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Centaurus A: A Multifrequency Review

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Abstract Due to its peculiar appearance in the optical, its proximity, and its importance for the understanding of active galaxies and their active galactic nuclei (AGN), Centaurus A has been observed frequently within the last 150 years in all accessible wavelength bands. Thus a wealth of data exist over a wide range in frequencies (wavelengths, energies), which have been compiled in the "NASA Extragalactic Database" (NED). A multifrequency combination of all those results allows to establish the important spectral energy distributions (SEDs) of this variable AGN in different emission states, and due to its nearness and the improving spatial resolution of new generation telescopes in all wavelength regimes, an attempt could be made to derive SEDs of different parts of the spatially resolved inner region of this AGN. The difficulties and problems to do this are described in this review.

Key words: black hole physics — galaxies: active — galaxies: individual (NGC 5128, Cen A) — galaxies: peculiar — galaxies: photometry

1 INTRODUCTION

With a distance of only 3.84 ± 0.35 Mpc (Rejkuba 2004), Centaurus A (Cen A, NCG 5128) is the nearest active galaxy. It contains an active galactic nucleus (AGN) with recent mass estimates of the central black hole in the range of $10^8\ M_\odot$ (Marconi et al. 2001; Silge et al. 2005). Its proximity makes it uniquely observable among such objects, even though its bolometric luminosity is not large by AGN standards. Besides the huge radio lobes which extend 10° on the sky, Cen A possesses an inner jet close to the nucleus with a large inclination to the line-of-sight ($\sim 70^\circ$; see e.g. Tingay et al. 1998) which is detected in the radio and X-ray regime (cf. Fig. 1). It is therefore one of the best examples of a radio-loud AGN viewed from the side of the jet axis (Graham 1979; Dufour et al. 1979; Jones et al. 1996) sometimes called a "misdirected" BL Lac type AGN ("blazar") at higher energies (Morganti et al. 1992).

Cen A as an active galaxy is usually classified as a FR I type radio galaxy and as a Seyfert 2 object in the optical (Dermer & Gehrels 1995).

Emission from Cen A is detected from radio to high-energy gamma-rays (Israel 1998, Johnson et al. 1997, Clay et al. 1994) making it the only radio galaxy detected in MeV gamma-rays. All other identified AGN detected in MeV gamma-rays are blazars (Collmar et al. 1999) where current models require the jet to be aligned almost parallel to the line-of-sight. Because the jet in Cen A is seen under a much larger angle, Centaurus A may be a representative of the many other "normal" active galaxies where we do not view along the jet axis and which are just too far away to be detected with present day instrument's sensitivity at high energies (gamma rays and beyond).

To study the global spectral energy distribution (SED) of Cen A over all available frequencies (energies), in different emission states, and with high spatial resolution, gives insight into the emission processes in AGN. As Cen A may represent the majority of all AGN, i.e. AGN not pointing with their jets towards us, it may even be an example of a class of objects contributing to the cosmic diffuse background at gamma-ray energies (Weidenspointner & Steinle 2001).

Due to the page limitation for this proceedings and the general topic of this workshop, emphasis has been given to discuss in this paper mainly some of the features and problems which arise when combining and interpreting measurements of Centaurus A at higher energies.

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2 MORPHOLOGY OF CENTAURUS A (NGC 5128) ACROSS THE SPECTRUM

The elliptical (S0) galaxy NCG 5128 is the stellar body of the giant double radio source Centaurus A. It is one example of the family of elliptical galaxies that have an absorbing band of gas and dust projected across their stellar body (see Fig. 1). The prominent twisted disk of gas and dust contains many H II regions and is lying approximately along the galaxy's minor axis, obscuring the nucleus at optical wavelengths. (This dust lane's rotation was determined by Burbidge & Burbidge 1962 in a way, that the south-east side is approaching and the north-west side is receding.)

The dust lane and the extended shell structures detected in long exposure optical images (Malin et al. 1983) are thought to be remnants of a recent ($10^7 - 10^8$ years ago) merger of a giant elliptical galaxy with a smaller spiral galaxy. A consistent modelling of this event as galaxy shredding, that includes two other 'peculiar' objects in the vicinity of Cen A, is given by Thomson (1992).

Narrow emission lines in the (sub) millimeter regime originate in the dust band that crosses the optical picture of Cen A (Eckart et al. 1990).

