Compton Gamma-Ray Observatory observations of the Centaurus A region in the years 1991 to 1995

H. Steinle[1] **and the COMPTEL Collaboration**[1,2,3,4]

[1] Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse, Postfach 1603, D-85740 Garching, Germany
[2] SRON-Utrecht, Sorbonnelaan 2, NL-3584 CA Utrecht, The Netherlands
[3] University of New Hampshire, Institute for Studies of Earth, Oceans and Space, Durham, NH 03824, USA
[4] Astrophysics Division, Space Science Departement of ESA/ESTEC, NL-2200 AG Noordwijk, The Netherlands

14 October 1996

Abstract. The Compton Gamma-Ray Observatory (CGRO), as one of NASA's Great Observatories, provides for the first time coordinated observations over six decades of energy in the gamma-ray range. Four instruments cover, with some overlap, the energy band from few keV up to 30 GeV. Launched in April 1991, it is now in it's sixth year (Phase IV / Cycle 6) of flawless operation and has observed the Centaurus A region several times with all instruments.

BATSE is monitoring Cen A continuously in the low gamma-ray energies ($<$ 100 keV).

OSSE, covering the gamma-ray energies from 0.05 to 4 MeV, has observed Cen A five times. All exept one observation were simultaneous with COMPTEL and EGRET.

The imaging Compton telescope COMPTEL on board the Compton Gamma-Ray Observatory measures γ-rays in the energy range 0.75 - 30 MeV. The region on the sky including the radio galaxy Centaurus A, was in the wide field-of-view of COMPTEL in 15 pointings of various duration.

Although the Cen A region was also in the EGRET field-of-view during the COMPTEL observations, no strong signal can be associated with Cen A at higher gamma-ray energies (above 100 MeV).

The COMPTEL energy spectra in the energy range 0.75 - 30 MeV fit very well to the published Centaurus A spectra in the energy range 0.05 - 4 MeV from the OSSE instrument on board CGRO. Changes in intensity are observed in short and long term time intervals in all energy ranges and the spectral slope differs between the two observed global emission states.

1. Introduction

Centaurus A (NGC 5128, PKS 1322-427), the nearest active radio galaxy at a distance of $\leq$4 Mpc (Harris et al. 1984; Hui et al. 1993), was one of the few known MeV gamma-ray sources when the Compton Gamma-Ray Observatory was launched (Gehrels & Cheung 1992). Since then, it is among the objects which have been observed repeatedly by all CGRO instruments (Kinzer et al. 1995; Paciesas et al. 1993; Steinle et al. 1993; Thompson et al. 1995) and has been detected well into the MeV range.

Because of the peculiar appearence in the optical and the relative closeness, Cen A was and is the object of many observations over the whole frequency spectrum. Radio observations revealed the huge lobes, which extend to an apparent diameter of 10°on the sky, optical observations showed filaments related to the jet seen in the radio and X-ray regimes, and X-ray observations revealed flux variations on timescales of days. Gamma-ray observations also detected Cen A at very different flux levels (see e.g. Kinzer et al. 1995, Steinle et al. 1993)

In this paper we mainly report the results of the 15 observations made of the Centaurus A region in the 0.75 - 30 MeV range with the imaging Compton telescope COMPTEL on board CGRO between October 1991 and July 1995. A comparison with simultaneous OSSE observations is made and the BATSE long term monitoring data are used in this investigation.

2. Data

2.1. Observations

In 15 pointings during the CGRO observation phases I, II, III, and IV, the Centaurus A region was in the wide field-of-view of COMPTEL. A compilation of these observations is given in Table 1. The first 5 observations are from Phase I (the sky survey), the next 4 observations are from Phase II, 3 observations each were made in Phase III and Phase IV / Cycle 4.

3. Results

The analysis of the COMPTEL data obtained from the Centaurus A region during Phases I, II, III, and IV, gives the following results.

