EINSTEIN OBSERVATIONS OF ACTIVE GALAXIES AND QUASARS

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INTRODUCTION

The study of active galaxies in extragalactic X-ray astronomy covers a substantial range of objects between "normal" galaxies, such as our own, and clusters of galaxies. The X-rays from normal galaxies can be considered as the summed emission from individual galactic X-ray sources, as observed in our own galaxy, described as primarily supernova remnants and binary systems containing accreting white dwarfs, neutron stars, or black holes. Clusters of galaxies may contain individual X-ray emitting galaxies, but the emission is dominated by hot intracluster gas. In between these two lies a zoo of X-ray emitting objects including radio galaxies, emission line galaxies, Seyfert galaxies, BL Lac objects and quasars. The nature of these objects, their energy generating mechanisms and their relation to each other is not fully known. However, it is likely that the bulk of the X-ray emission from them all is associated with activity in galactic nuclei. We thus look toward the X-ray observations to help us understand these objects.

The Einstein Observatory can contribute toward this study in two areas, both of which illustrate the power of an imaging observatory. First, we can resolve the comparatively nearby objects and thus obtain direct information on their detailed structure. Second, we can use the greatly increased sensitivity of an imaging instrument to detect many more of each class of object. Since many of these objects, in particular QSO's, are at cosmological distances and thus very faint despite their high intrinsic luminosity, this increase in sensitivity is essential to observing enough objects to study class properties.

This report contains examples of both these areas of study. In the first category, the radio galaxies Centaurus A and Cygnus A will be discussed. Centaurus A is comparatively closeby and has been studied in detail for some time; the Einstein observations have nevertheless revealed new aspects about its structure. Cygnus A is one of the brightest radio sources in the sky; however it is some 60 times farther away and obscured by our own galaxy and thus has been harder to study. In both these sources, a comparison of the radio and imaged X-ray flux is allowing us to measure magnetic fields. The results presented here are from work done personally with assistance from several people at CFA, in particular Rick Feigelson. In the second category, Einstein observations of quasars will be discussed. Here, we not only study details of specific QSO's, but with 1000 times the sensitivity of previous observations, we have increased the number of known X-ray emitting QSO's from 3 to 22, and have seen QSO's at distances corresponding to an age of 15 billion years. This allows us to show that quasars contribute significantly to the X-ray background. These QSO results are from a group effort headed by Harvey Tananbaum.

CENTAURUS A

Centaurus A, or NGC 5128, is one of the most unusual and spectacular galaxies in the sky (Fig. 1). At a distance of about 5 Mpc, it is the nearest radio galaxy, providing an excellent laboratory for investigating X-ray emission from active galactic nuclei and extended radio features.

Optically, NGC 5128 appears to be an elliptical galaxy with a dark lane through the central region, most likely a disk at large inclination to the plane of the sky. At radio wavelengths it exhibits two sets of radio lobes, giant ones extending several degrees, and smaller inner lobes several arc min to the northeast and southwest. The nucleus is a compact radio, infrared, X-ray, and gamma ray source. Its hard X-ray emission, with 2-10 keV luminosity of approximately 1×10^{42} erg/sec, is variable on timescales of years to hours. The light travel time thus limits the size of the hard X-ray emitting region to be $\lesssim 10^{15}$ cm in size. The X-ray spectrum is strongly cut off at low energies, consistent with the source being at the nucleus.

We have used both the HRI and IPC detectors of the Einstein Observatory in a complementary fashion to study the structure of the X-ray emission in the central regions of Centaurus A. Our data show four distinct spatial components representing a variety of physical conditions and emission mechanisms:

1) The previously known point source at the nucleus.

2) A diffuse component extending approximately 2 arc min from the nucleus.

3) X-ray emission associated with the inner radio lobes.

4) A new feature or X-ray jet between the nucleus and the northeast radio lobe.

Figure 2 shows the IPC image, containing about 20 000 counts in a 3 hr exposure. Although the central component is dominant, there are asymmetries associated with the inner radio lobes. These can be displayed by suppressing the central source as shown in Figure 3. A more quantitative display of the data on Figure 4 shows that the excess flux associated with the lobes is significant at the 4-sigma level. The lobes contain approximately 1000 counts, or 5 percent of the nuclear emission in the IPC spectral band, corresponding to an X-ray luminosity of 10^{39} to 10^{40} ergs/sec. This weak feature is comparable to the entire X-ray emission from a normal galaxy. The most likely model is inverse Compton scattering of highly relativistic electrons with the 3° microwave background. If this model is correct, comparison of the X-ray and radio fluxes allows us to measure the mean magnetic field in the lobes to be a few micro-Gauss. This is an order of magnitude lower than the equipartition field strength. However, inverse Compton scattering of less energetic electrons off starlight photons may contribute substantially to the X-ray flux, allowing greater magnetic fields. The important thing is that we are measuring a magnetic field in intergalactic space.

Figure 5 shows the HRI image of Centaurus A. The inner lobes are not apparent due to their extent and low surface brightness. However, a previously unknown feature one arc min to the northeast of the central point source is clearly seen. The new component lies much closer to the center than the inner radio lobe. The HRI also shows a diffuse component distributed isotropically about the nucleus. A plot of the radial surface brightness distribution is shown in Figure 6. There is a significant excess of counts above background, as compared to a calibration point source. The new northeast component produces the small bump at 1 arc min, and is not responsible for the isotropic, diffuse halo about the nucleus.

Figure 7 shows a contour map of the same data, along with a diagram of recently discovered optical filaments shown on the same scale. The X-ray and optical features are clearly coaligned and appear to be related to each other. Furthermore, they are aligned with the radio lobes. One can interpret the new X-ray feature either as a new lobe, which has not yet cooled and expanded enough to start emitting in the radio, or alternatively, as evidence for a jet from the central energy source. This would be consistent with the need for an energy supply from the central source to power the radio lobes.

The radio lobes require about 10^{41} erg/sec to stay alight. If this energy is provided by a relativistic jet of particles from the galactic nucleus, this jet would have sufficient pressure to shock heat about 10^{6} $M_{\odot}$ of plasma to X-ray temperatures. This would provide 10^{39} to 10^{40} erg/sec, about what we see. (The optical filaments could have been accelerated to their current position from the nucleus by the jet, or could have condensed out of the hotter medium by thermal instability.) Thus, the same energy source could power the inner lobes and account for the close-in X-ray/optical features. The lack of a jet to the southwest is not yet explained, although there have been suggestions of alternating production of lobes in double radio sources.