The giant double radio source Centaurus A which extends 10° on the sky can be resolved down to sub-arcsecond resolution in the inner radio structures which corresponds to several pc due to it's proximity. A detailed description of the radio morphology is given in Meier et al. (1989).

Optical observations show filaments related to the inner jet seen in the radio and X-ray regimes (Morganti et al. 1991).

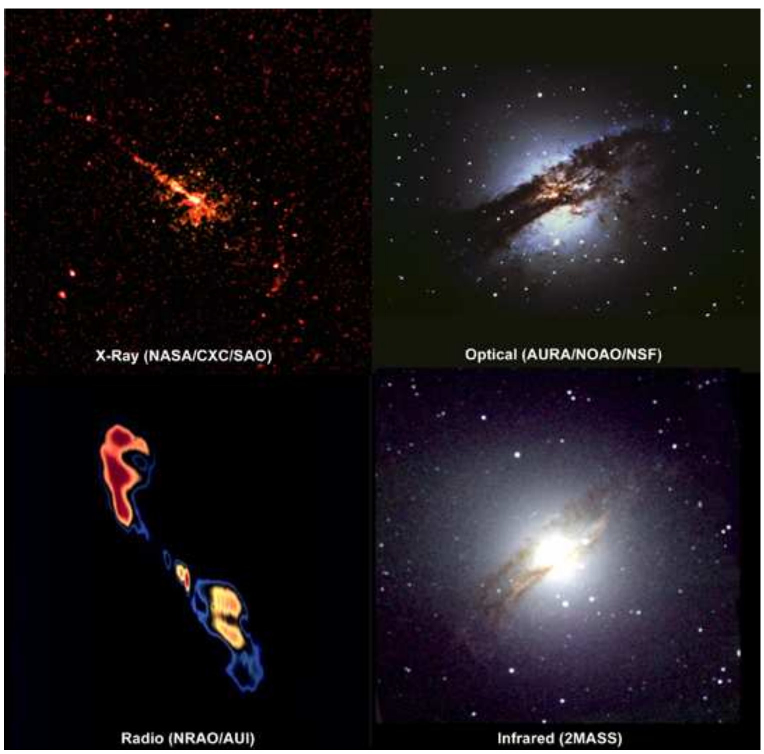

Fig. 1 Centaurus A in different wavelength regimes. The images have slightly different scales (X-Ray: $15' \times 15'$; optical: $7.5' \times 7.5'$; radio: $12.5' \times 12.5'$; infrared: $10' \times 10'$). The orientation is also slightly different among the frames probably due to the mixed use of Galactic and Equatorial coordinates! North is up and East to the left. (Image credit: NASA/CXC/NAO).

The inner part of Cen A, observable with high spatial resolution mainly in the infrared, shows a circum-nuclear disk of about 400 pc diameter and a central cavity of about 90 pc. This disk is emitting in the (sub) millimeter range. Against this emission, a variety of molecular absorption lines are seen (Israel et al. 1990).

In addition, evidence for a thin disk of ionized gas with a diameter of 40 parsec centered on the nucleus of Centaurus A has been found (Schreier et al. 1998). This disk is not perpendicular to the jet and thus not thought to be the accretion disk of the central black hole.

Cen A was one of the few known MeV gamma-ray sources when the *Compton* Gamma Ray Observatory (CGRO) was launched in 1991 (Gehrels & Cheung 1992) and it has therefore been observed repeatedly by all CGRO instruments throughout the whole mission that ended in June 2000 (Kinzer et al. 1995; Paciesas et al. 1993; Steinle et al. 1998; Thompson et al. 1995). Thus a very good coverage of the Cen A spectrum at high energies exists.

Several observations of Centaurus A at very high energies (Gev and TeV) have been published (Clay et al. 1994), but a confirmation of the often marginal results is still open.

3 THE SPECTRAL ENERGY DISTRIBUTION

With the inclusion of most of the high energy data (gamma-ray data) into the "NASA Extragalactic Database" (NED), a very useful data base of almost all measurements of Centaurus A has become available covering 23 decades in the frequency range from 10^7 to 10^{30} Hz. Figure 2 shows an unclassified plot of all measurements listed in the NED. The very important in the context of this paper is the fact, that in the NED also the references to the original publications of the data are given, which enables it in most cases, to look up the details of the measurements.

