A-3 SCIENTIFIC RESULTS - EXTRAGALACTIC

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As Roger Doxsey said, we will be splitting this talk in half, so I will start a little abruptly. I would like to discuss three specific topics in extragalactic astronomy to which the HEAO-1/A-3 experiment has made a unique contribution: first, the discovery of relatively condensed X-ray emission in the cores of those clusters of galaxies which are dominated by a giant elliptical or cD galaxy [1]; second, the discovery of extended X-ray emitting plasma in groups of galaxies [2,3]; and third, the demonstration that BL Lac objects are a new class of X-ray source [4,5,6].

What is a cluster of galaxies? Figure 1 shows the central portion of the Virgo cluster, the nearest rich cluster to our own galaxy, at about 20 Mpc.[1] Each of the fuzzy images is a galaxy, containing anywhere from a million to a trillion stars. Some of them are spiral galaxies like our own, others are elliptical galaxies which are distinguished by lack of gas and dust and lack of star formation. Clusterings of anywhere between 10,000 galaxies, as in the case of Coma, down to a few such as our own Milky Way and its neighbor Andromeda, are the rule rather than the exception in the universe. This imposes a stark contrast between the observation of the universe and the theories of general relativity which assume a uniform, isotropic, homogeneous universe for the scenario of the origin and nature of things. The formation and evolution of galaxies and of clusters is indeed one of the outstanding problems in astrophysics today. I will not solve this problem, but I think throughout the two days you will be hearing a lot of relevant observational data of a new kind which is now available from X-ray astronomy.

The scanning modulation collimator [7,8], because of its 4 arc min and 16 arc min periodicities, is not very sensitive to extended sources. They tend to be demodulated. In fact, we do not see most of the approximately 50 clusters known prior to HEAO-1 to be emitting X-rays, even though they are all strong enough that they formally are above our sensitivity level. The ones we do detect are of a special type. Shown in Figure 2, at the center of the cluster Abell 2199, is a so-called cD galaxy, a giant elliptical galaxy with an extended faint envelope of stars surrounding it, maybe five times the size of our own galaxy. By using previous X-ray error boxes (shown in addition to HEAO error boxes is an Ariel 5 survey [9] labeled 2A), we can typically reduce the multiple

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1. 1 parsec (pc) = 3.08×10^{18} cm = 3.25 light years. 1 Mpc = 10^6 pc.

positions which come out of the modulation collimator experiment. In this case, we would reduce it to the region between the pair of lines on the right and identify the centroid of X-ray emission with the region right around the cD galaxy. We detect this Abell cluster only in our 2 arc min collimator, not in our 30 arc sec collimator, which is an indication of its finite size.

Figure 3 shows more clearly how we infer the finite size of extended sources. This is our typical best case result, the cluster Abell 85. In the 2 arc min collimator (MC2), we have a solid line fit to a "point" source. A point source of this strength would give a predicted counting rate as shown by the dashed line in the 30 arc sec collimator (MC1). The absence of such a response is a clear indication of finite size, about 4 arc min in this case. In general, we do not have sufficient statistics in the A-3 experiment alone to do this kind of study in the two collimators. In effect, what we do is get our predicted triangle based on previous X-ray fluxes such as catalogued by Uhuru [10] and Ariel 5 [9], and expecially through a collaboration with the HEAO/A-2 experiment [1], which observes simultaneously to ours.

Figure 4 shows six cases in which we detect the cluster and locate the centroid near the cD galaxy (indicated by the arrow) and for which we measure finite size via demodulation of the signal in our detectors. We also have two other cases with the cD galaxy inside our location uncertainty, and two cases (A478 and A496) where the galaxy is outside but close to our measured position. One interesting case is A754, where the cD galaxy is very far (8 arc min) from any of our possible locations. This particular cluster may be in a very different state of evolution, or possibly we are being fooled by an extraneous point source superposed on the field.