To review, the Einstein observations clearly show four components in the X-ray emission from Centaurus A. First, there is the point source, whose HRI position lies 1 ± 2 arc sec of the infrared nucleus, and is clearly the highly variable source that dominates the hard X-ray band. It is comparatively weak in the Einstein observations (particularly the HRI) because of the absorption of the soft X-rays by matter surrounding the nucleus of the galaxy. Second, there is a diffuse arc min "halo" about the nucleus, which may be due to Thompson scattering of X-rays from the central source due to electrons in the surrounding gas. Such an electron scattering halo has been predicted. Third, there is X-ray emission from the inner lobes, which is allowing us to measure the magnetic field in the source. Fourth, there is an X-ray jet pointed toward the northeast radio lobe, and associated with unusual optical features. This may be a link between the central source and the radio lobes, and would thus help solve the long standing problem of how radio lobes are powered.

CYGNUS A

Moving on to Cygnus A, we have another radio galaxy some 10 000 times more luminous than Centaurus A, but 65 times further away. It is one of the brightest radio sources, consisting of two lobes separated by about 2 arc min with a luminosity of approximately 2×10^{45} erg/sec, and a weak compact component centered on a cD galaxy. The galaxy itself has a luminosity of approximately 10^{45} erg/sec in line emission and there is comparable emission in the IR. The galaxy looks superficially like Centaurus A, with an obscuring dust lane. However, it is located at the center of a rich cluster; X-ray emission at a level of a few Uhuru counts/sec, also close to 10^{45} ergs/sec, has been seen.

Cygnus A has been well studied in the radio, being relatively nearby for a very strong source. However, its location in the galactic plane has made optical studies very difficult. The X-ray data has also been subject to various interpretations ranging from hot cluster gas to active galaxy models, although HEAO/A-3 observations reported recently by Fabbiano fairly conclusively established the existence of a small extended source of order 2 arc min.

The Einstein Observatory looked at Cygnus A shortly after launch in November 1978. The trials and tribulations of activation led to both good and bad results. Only a portion of the desired data was obtained, due to ACDS problems. However, the problems with the BOD control of the filter gave us some spectral data. Interesting features on several spatial scales have begun to resolve the remaining observational contradictions.

Figure 8 shows a 16 000 sec HRI image of the 10 arc min field centered on Cygnus A. The HRI has a resolution of several arc seconds;

the arc minute extent of Cygnus A is obvious. The formal centroid of the X-ray emission lies approximately 7 arc sec from the galaxy. This is greater than the estimated aspect error of approximately 2 arc sec, however, it is important to note that the X-ray emission is not radially symmetric. Thus, the formal centroid is not meaningful at the arc second level. It is in fact apparent from Figure 9 that the emission is more extended in the east-west direction. This may be compared with the alignment of the radio lobes which is approximately 20 degrees from the east-west line.

To study the spatial structure further, we performed azimuthal summations at various radii centered on the active galaxy (Fig. 10). Both the observed and background subtracted surface brightness distributions are shown. The 50 percent power point is at a radius of approximately 2 arc min; in fact, only one-third of the total power is seen within the 1 arc min radius which contains the radio lobes. The emission extends out to greater than 9 arc min, where the data becomes too dependent on background subtraction. This, along with the asymmetric distribution within the central arc minute, leads to the obvious working hypothesis that there are two components to the X-ray emission: one tied to the active galaxy and radio source, and the other to emission from the cluster.

Figure 11 shows a rough fit of isothermal sphere models to the data outside about 2 arc min. The core radius would appear to be about 600 to 800 kpc. The measurements allow us to estimate cluster density and mass, which are intriguingly high, but not inconsistent with a very rich cluster. Although these results are preliminary, the X-ray observations again appear to tell us about clusters even where optical data is lacking. Further IPC observations of Cygnus A are scheduled, to obtain spatially resolved spectral data on a larger spatial scale.

The MPC data was used to calibrate the HRI flux. The equivalent of approximately 3 UFU (2-6 keV) was seen, with a canonical spectral fit. The total HRI counting rate of approximately 0.16 cts/sec is consistent with this flux and spectrum.

The central structure of the X-ray source was also examined in some detail. In the central arc minute or so, a formal FWHM of approximately 35 arc sec is seen. An upper limit of approximately 1 percent is obtained for a point source at the active galaxy; this corresponds to a few times 10^{42} erg/sec. If significant intrinsic absorption of a point source is present, as with Cen A, this upper limit becomes about 1×10^{43}. The deviations from radial symmetry are being mapped in more detail. One area of particular interest is of course emission from the radio lobes. We binned the data azimuthally in an annulus from 40 arc sec to 80 arc sec from the central galaxy. Figure 12 shows the result: an enhanced emission located to the east-southeast at the 2.5 sigma level.

This increased emission appears correlated with the E(sf) radio lobe. We then performed the same analysis on the data taken with and without the Beryllium filter which attenuates the lower energy X-rays. The apparent excess in flux is more pronounced with the filter, indicating a harder spectrum which would be characteristic of inverse Compton emission of the microwave background scattered by the relativistic electrons. If we consider the 2.5 sigma detection, the positional coincidence, and the spectral hardness as evidence of X-ray emission from the radio lobe, we can calculate the magnetic field in the lobe based on the inverse Compton model. The resultant field is within a factor of two of that predicted by equipartition. Again, we will for the first time be able to measure and compare magnetic fields in different regions of intergalactic space.

QSO OBSERVATIONS

Leaving the comparatively nearby radio galaxies, I would like to briefly review the status of the Einstein observations of quasars, objects which are most likely at very large distances and of direct cosmological significance. It is relevant to note that prior to the launch of Einstein there were only three known X-ray emitting quasars, all nearby. With a thousandfold increase in sensitivity, we are carrying out a program of observations of known quasars with a wide variety of radio and optical properties, over a significant range of redshifts. In addition, we are discovering new quasars through optical identification of X-ray sources detected in our sky survey; three such quasars have already been identified in Einstein deep surveys.