To test their model of the emission of a jet which consists of a spine and a surrounding layer, Ghisellini et al. (2005) used a "nuclear" sub set of this data as defined by Chiaberge et al. (2001) together with the fits to the high energy data shown in Figure 5. As can be seen in Figure 3, the two maxima in the emission of Cen A (and those of other AGN) are reproduced quite well in the frequency region modelled. Like in most models, no attempt has been made so far to include the features at very low and very high frequencies which are present e.g. in Figure 2.

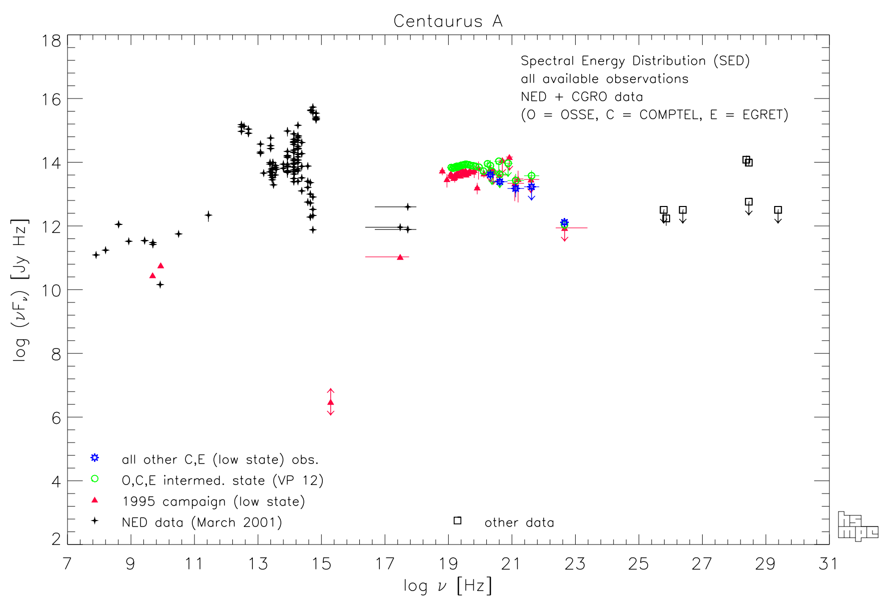

Fig. 2 The Spectral Energy Distribution (SED) of Centaurus A using all available data. No further classification of the data has been applied.

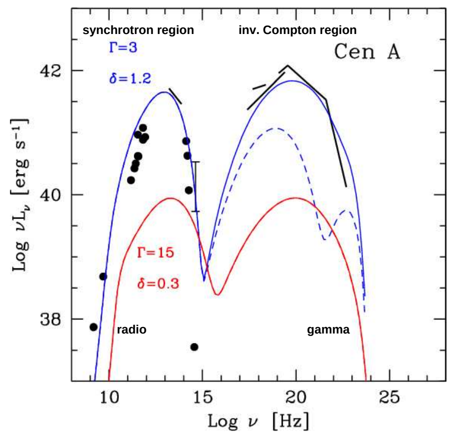

Fig. 3 Spine-layer model of the emission of Centaurus A as proposed in Ghisellini et al. (2005). The two solid lines differ in the parameters Γ and δ which are the Lorentz factor and Doppler factor respectively. The dashed curve shows the effect if only one component (spine or layer) is used (Ghisellini et al. 2005 adapted).