Table 1. Observation journal of the Centaurus A region for phases I, II, III, and IV of the CGRO observations

Obs.No.	date start	date end	TJD start	TJD end	duration	distance from pointing	eff. obs. time	OSSE observations	group
	(yy-mm-dd)		(JD - 2440000.5)		(d)	(°)	(d)		
Phase I									
12.0	91-10-17	91-10-31	8546.6	8560.6	14	3.0	4.4	yes	a
14.0	91-11-14	91-11-28	8574.7	8588.5	14	31.4	1.2	no	a
23.0	92-03-19	92-04-02	8700.6	8714.5	14	20.5	1.5	no	b
27.0	92-04-28	92-05-07	8740.6	8749.6	9	27.9	0.8	no	b
32.0	92-06-25	92-07-02	8798.6	8805.5	7	23.8	0.7	no	b
Phase II									
207.0	93-01-12	93-02-02	8999.6	9020.6	21	12.8	3.2	no	c
208.0	93-02-02	93-02-09	9020.6	9027.7	7	2.4	1.5	no	c
215.0	93-04-01	93-04-06	9078.7	9083.8	5	4.0	1.0	yes	d
217.0	93-04-12	93-04-20	9089.6	9097.6	8	4.0	1.7	yes	d
Phase III									
314.0	94-01-03	94-01-16	9355.7	9368.6	13	20.6	2.1	no	
315.0	94-01-16	94-01-23	9368.7	9375.6	7	20.6	1.0	no	
316.0	94-01-23	94-02-01	9375.7	9384.6	9	0.0	2.4	yes	
Phase IV / Cycle 4									
402.0	94-10-18	94-10-25	9643.6	9650.6	7	24.4	0.8	no	e
402.5	94-10-25	94-11-01	9650.6	9657.6	7	23.4	0.8	no	e
424.0	95-07-10	95-07-25	9908.6	9923.6	15	3.0	3.9	yes	

3.1. Detection of a Source

A **known** source is defined as detected, if at least in one observation (or a combination of observations) it is seen with a statistical significance $\geq 3\sigma$. Although may upper limits had to be listed in Table 2, there are also many measurements with more than 3σ. Following the above definition, Centaurus A is a well detected source.

3.2. Spectra

Centaurus A is known to be variable on time scales of days to months in all wavelenght bands (see section 3.3.). Therefore, to derive meaningful spectra, a compromise had to be found between the need to add observations to improve statistics and the danger to average out variations, if observations are added, which are separated by a too large time span. Under this consideration, we have added only observations which were separated not more than few months. The resulting groups of observations (a - e) are marked in the last column of Table 1.

An attempt to fit a model to the spectrum of an observation (or a combination of observations) has only been made, if at least three data points $\geq 1\sigma$ have been measured. This is only the case in the viewing periods listed in Table 2. A special case (all observations exept VP 12) for comparison with OSSE was added as well. Due to the small number of data points, only single power-law models have been used and the resulting fit-parameter values for a model of the form $I_0 \times E^{-\alpha}$ are given in Table 2 for all seven spectra together with the two OSSE fits to VP 12 and the sum of all other OSSE observations of Cen A given in Kinzer at al. (1995).

Table 2. Fit parameter values for a single power-law model ($I_0 \times E^{-\alpha}$; E in MeV) derived from the COMPTEL observations of the Centaurus A region with more than 2 data points. For comparison, the high energy part of the broken power-law fit to the simultaneous OSSE observation in viewing period 12 and the sum of all other OSSE observations of Cen A in Phases I to III are also listed. The agreement for VP 12 is excellent.

Observation	I_0 (10^{-5}cm^{-2} s^{-1})	α	reduced χ^2
VP 12.0	37^{+35}_{-33}	$2.3^{+0.6}_{-0.9}$	1.1
VP 208.0	30^{+47}_{-28}	$2.3^{+4.0}_{-1.1}$	0.2
group a	46^{+20}_{-21}	$4.6^{+3.9}_{-1.5}$	1.2
group b	15^{+18}_{-12}	$2.2^{+1.9}_{-0.8}$	0.2
all Phase I	31^{+17}_{-16}	$3.2^{+1.7}_{-1.0}$	0.3
all exept VP 12	21^{+9}_{-9}	$2.6^{+0.8}_{-0.6}$	0.2
sum of all obs.	18^{+10}_{-9}	$2.9^{+1.5}_{-0.6}$	1.2
OSSE VP 12	32.0 ± 1.4	2.3 ± 0.1	
all other OSSE	32.9 ± 1.4	2.0 ± 0.1	

Of special interest are of course the viewing periods, in which OSSE simultaneously observed Centaurus A, so that data over a much wider energy range are available. The longest published (Kinzer et al. 1995) simultaneous observation occured in viewing period 12. The spectra are in good agreement in the overlapping region (Figure 1). The extrapolation of the broken power-law spectral fit to the OSSE data (0.05 - 1 MeV), with has a spectral index of α = -2.28 above the break energy of 150 keV, fits also extremely well to our data.