The first QSO ever seen in X-rays was 3C273; it is not only among the most luminous quasars, but is comparatively nearby. A very deep exposure of 3C273 was taken to try to resolve any emission from the optical jet. Figure 13 is not 3C273, but for comparison and historical interest is an image of an X-ray test source from the observatory calibration here at MSFC in 1977 and shown at a software review approximately a year ago. The mirror support structure is obvious here as in Figure 14, which shows some 70 000 photons from 3C273 from an 80 000 sec exposure. Pat Henry is currently analyzing this data and so far can limit any contribution from the jet to less than 1 percent of the flux. We may eventually be able to relate the jet of 3C273 with the features just discovered in Cen A and those seen for other sources.

The IPC image obtained for the quasar B2 1225+31 at a redshift of 2.2 is shown in Figure 15. In 6000 sec of observation, a total of 296 counts were observed from a 3.6 × 3.6 arc min region centered on the source. In X-rays, the quasar stands out clearly; in visible light there are at least 200 objects as bright as the 16th magnitude quasar in the same area of sky, requiring detailed spectral observations to pick out the quasar. We have now observed two known quasars even further away, at a redshift of 3.1 (a redshift 3.1 corresponds to an age of about 15 billion years). Figure 16 is a 10 000 sec exposure for the 20th magnitude quasar 0537-286 which emits more than 10^{47} erg/sec^{-1} in the 0.5 to 4.5 keV band. Again we readily detected the quasar. Other objects detected in the field include a 5.3^m F2 and a 7.2^m F5 star, as well as 3 or 4 other sources whose optical counterparts are fainter than 15^m and which are probably extragalactic.

Our observations of two bright quasars at redshifts of 3.1 indicate that we can expect to detect still more distant quasars. In the next few months we will be observing 15 of the most distant known quasars with redshifts from 3 to 3.5. An interesting question is whether still more distant quasars exist; none have yet been observed in the visual. Since the quasars were probably the first objects to condense out of the expanding big bang gas, the time at which they first formed is a most intriguing issue. Either the optical observations to date have been limited by instrumental effects as many have suggested, or the quasars only formed at the epoch given by redshift 3.5. Since our X-ray deep surveys are capable of detecting and locating sources much weaker than these, and hence, possibly much more distant than we have discussed, we should be capable of detecting these more distant quasars if they exist at all.

A second important question about the quasars concerns the nature of the underlying energy mechanism capable of producing luminosities up to 10^{47} ergs/sec^{-1}. The X-ray observations may be able to provide insight into this question. Figure 17 shows time variability of 3C273: approximately 10 percent in less than a day. Figure 18 shows our observations of the quasar OX169, which is a weak X-ray source, but nonetheless, easily detected by Einstein. The slide shows the data we obtained for six orbits of HRI observations. The decrease from 6.5 counts/1000 sec to 2.0 counts/1000 sec is not consistent with a constant source. The probability of such an occurrence is less than 10^{-4} for a constant intensity. The observed intensity variation in $\lesssim 100$ min corresponds to a nominal decrease in luminosity from 2.0 to 0.6×10^{44} ergs/sec^{-1}, although the exact size of the decrease is not known precisely.

Observations of time variability, such as we show for OX169, may be a signature of the ultimate energy source in the quasars. For a process involving conversion of a mass into energy, rapid variations in a powerful emitter require a high conversion efficiency, supporting models involving release of gravitational energy through accretion onto a compact object. If one assumes that the X-ray emission is powered by accretion onto a massive black hole, the observed luminosity and time scale for variability can be used to estimate the mass of the black hole. A minimum central mass is required to produce a given luminosity. On the other hand, the time scale for variability sets a maximum size for the emitting region. Our observations of OX169 would require a black hole of between 1 and 100 million solar masses based on scattering models with gas temperature $\geq 10^9$ K. Observations such as these show the importance, and perhaps the unique role, of the X-rays as a probe of the central energy source. The short time scales indicate that the X-rays are produced very close to the central source, and may therefore provide the means for ultimately understanding the quasars and active galaxies in general.

Figure 19 summarizes some of our observations of quasars. We have plotted the observed 0.5 to 4.5 keV X-ray luminosity, as well as a few upper limits, for the individual sources as a function of redshift. The three nearby quasars known prior to the launch of Einstein are shown, as are the Einstein observations for more than 20 quasars now extending to a redshift of 3.1. The luminosities range from 10^{44} erg/sec^{-1} to 10^{47} erg/sec^{-1} with no obvious dependence of luminosity on redshift. The absence of low luminosity, high redshift quasars is primarily a measure of the instrument sensitivity limit for a several thousand second observation.

Our observations to date clearly do not satisfy the statistical requirements for a complete sample; for example, they are strongly biased towards radio quasars. Thus, we cannot yet formulate an X-ray luminosity function to be studied on its own or to be used in estimating the contribution of the quasars to the diffuse X-ray background. Eventually through the Einstein Observatory surveys and follow-up optical identifications, we should be able to generate an unbiased, complete sample of X-ray emitting quasars.

In the meantime, we can use the optical luminosity function for quasars plus a tentative relationship between the optical and X-ray fluxes in order to estimate the possible contribution of the quasars to the X-ray background.

Figure 20 shows the local optical luminosity function that different observers have obtained. I show this mainly to point out that the Seyfert galaxies merge with quasars near an equivalent X-ray luminosity of 10^{44} ergs/sec^{-1} which suggests a possible link between these two types of active galaxies. Using rough estimates of evolution, etc., we have estimated the contribution of quasars to the X-ray background. The rough calculation actually predicts an X-ray background 2.5 times the observed "extragalactic" background at 2 keV. The disagreement suggests that one of several hypotheses used is wrong. This problem will be helped by further data and analysis, but it is already clear that the presence of the diffuse X-ray background (and the gamma ray background as well) can provide significant constraints on the quasar numbers, particularly as we accumulate more data on the individual source luminosities. Going the other way, it is also clear that the QSO's contribute significantly to the X-ray background.

In a related context, there have been suggestions that quasar redshifts are noncosmological or local. A local interpretation of the redshifts would however require many more faint quasars. This in turn would require a large optical to X-ray slope if the X-ray background were not to be exceeded, in contradiction with what we observe, strongly suggesting that QSO's are indeed at great distances.