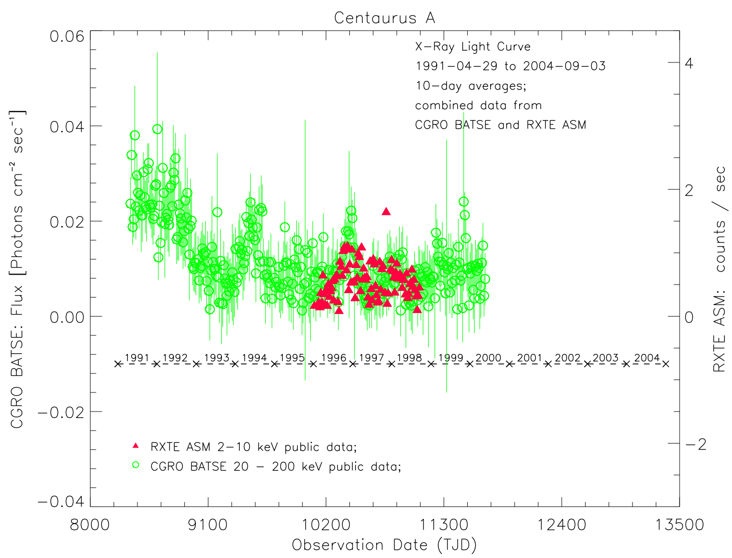

Fig. 4 A compilation of the Cen A 20–200 keV flux data measured with the BATSE instrument onboard CGRO shown together with the 2–10 keV data of the RXTE all sky monitor (ASM) to show the variability of this AGN on a 10-day scale. The BATSE instrument was active during the whole CGRO mission from May 1991 until June 2000. The still active (August 2005) ASM of RXTE started its measurements in January 1996. In the overlapping interval, a good correlation of the flux values measured in the different energy bands is observed. Included in the plot as a dotted line is the trigger threshold for the proposed high emission state ToO observations mentioned in the text.

As in many other models of the emission of Cen A and other sources, two important parameters of the observations, which may contribute significantly to the SED, have only marginal been taken into account: the epoch and duration of the measurements and the spatial resolution. This will be discussed in the next sections 4.2 (variability) and 4.3 (spatial resolution).

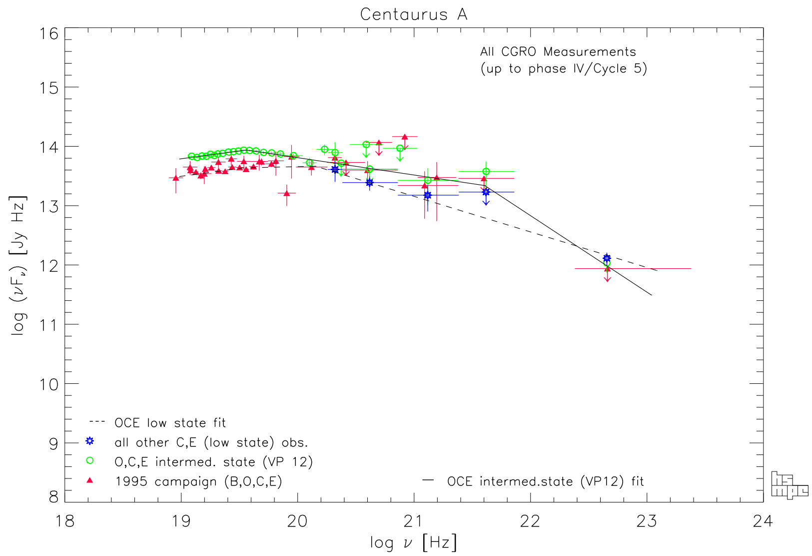

Fig. 5 The high energy spectrum of Centaurus A in the two different emission states observed with CGRO (Steinle et al. 1998).

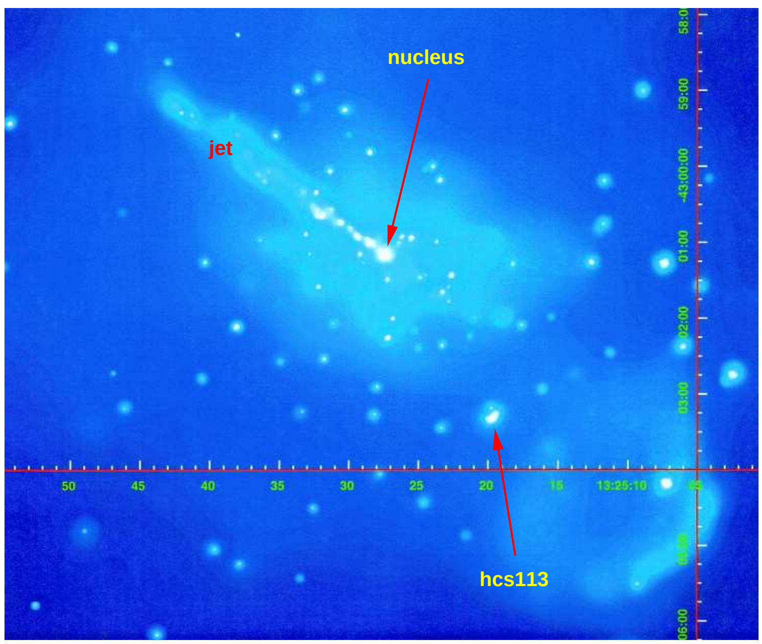

Fig. 6 Chandra image ($14' \times 8'$) of the central part of Centaurus A in the 1–3 keV band. Besides the nucleus and the jet, many other X-ray sources are detected. The highly variable source hcs113 described in the text, which is at a distance of only 2.5 arcmin from the nucleus, is marked. (Image: Kraft et al. 2001 adapted).