The combined data double the energy range so that they span now almost 3 decades. We fitted a broken power-law model of the form $I_0 \times (E/E_b)^{-\alpha_1}$ for $E < E_b$ and $I_0 \times (E/E_b)^{-\alpha_2}$ for $E \geq E_b$ (E_b is the energy in MeV at the break) to the data. The resulting parameter are: I_0 = $(2.34^{+0.6}_{-0.6}) \times 10^{-2}$, E_b = $0.15^{+0.03}_{-0.02}$, α_1 = $1.74^{+0.05}_{-0.06}$, α_2 = $2.29^{+0.1}_{-0.1}$. Figure 1 shows the combined data and the model fit, together with the fit to the OSSE data alone. Both fits are in almost perfect agreement.

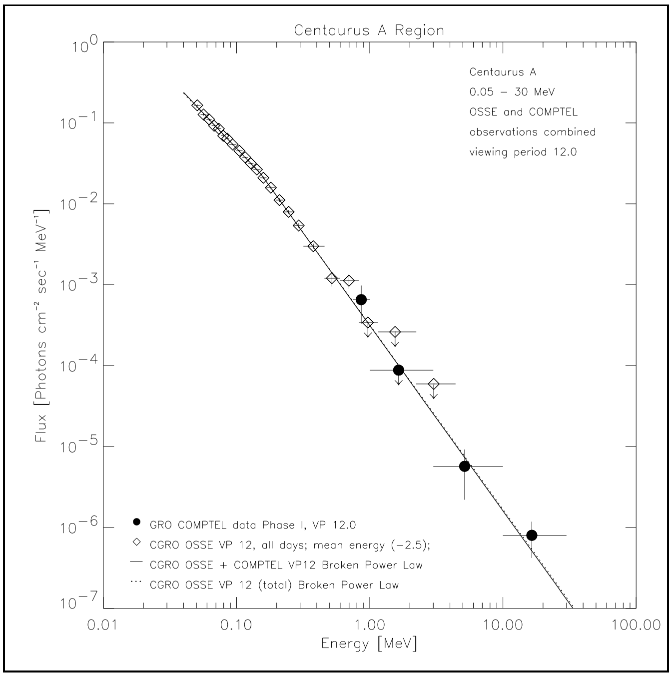

Fig. 1. Combined spectrum from the Centaurus A region as measured by OSSE (0.05 - 4 MeV) and COMPTEL (0.75 - 30 MeV) simultaneously during viewing period 12 of Phase I. The solid line is the broken power-law fit to the combined data, the dotted line is the fit to the OSSE data alone as given in Kinzer et al. (1995). Both fits are almost on top of each other (see also Table 2).

3.3. Variability

Variability is one of the well known features of Centaurus A and is observed in all wavelength regimes from radio to gamma rays (Abraham et al. 1982 (radio), Terrell 1986 (X-ray), Jourdain et al. 1993 (SIGMA), Kinzer et al. 1995 (gamma-ray)). Variability is also present in our data, although due to the limited statistics, only crude statements can be made and no time resolution within an observation is possible.

On short time scales, the largest flux variation between adjacent observations occured in the energy band 0.75 - 1 MeV in Phase III between VPs 314 and 315 (see Figure 2). Both observations are separated by $\sim$ 10 days and the drop in the intensity is more than 2σ , a significant change if one takes into accout, that the VP 315 observation is a 2σ upper limit.

The largest variation observed, is in the total energy band 1 - 30 MeV between Phase II and Phase III, where the flux drops by more than 3.3σ (see Figure 3).