A wide range of cosmological questions can be approached by means of observations and analyses such as the ones described. Time variability measurements as discussed may give unique insights into the basic energy generating mechanism. Studies of the spatial structure of the nearer active galaxies should also contribute, as will the class property studies which may allow better comparison between the various types of galaxies. The Einstein Observatory is adding a qualitatively new dimension to this extragalactic research.

Figure 1

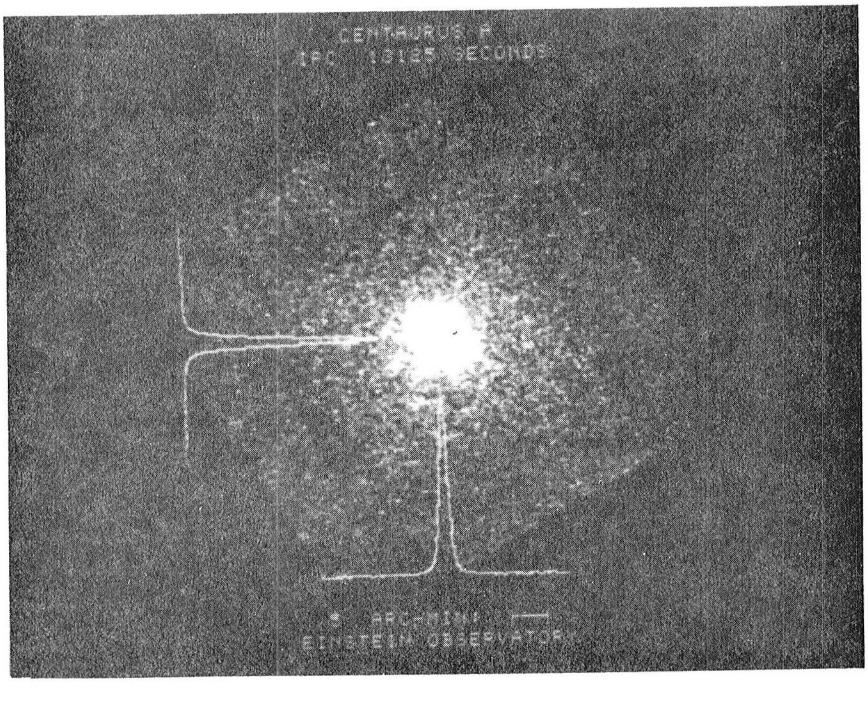
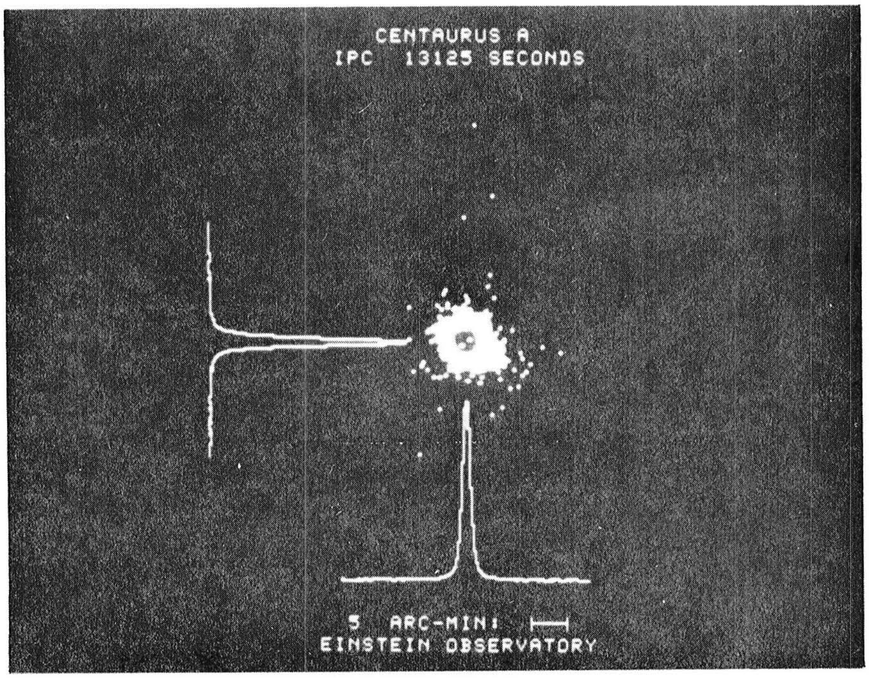


Figure 2



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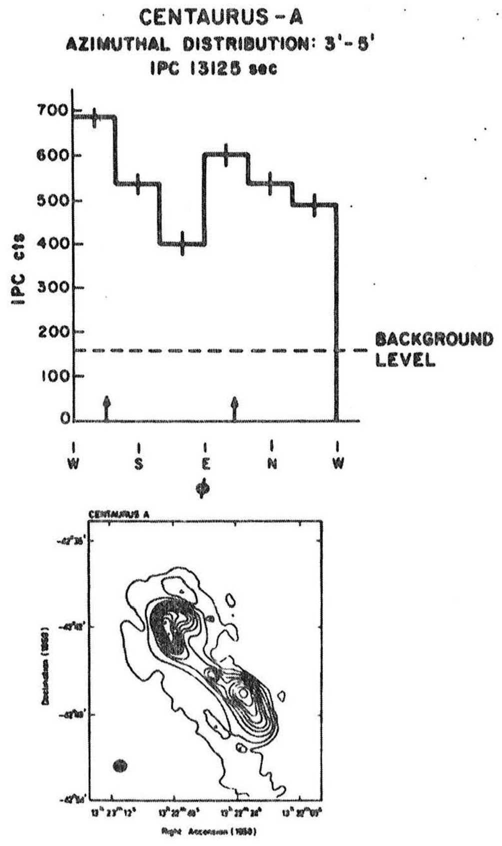

