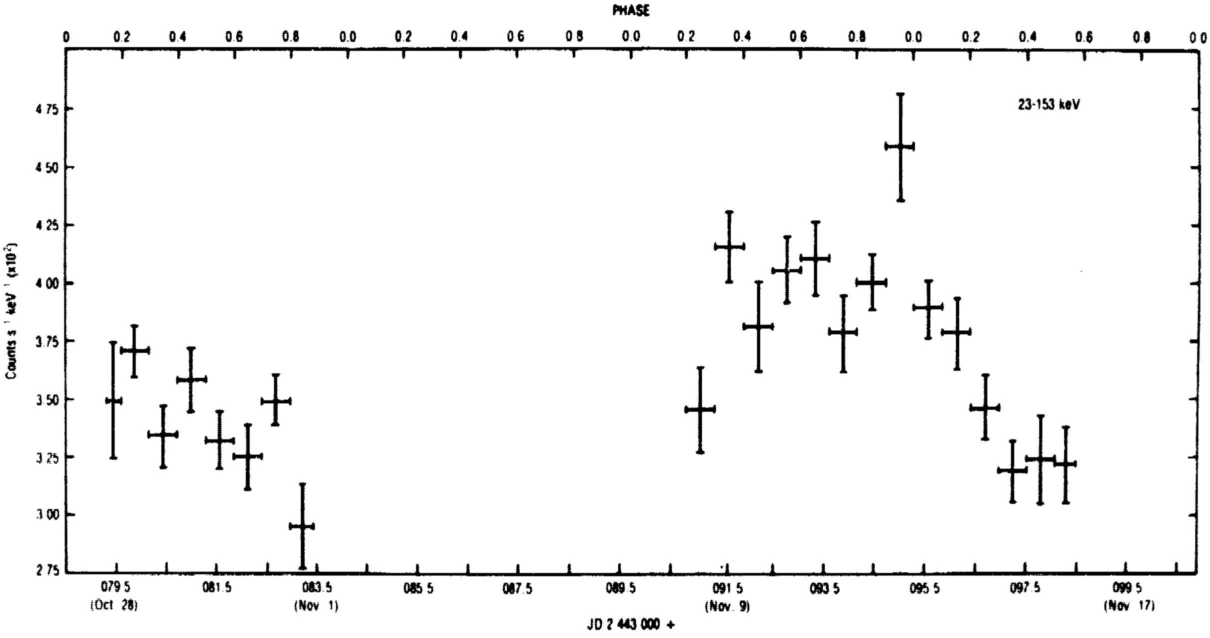

Figure 7. The counting rate observed from Cyg XR-1 in the energy range 23 to 153 keV during 1976 as a function of the binary phase of the system.

153 keV flux after the transition is still above that observed by us before the transition in 1975. Instead, it illustrates the large intrinsic variability present in the source even when in the "low" state at lower x-ray energies. No 3 to 6 keV proportional counter data are available for comparison as of this writing.

Typical spectra taken during periods of high and low intensity are shown in Figure 8. Both spectra are well represented by power law spectra of the form $dN/dE = C(E/E_0)^{-\alpha}$. The quoted uncertainties are 68% confidence intervals calculated according to the method outlined by Lampton et al. (1976). The anti-correlation between intensities at lower and higher energies indicates that the spectrum must pivot about a point between the two energy ranges. From the observations of Coe et al. (1976), this pivot point occurs at ~7 keV.