4 VARIABILITY AT HIGH ENERGIES

Centaurus A is known to be a highly variable object in all wavelength bands (Bond et al. 1996, Baity et al. 1981, Turner et al. 1997, Steinle et al. 1998). It shows distinct high, intermediate, and low emission states in X-rays which have been defined by Bond et al. (1996).

A continuous monitoring of Cen A in (hard) X-rays started in 1991 when the BATSE instrument on board CGRO observed Cen A for more than 9 years until 2000. With the launch of the Rossi X-ray Timing Explorer (RXTE) in 1995 a second instrument joined the monitoring and this all sky monitor is still active today. Thus, a continuous data base of the Cen A flux in X-rays with a resolution of few hours exists since 1991 and it is still growing. A compilation of the 10-day average fluxes is shown in Figure 4.

Using the definition of the emission states in Bond et al. (1996), the many CGRO observations of Centaurus A performed by the CGRO instruments OSSE (0.05–4 MeV) COMPTEL (0.75–30 MeV) and EGRET (> 50 MeV), occurred all but one during low emission states (Steinle et al. 1998). Only the very first observation of Cen A in October 1991 was made during an intermediate emission state (see Fig. 4). Cen A has remained in an extended low state since then. Of extreme interest would be of course a detailed observation at high energies in a high emission state as the only observed intermediate state seems to indicate a steepening of the SED at higher energies if the emission state increases (see Fig. 5). To be prepared, target of opportunity (ToO) observations with several instruments covering a wide frequency range with the best possible spatial and temporal resolution have been prepared and are just awaiting cooperation from Cen A. Among other trigger sources for this ToO, the RXTE ASM flux will be one of the trigger criteria if it exceeds a certain count rate over a time interval of several days. This trigger threshold is indicated in Figure 4.

4.1 The Contribution of Unresolved Sources to the Variability of Cen A

The detection of a bright X-ray transient at the small apparent distance of only $2'.5$ to the nucleus of Cen A in ROSAT images taken in 1995 (Steinle et al. 2000) may shed new light on the reported variability of Cen A if measured with instruments with low spatial resolution. The transient was the brightest point source in a $12' \times 12'$ wide field around the center of Cen A and the total luminosity was about 30% of the combined luminosity of the nucleus and jet. This object, marked as hcs113 in Figure 6, was not detected in any other ROSAT observation in the years before and after 1995.

Figure 6 shows a Chandra image adding two observations from 1999 and 2000. More than 200 X-ray sources, the majority of them variable, were found in a $25' \times 25'$ field around the center of the galaxy. The transient hcs113 is detected again in the composite image. However, between the two Chandra observations, it varied by at least a factor of 500, being not detected in the second observation (Kraft et al. 2001). hcs113 is supposed to be an X-ray binary accreting close to the Eddington limit, like several other X-ray binaries observed in other galaxies.

If Cen A would have been observed in 1995 with an X-ray instrument with lower spatial resolution, the change in luminosity, even caused by only one such object, would probably have been attributed to the AGN. As almost all of the early X-ray observations had lower spatial resolution, the detected variability in those observations has to be taken with caution when attributed to the AGN.

4.2 Variability and the SED

Historically, Cen A has exhibited greater than an order of magnitude X-ray intensity variability (Bond et al. 1996) on timescales of days with an intensity-independent spectral shape below about 100 keV. Most measurements, when fitted with models including a spectral break, show no distinct change of the spectral index ($\alpha \sim 1.7 - 1.8$) below the break (i.e. at lower energies than ~ 100 keV) when the intensity changes (e.g. Baity et al. 1981, Feigelson et al. 1981, Morini et al. 1989, Maisack et al. 1992, Jourdain et al. 1993).