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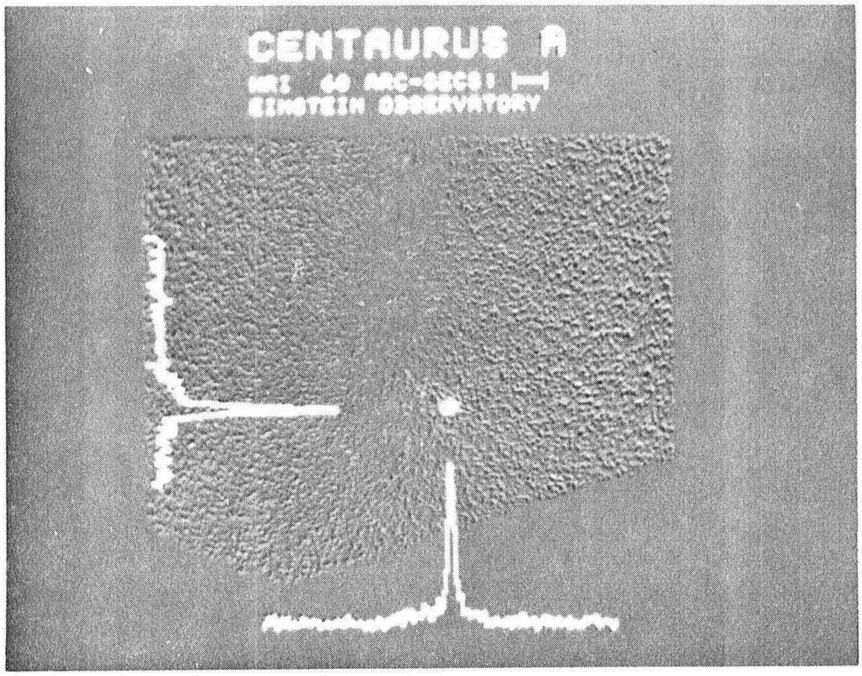

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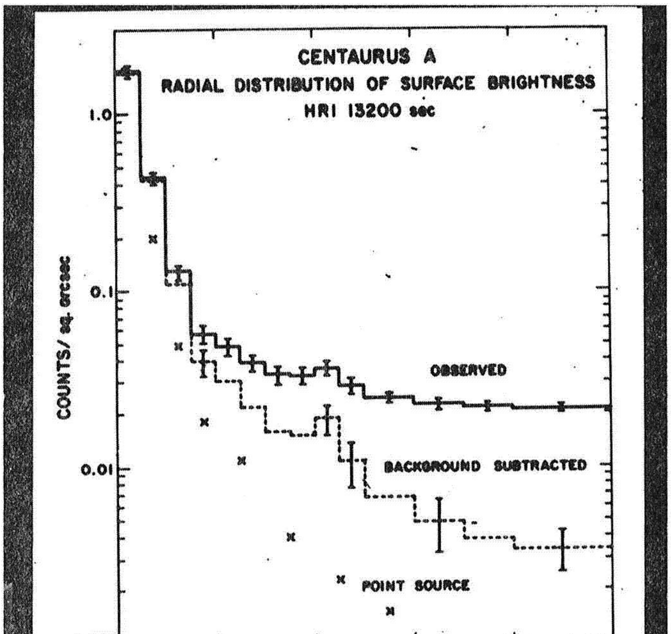

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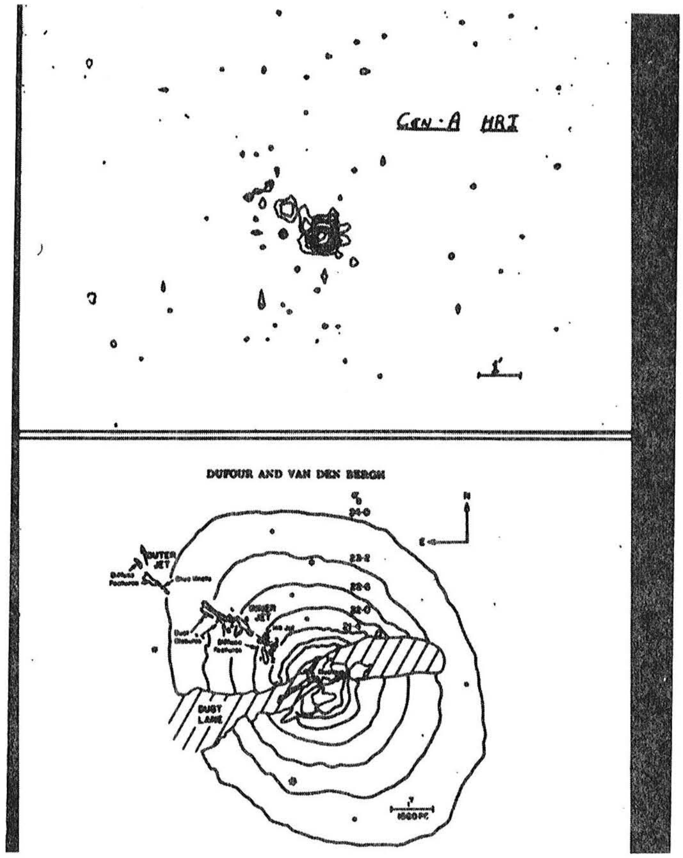

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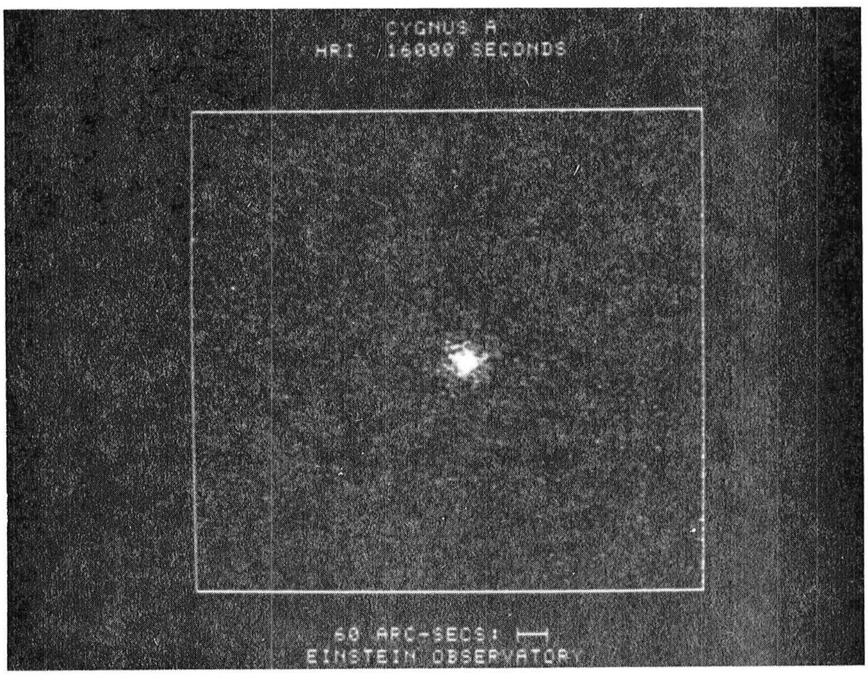