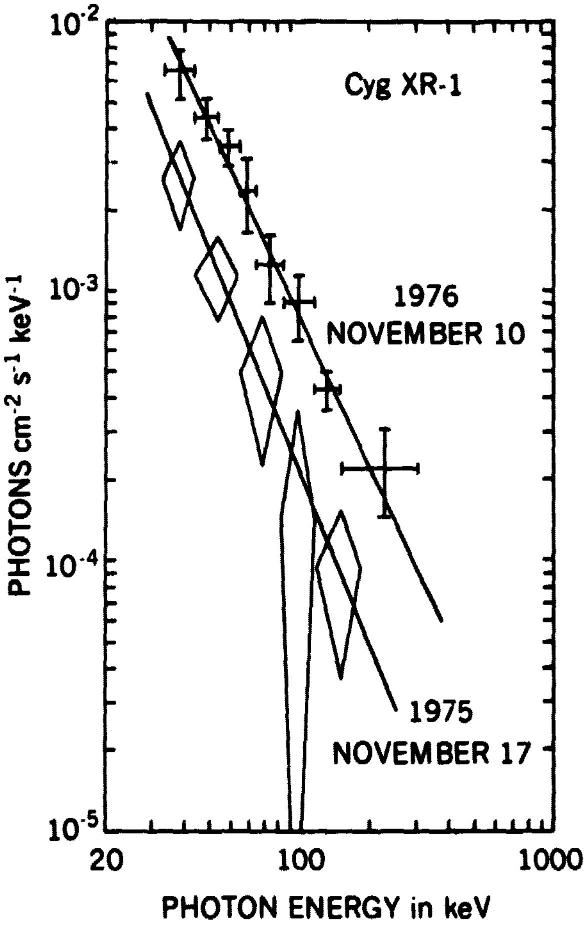

Figure 8. Typical photon spectra by Cyg XR-1 observed during a 3 to 6 keV "low" state (crosses, above) and a "high" state (diamonds, below). The error bars represent ± one standard deviation in the measured flux. The straight lines are power law fits to the spectra with $C = 1.8(\pm 0.1) \times 10^{-3}$ photons cm^{-2} s^{-1} keV^{-1} and $\alpha = 2.1(\pm 0.1)$ for $E_0 = 73.6$ keV on 1976 November 10 and $C = 1.0(\pm 0.2) \times 10^{-3}$ photons cm^{-2} s^{-1} keV^{-1} and $\alpha = 2.4(\pm 0.4)$ for $E_0 = 57.2$ keV on 1976 November 17.

This pivoting behavior (or "see-saw" effect) is predicted by models in which the x-ray emission is produced in a two-temperature accretion disk surrounding the secondary component of the binary system. A discussion of the results presented here is given by Dolan et al. (1977a) in light of these models. That analysis leads to the speculation that transitions in the luminosity are linked to variations in the mass transfer rate from the primary to the accretion disk surrounding the secondary. In a model proposed by Alme and Wilson (1976) nearly all the mass is transferred in an interval approximately one day long near periastron. It will be interesting to see whether the correlation of commencement time with phase near periastron is borne out in future transitions.

4. CENTAURUS A

Centaurus A (NGC 5128) is a peculiar radio galaxy with an active nucleus that emits radiation over the entire electromagnetic spectrum. In the radio range, Cen A consists of two separate sets of radio lobes (Wade et al. 1971) centered on the nuclear component. The outer radio lobes are approximately 5 degrees apart and the inner lobes are separated by 3.5 arc minutes. Optically, Cen A is an EO type galaxy with an obscuring dust lane girdling the equator. A near infrared (<1 micron) "hot spot" with an angular size of approximately 5 arc seconds (linear dimension of ~20 pc) has been observed at the center of the galaxy by Kunkel and Bradt (1971).

Cen A has been observed at x-ray wavelengths intermittently since 1971. These observations provide evidence for marked variability in the intensity and also suggest changes in the spectral index. An increase of the x-ray flux in the energy range 2-60 keV over an interval of six days has been observed by Winkler and White (1975). At 100 keV, the photon flux is sufficiently low that day-to-day variations are difficult to measure and none has been observed, but a significant increase did occur in the interval between 1971 and 1973 at this energy. At γ ray energies, an upper limit of 10^{-32} ergs cm^{-2} s^{-1} Hz^{-1} at approximately 250 Mev has been obtained by Fichtel et al. (1976). An integral flux of $4.4 \pm 1 \times 10^{-11}$ photons cm^{-2} s^{-1} at energies greater than 3×10^{11} eV has been reported by Grindlay et al. (1975).