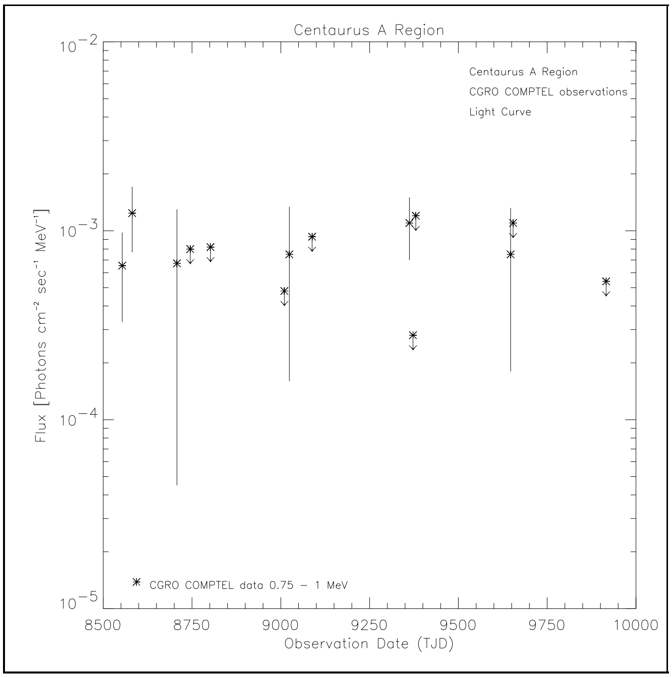

Fig. 2. Light curve of Centaurus A in the energy band 0.75 - 1 MeV as observed by COMPTEL covering the years 1991 to 1995. The most significant flux decrease observed is between the adjacent VPs 314 and 315, which are around TJD 9370, separated by $\sim$ 10 days. The flux decrease is more than 2σ.

Variations are also present in the power-law index of the derived seven spectra for which a model fit to the data was possible (see Table 2). As already noticed by Kinzer et al. (1995) for the OSSE observations, based on the intensity at low gamma-ray energies (below 100 keV) measured by BATSE and OSSE, our measurements fall into two distinct groups. Only one COMPTEL measurement (VP 12) was made in the "high state" at low gamma-ray energies and all other 14 observations were made in the "low state". (This "high state" is relative to all our observations and is only moderate if compared to historical high states of Centaurus A.)

Compared to the spectrum of VP 12, we find that the spectra measured in the "low state", are in almost all cases steeper. Kinzer et al. (1995) present model fits to the combined "low state" OSSE observations and we used this fit parameters to make a comparison with our combined "low state" data (all ob-

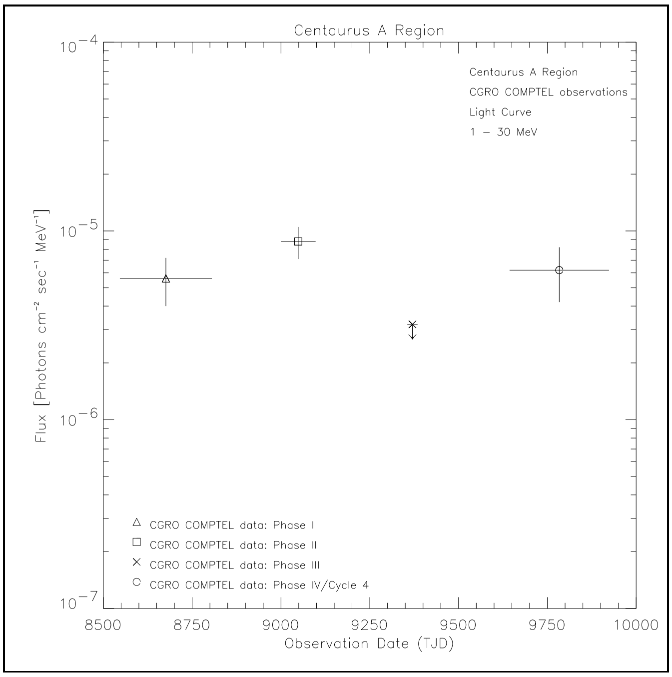

Fig. 3. Light curve of Centaurus A in the total energy band 1 - 30 MeV as observed by COMPTEL covering the years 1991 to 1995. The most significant flux decrease observed is between the Phases II and III and is more than 3.3σ.