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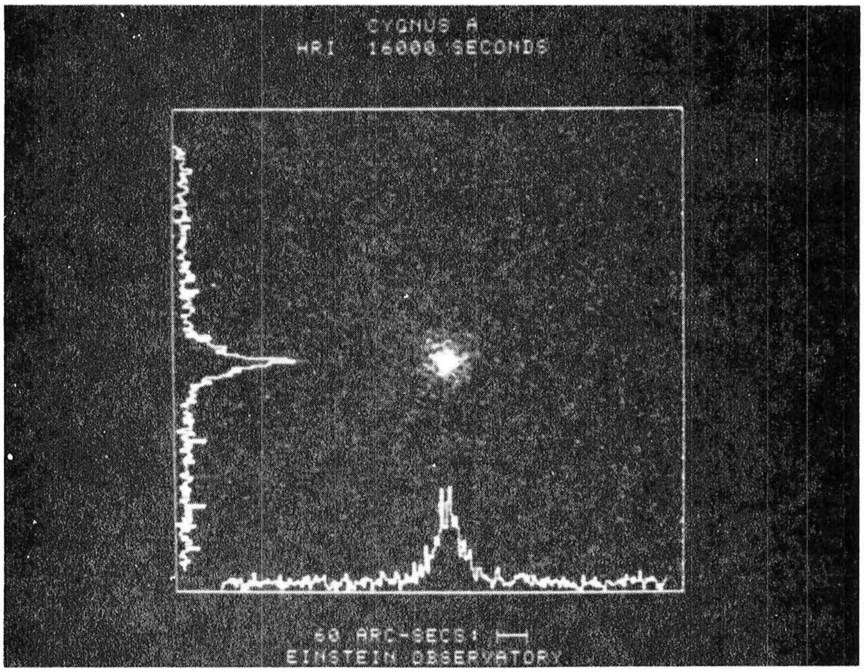

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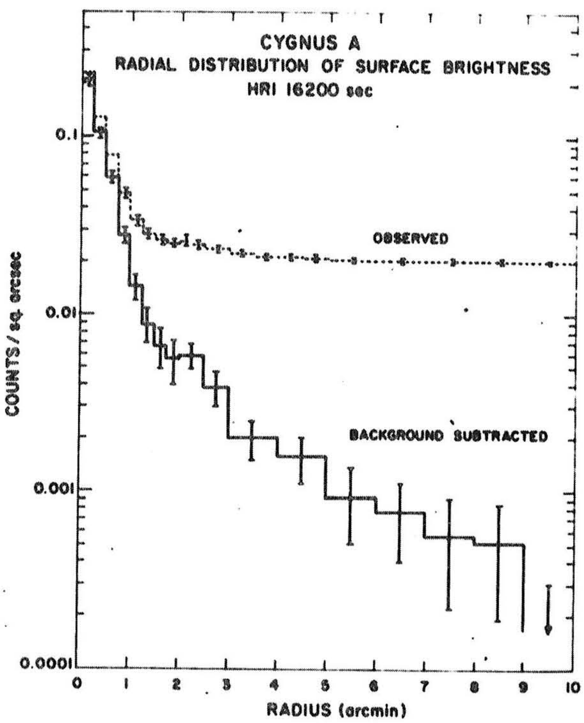
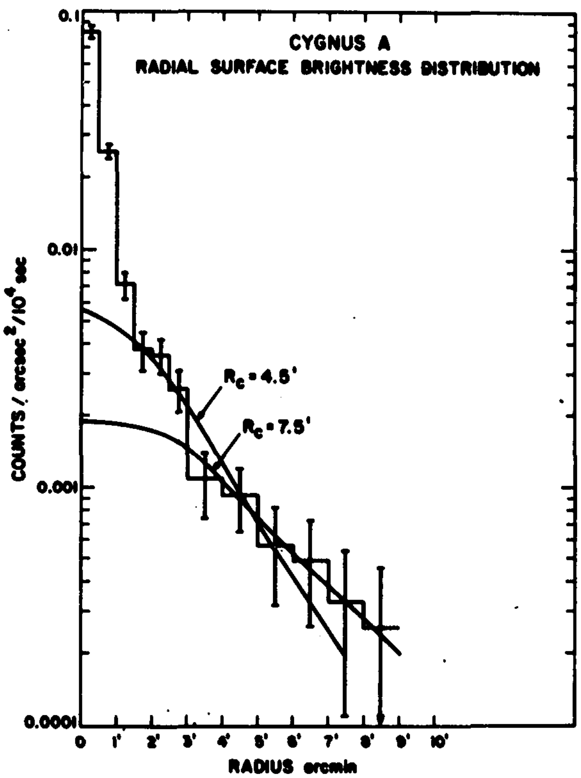


Figure 10



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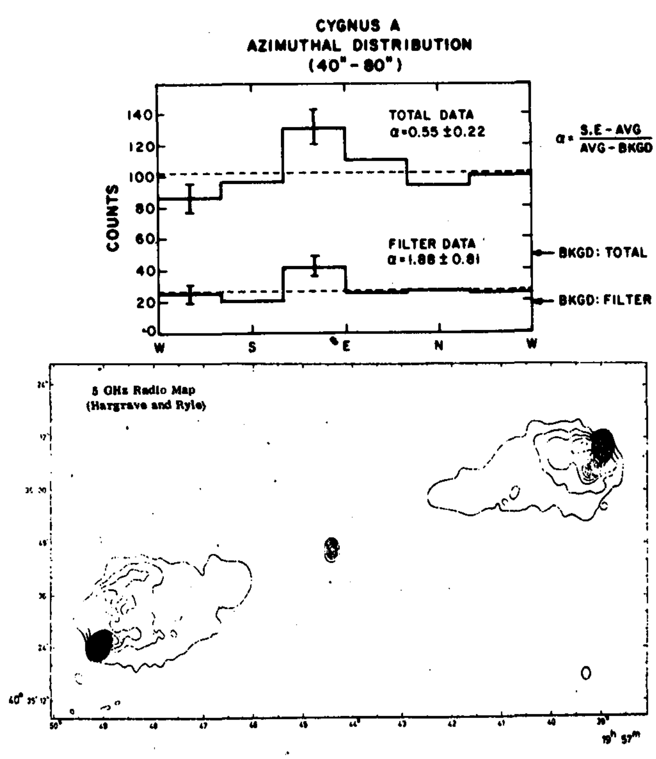