Observations of Cen A were carried out with the high-energy scintillation spectrometer on board OSO 8 in 1975 from July 29 to August 3 and again in 1976 from July 28 to August 7. Radio microwave observations of Cen A were also carried out throughout this time period. These data, together with x-ray and radio observations are discussed in detail by Beall et al. (1977). Day-to-day variability is seen in the microwave flux and in the 1 to 40 keV x-ray flux reported by Winkler and White (1975). These short term variations are superimposed on longer term variability which is seen also in the 100 keV x-ray flux density, presented in the upper portion of Figure 9. The x-ray spectrum of Cen A is well represented by a power law as shown for the 1975 observations in Figure

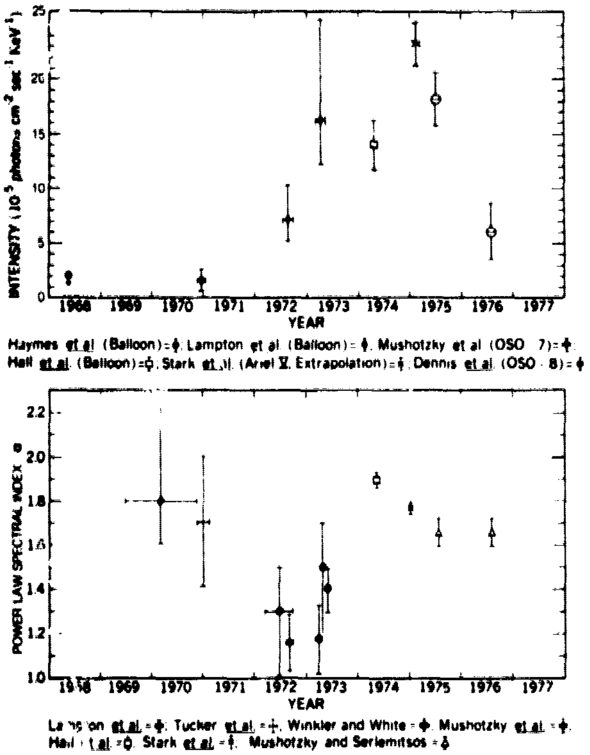

Figure 9. History of the 100 keV intensity and the power law spectral index of Cen A from 1968 to 1977.

10. The index, however, varies as can be seen in the lower portion of Figure 9. The observed radio and x-ray intensities show some concurrent variations but do not track one another throughout these observations.

A new model has been proposed by Beall et al. (1977) to explain the temporal and spectral characteristics of the electromagnetic radiation from Cen A. As in the models of Grindlay (1975) and Mushotzky (1977), the radio emission is assumed to be due to synchrotron radiation. In contrast to these other models, Beall et al. suggest a model for the nucleus of Cen A in which x-rays are produced by inverse Compton scatterings of a blackbody radiation field by the relativistic synchrotron electrons. The blackbody photon distribution is assumed to come from stars in the nucleus as suggested by both the infrared measurements of Kunkel and Bradt (1971) and by the optical measurements of van den Bergh (1975). The angular diameter of 5 arc second and the temperature of 250 K obtained for the infrared source places an upper limit on the energy in the relativistic electrons in the emitting region. The concentration of hot blue stars in the vicinity of the nucleus suggested by van den Bergh (1975) implies a starlight photon field with a temperature of 10^4 K. This blackbody photon distribution is used in calculating the magnetic field and the linear dimension of the source. The lack of concurrent variability between the radio and x-ray data is interpreted within the blackbody-Compton model as being the result of an expanding cloud of relativistic synchrotron electrons leaving the region in which the energy density of the blackbody photons is high. Upper limits obtained with the model indicate that there may be sufficient energy available in the nucleus to form radio lobes with the same total energy as those already present.