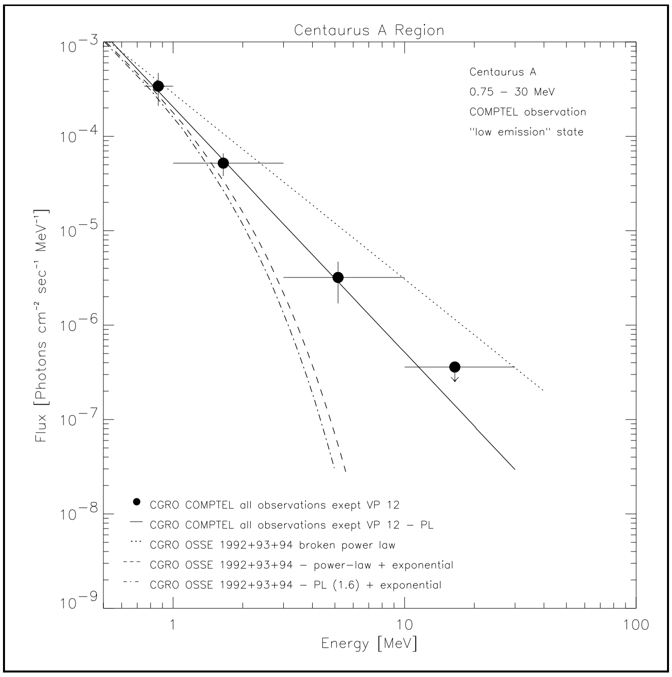

Fig. 4. COMPTEL "low state" data with a power-law fit (solid line), the high energy part of the OSSE broken power-law model (dotted line), the OSSE power-law model with an exponential cut-off (dashed line) and the same with a fixed power-law index of $\alpha = 1.6$ (dash-dot line). See text for more details.

servations exept VP 12). The OSSE high energy broken power-law index $\alpha = 1.97 \pm 0.11$ is much harder than the index derived for VP 12 (high state; $\alpha = 2.3 \pm 0.1$) and even more than our derived value of $\alpha = 2.6^{+0.8}_{-0.6}$. However, Kinzer et al. note, that an equally good fit to their data is obtained by using a power-law with an exponential cut-off. If we plot the extrapolation of the three possible fit models to the OSSE data in a plot with our "low state" data and our best fit to those COMPTEL data, our results are just between and thus again consistent with the OSSE results (Figure 4), and the intensity matches well in the overlapping region (around 1 MeV).

Acknowledgements. This research was supported by the Bundesministerium für Forschung und Technologie under the grant 50 QV 9096, by NASA contract NAS5-26645 and by The Netherland's Organization for Scientific Research (NWO). It also has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, CALTECH, under contract with the National Aeronautics and Space Administration.

References

Abraham Z., Kaufmann P., and Botti L.C.L., 1982, AJ 87, 532-536

Gehrels N., Cheung C., 1992, in: Testing the AGN Paradigm, eds. Holt S.S., Neff S.G., and Urry C.M., AIP Conference Proceedings 254, pp. 348-355

Harris G.L.H., Hesser J.E., Harris H.C., and Curry P.J., 1984, ApJ 287, 175-184

Hui X., Ford H.C., Ciardullo R., Jacoby G.H., 1993, ApJ 414, 463-473

Jourdain E., Bassani L., Roques J.P., Mandrou P., Ballet J., Claret A., Laurent P., Lebrun F., Finogenov A., Churazov E., Gilfanov M., Sunyaev R., Dyachkov A., Khavenson N., Sukhanov K., and Kremnev R., 1993, ApJ 412, 586-592

Kinzer R.L., Johnson W.N., Dermer C.D., Kurfess J.D., Strickman M.S., Grove J.E., Kroeger R.A., Grabelsky D.A., Purcell W.R., Ulmer M.P., Jung G.V., McNaron-Brown K., 1995, ApJ 449, 105-118

Paciesas W.S., Harmon B.A., Pendleton G.N., Finger M.H., Fishman G.J., Meegan C.A., Rubin B.C. and Wilson R.B., 1993, A&AS 97, 253-255

Steinle H., Bloemen H., Collmar W., Diehl R., Hermsen W., Lichti G., McConnell M., Ryan J., Schönfelder V., Stacy G., Strong A.W., Swanenburg B.N., Varendorff M., Williams O.R., 1993, Adv. Space Res. Vol. 13, No.12, pp. 731-734

Terrell J., 1986, ApJ 300, 669-674

Thompson D.J., Bertsch D.L., Dingus B.L., Esposito J.A., Etienne A., Fichtel C.E., Friedlander D.P., Hartman R.C., Hunter S.D., Kendig D.J., Mattox J.R., McDonald L.M., Montigny C.v., Mukherjee R., Ramanamurthy P.V., Sreekumar P., Fierro J.M., Lin Y.C., Michelson P.F., Nolan P.L., Shriver S.K., Willis T.D., Kanbach G., Mayer-Hasselwander H.A., Merck M., Radecke H.D., Kniffen D.A., Schneid E.J., 1995, ApJS 101, 259-286