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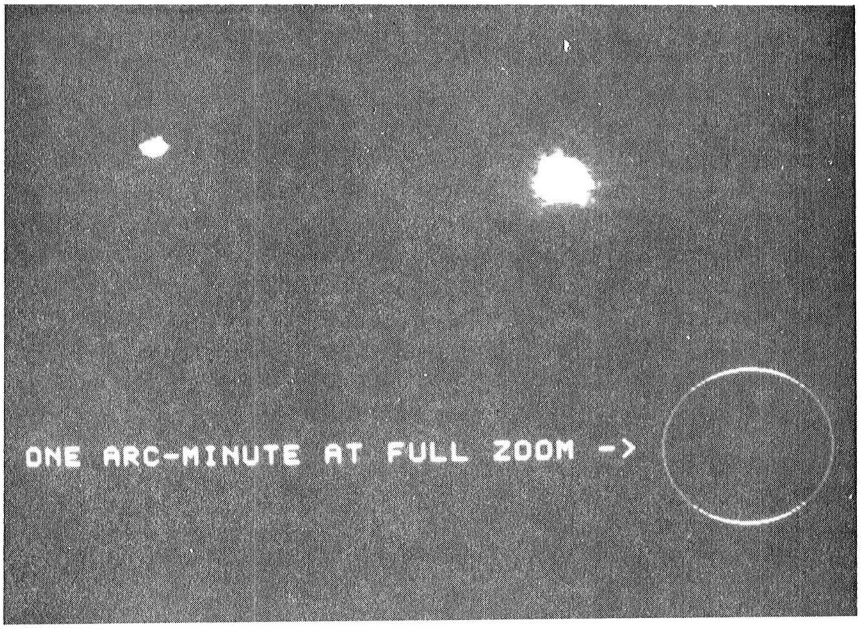

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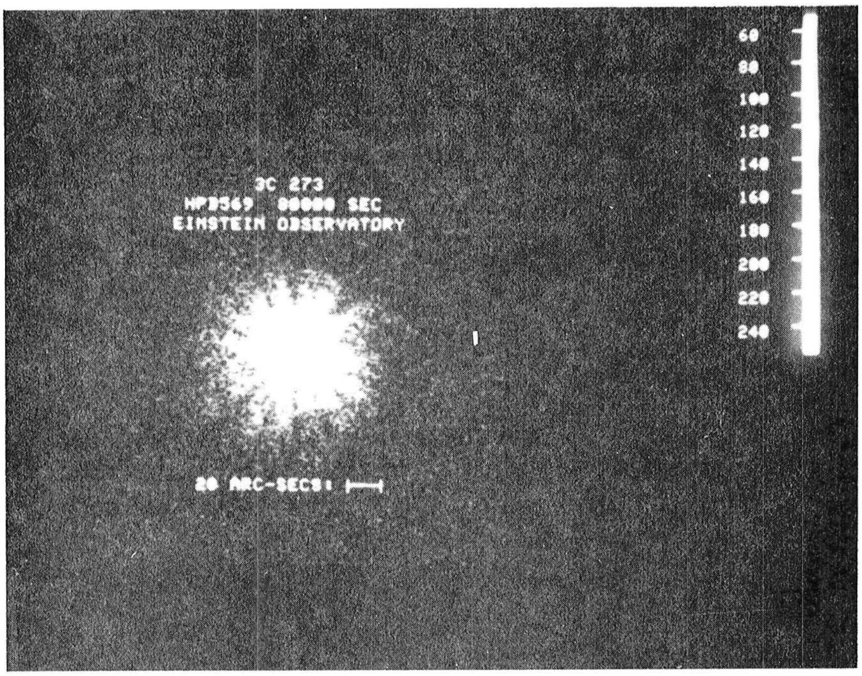

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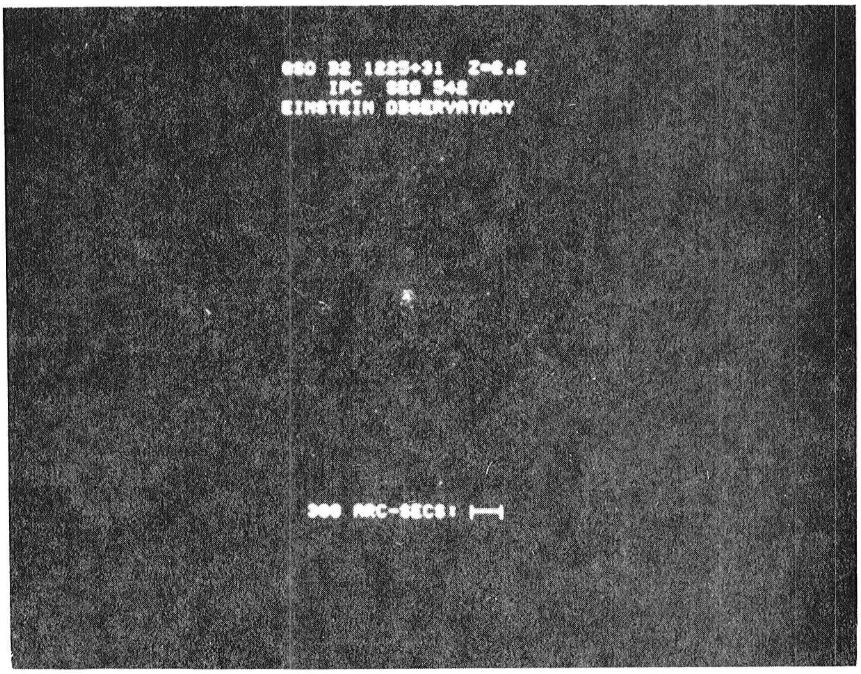