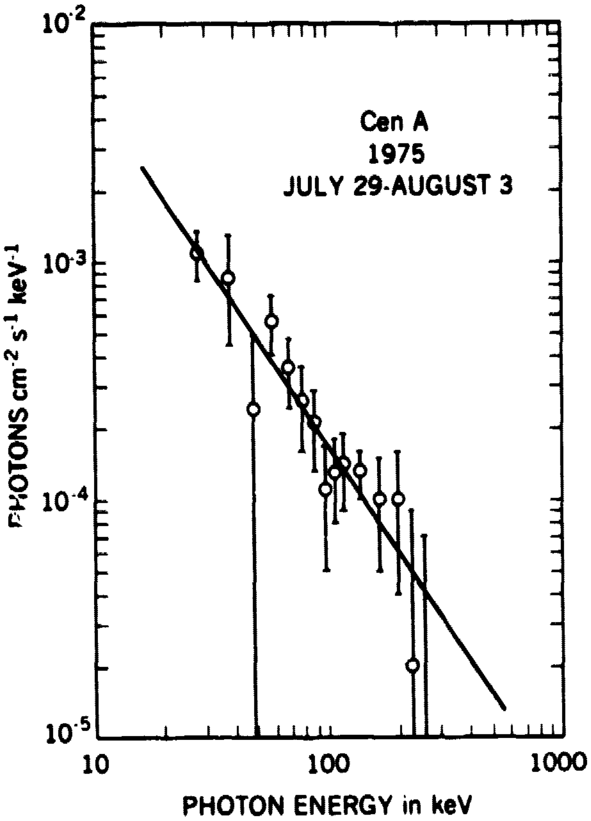

Figure 10. The photon spectrum of Cen A observed between 1975 July 29 and August 3. The error bars represent ± one standard deviation in the measured flux. The straight line is a power law fit to the data with C = 1.7(±0.2) x 10^{-4} photons cm^{-2} s^{-1} keV^{-1} and α = 1.49(±0.18) for E_0 = 100 keV.

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6. REFERENCES

Alme, M. L. and Wilson, J. R. 1976, Ap. J. 210, 233.

Beall, J. H., Rose, W. K., Graf, W., Price, K. M., Dent, W. A., Hobbs, R. W., Conklin, E. K., Ulich, B. L., Dennis, B. R., Crannell, C. J., Dolan, J. F., Frost, K. J., and Orwig, L. E. 1977, submitted for publication in Ap. J.

Carpenter, G. F., Coe, M. J., and Engel, A. R. 1976, Nature 259, 99.

Cocke, W. J. 1975, Ap. J. 202, 773.

Coe, M. J., Engel, A. R., and Quenby, J. J. 1976, Nature 259, 544.

Dennis, B. R., Frost, K. J., Lencho, R. J., and Orwig, L. E. 1977, Space Sci. Instr. (in press).

Dolan, J. F., Crannell, C. J., Dennis, B. R., Frost, K. J., and Orwig, L. E. 1977a, Nature (in press).

Dolan, J. F., Crannell, C. J., Dennis, B. R., Orwig, L. E., Maurer, G. S., and Frost, K. J. 1977b, Ap. J. (in press, 1977 November 1).

Eardley, D. M. and Lightman, A. P. 1976, Nature 262, 196.

Fichtel, C., Kniffen, D., Thompson, D. 1976, private communication.

Frost, K. J., Rothe, E. D., and Peterson, L. E. 1966, JGR 71, 4079.

Grindlay, J. E., Helmken, H. F., Hanbury Brown, R., Davis, J., and Allen, L. R. 1975, Ap. J. (Letters) 197, L9.

Grindlay, J. E. 1975, Ap. J. 199, 49.

Helmken, H. 1975, Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, 128.

Holt, S. S., Kaluzienski, L. J., Boldt, E. A., and Serlemitsos, P. J. 1976, Nature 261, 213.

Kunkel, W. E. and Bradt, H. V. 1971, Ap. J. (Letters) 170, L7.

Lampton, M., Margon, B., and Bowyer, S. 1976, Ap. J. 208, 177.

Maurer, G. S., Orwig, L. E., Crannell, C. J., Dennis, B. R., Dolan, J. F., and Frost, K. J. 1977, in preparation.

Mushotzky, R. F. 1977, submitted to Ap. J.

Shapiro, S. L., Lightman, A. P., and Eardley, D. M. 1976, Ap. J. 204, 187.

Schwartz, D. A. 1969, Unpublished Ph. D. thesis, University of California, San Diego.

Thomas, R. M. and Fenton, K. B. 1975, Proceedings of the Fourteenth International Conference on Cosmic Rays, Munich, 188.

Torr, A. and Seward, F. D. 1974, A. J. 79, 995.

van den Bergh, S. 1975, Ap. J. (Letters) 208, L673.

Wade, C. M., Hjellming, R. M., Kellermann, K. I., and Wardle, J. F. C. 1971, Ap. J. (Letters), 170, L11.

Winkler, P. F. and White, A. E. 1975, Ap. J. (Letters) 199, L139.