In gamma rays, Cen A has been observed by various instruments and it has been found to exhibit states of low, intermediate, and high intensity as well (Bond et al. 1996, Kinzer et al. 1995, Steinle et al. 1998) and other than at energies below 100 keV, the spectral shape changes significantly (see Fig. 5). It is therefore very important to measure complete SEDs simultaneous at a given time and in the different emission states. This is mandatory to avoid confusion in the interpretation of the data and difficulties when models are fitted to the data. However, simultaneous multiwavelength observations covering a large interval in frequencies have so far only been organized once in 1995 (Steinle et al. 1998) when Cen A was observed in a low emission state. All other data have been taken at random times.

An other problem related to the variability is the fact, that especially observations with low sensitivity instruments require very often long integration time, which is much longer than the typical time scale for the Cen A variability. Gamma-ray measurements by the instruments on board CGRO lasted typically several weeks to gain enough statistics to derive a significant data point, whereas Cen A is known to be variable in the adjacent hard X-ray band on time scales of less than a day. Therefore, to combine this data into one SED and to fit models to it, is problematic.

4.3 Spatial Resolution and the SED

The other very important parameter in all observations of Cen A is the spatial resolution. With many present day instruments it is now possible to resolve the jet, nucleus, and other sources close to the center of this nearest active galaxy. Due to the lack of sufficient spatial resolution for almost all other active galaxies at greater distances, all this components together are usually called the AGN of such an object.

Simultaneous observations of Cen A with high spatial resolution in different (global) emission states will be able for the first time to disentangle the possible contribution of the different components to the overall spectrum (SED) and thus provide important information necessary to interpret the observations of Cen A and the more distant other active galaxies (and their AGN). So far, often the emission of an AGN was attributed to the "nucleus". But as said above, this region in distant AGN is a combination of true nucleus, jet, and many other sources as the example of Cen A has shown. It is not at all clear, if high energy emission from AGN, where the line-of-sight is not along the jet axis, is dominated by the nucleus or, as by definition in blazars, by the jet. Observations of Cen A can contribute to the solution of this problem. Unfortunately, the instruments on board the Integral satellite have not been a sufficient spatial resolution of better than $1'$ and are just not sensitive enough at gamma-ray energies at several MeV to enable the crucial measurements if Cen A remains in a low emission state. But the next generation instruments like advanced Compton telescopes or GLAST will be able to perform such observations.

Meanwhile it is planned to use all the information collected in the NED for the Cen A observations, to derive classified SEDs for the already existing data, where the measured fluxes in the observations are grouped according to the epoch, spatial resolution, and the "object" that was measured (i.e. galaxy, nucleus, jet, ...). But also the very important are new measurements.

5 OUTLOOK

Many investigations of Centaurus A in all wavelength bands are carried out at the moment. Almost all new instruments, if they can observe it, are usually pointed to this enigmatic object. A wealth of data exist already and new data are added continuously. As described in this review, the high detail in the information on Cen A due to its closeness can create problems because we see so much in detail (as with the Sun compared to distant stars), but on the other hand Cen A provides us with a "front seat" in the AGN theater. Taking into account the effects of the variability and the spatial resolution, we can investigate this AGN in so much detail, that it can well be, that Centaurus A will become the "Rosetta Stone" of AGN science!

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Appendix A: A DEDICATED CENTAURUS A WEB SITE

In an effort to collect and present all available information on Centaurus A, a set of dedicated web pages has been established at the Max-Planck-Institut für extraterrestrische Physik. The aim of this site is to provide the user with all (electronically) available up to date information "by a mouse click".

The dedicated Centaurus A Web Pages are available at: http://www.mpe.mpg.de/Cen-A/.

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DISCUSSION

MASSIMO CAPPI: Is the $2''$ (20 pc) - scale hot disk consistent with beeing the molecular torus that is hypothesized in AGN unified models?

HELMUT STEINLE: No. This thin disk of ionized gas (40 pc diameter) is not perpendicular to the jet and thus it can neither be the accretion disk nor the torus.

MASSIMO CAPPI: What is the mass of the black hole in Cen A? Is there a measurement of it from stellar dynamics?

HELMUT STEINLE: The mass currently assumed is about $10^8 M_\odot$. The most recent paper on the mass of the central object I know of, is using stellar kinematics! (Note added later: see Silge et al. 2005).