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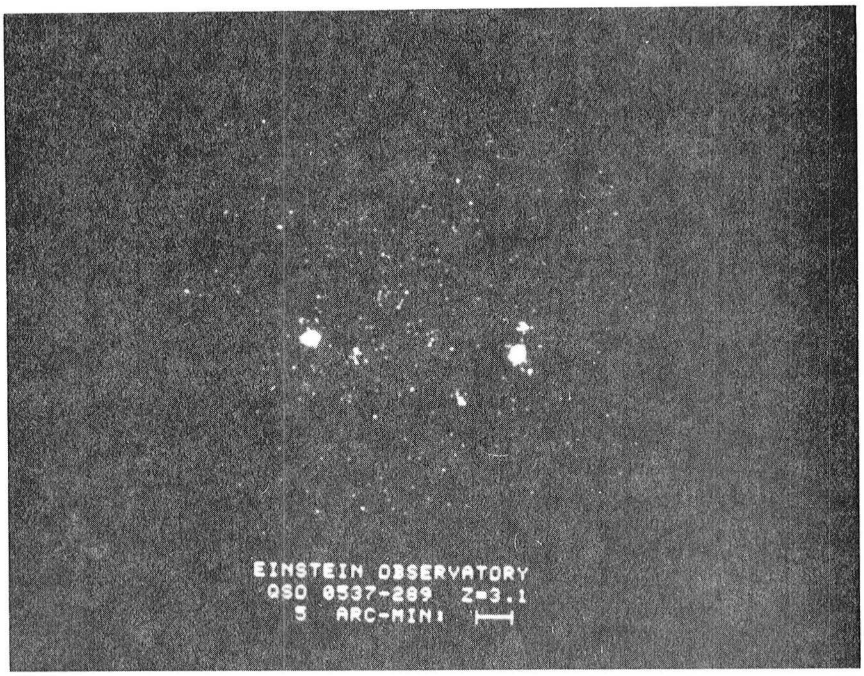
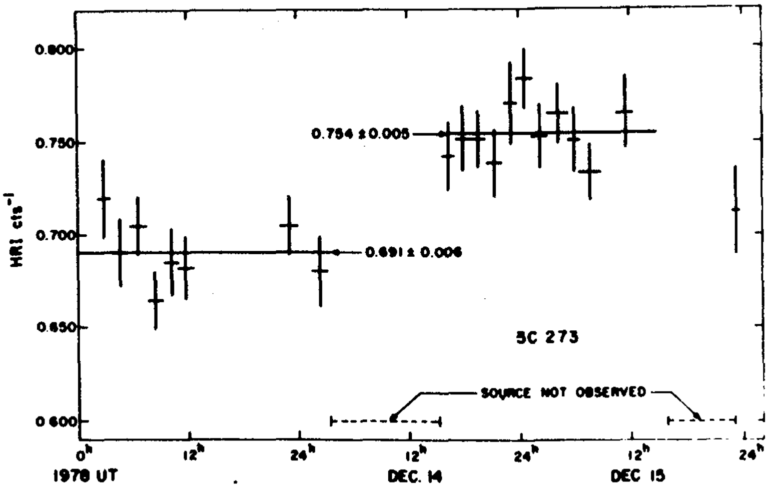


Figure 16



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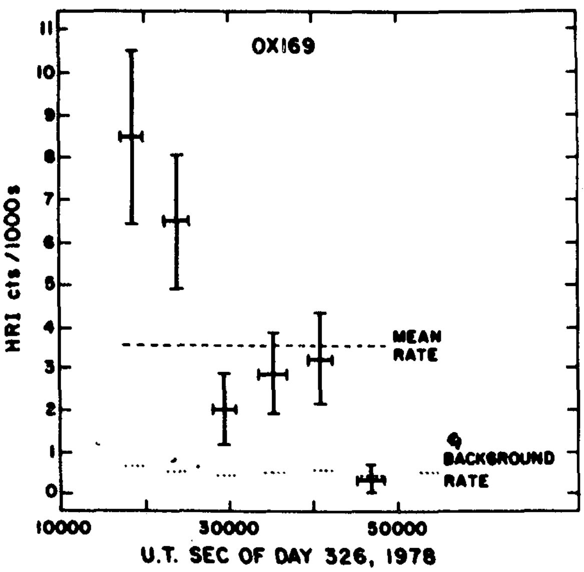

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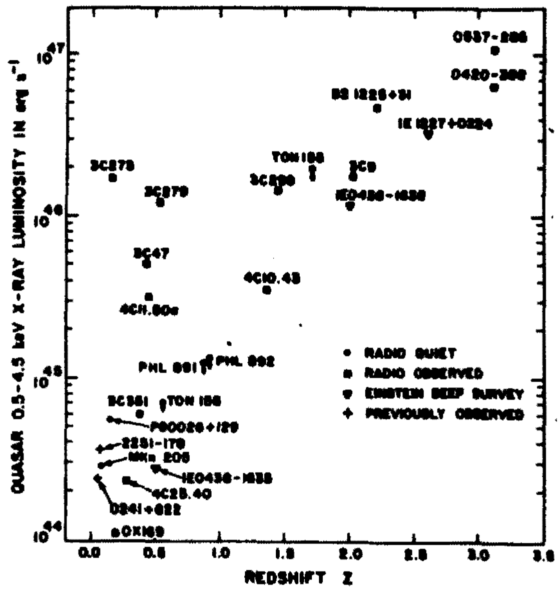

Figure 19

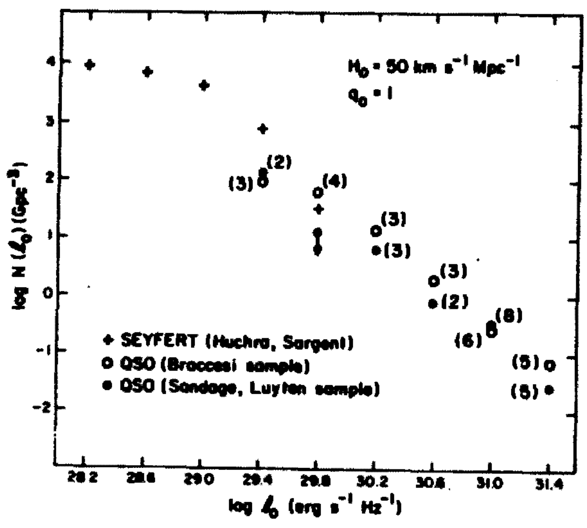

Figure 20