The association of the cD galaxy with the X-ray emission has two possible interpretations. Undoubtedly both of these represent actual physical processes which are taking place in various clusters of galaxies. In one picture, both the giant galaxy and the hot X-ray emitting gas are merely being attracted to the gravitational center of the cluster and they both happen to fall there. This picture is very nice for the theory whereby the cD galaxy is actually formed by cannibalism [11] by accreting and digesting its smaller neighbor galaxies and incorporating their stars. In the second interpretation the cD galaxies are actually responsible for enhanced X-ray emission in their own right [12].

Clusters of galaxies were recognized as a class of X-ray source by Uhuru largely because of the work of G. Abell [13] whose catalog of clusters was carefully selected according to objective statistical procedures. He defined as a rich cluster anything in which there were 50 or more galaxies within a range of a factor of 6.3 (2 mag) in brightness, all within a region of 3 Mpc radius. Given X-ray emission from clusters,

there were many suggestions that groups of galaxies less richly clustered should also be X-ray sources. This is very reasonable to expect on the basis of continuity arguments. There is nothing fundamentally different about these groups compared to richer clusters as far as we know. The key observational problem was that groups were so much more numerous than clusters that their presence in a typical error box of 1/10 of a square degree could not be ascribed to other than chance. The situation is actually a little worse since a group of galaxies is not a well defined concept among astronomers.

Figure 5 shows locations of the X-ray source 2A0251+413. It shows how we used previous error boxes from Ariel 5 and Uhuru (with a little extent imagined for the latter) along with lines of position determined by NRL and Goddard from their HEAO-1 experiments. I also show a few of the multiple locations that we determined (with marginal statistical significance) with our 2 arc min collimator. They all focused in on the western part of the 2A location. There is another source (denoted as MX) which is undoubtedly a variable since it was very much stronger when observed by MIT on the OSO-7 [14] experiment and, therefore, could not be ascribed to a group. The fact that the modulation collimator just barely detected 2A0251+413 compared to a very strong detection from the Goddard A-2 experiment allows us to infer that it is an extended source which we identify with the Albert, White, and Morgan [15] group number 7 (AWM7). This region of the sky is shown in Figure 6 which is a blow-up of a Palomar sky survey print. This group is distinguished by the presence of a giant elliptical galaxy, NGC 1129, like those cD galaxies in the clusters which I just discussed. The dashed line indicates the finite size, an effective 9 arc min full width half maximum (FWHM) for the extent of the X-ray emission. Depending on the true profile, the X-ray centroid might be revised somewhere along this line.

The luminosity of this group of galaxies is 10^{44} ergs per second, just very comfortably near the mean previously known for clusters of galaxies. Some of the other group members are designated by number in Figure 6. The most significant thing to note is the absence of spiral galaxies in this group. Perhaps the main conclusion from the discovery of X-ray emission from groups is that it looks very much like the emission from clusters of galaxies. Goddard OSO-8 results [16] on this particular X-ray source are shown in the spectrum of Figure 7. The key feature is the iron line emission at 6.7 keV, the ubiquitous signature of hot gas in clusters of galaxies which was used to prove that in fact thermal bremsstrahlung was the emission mechanism [16].

Figure 8 shows a 2 arc min collimator line of position for 4U1326+11, locating the center of X-ray emission with the Morgan, Kayser, and White [17] group number 11 (MKW 11), another group dominated by an elliptical D galaxy, NGC 5171. The other members of this group are scattered over this whole finding chart. The key thing to notice is the

absence of spiral galaxies. This fits in very well with the picture whereby spiral galaxies are stripped of their gas, as they pass through the hot gas medium that is emitting the X-rays, and with the suggestion that groups represent an older stage of the evolution of clusters. Also, if some groups do not emit X-rays, then this fits in with the empirical fact that low spiral galaxy content is correlated with high X-ray luminosity [18]. In fact, the X-ray luminosity of this group is only about 4×10^{43} ergs per second, within a factor of two of the weakest Abell clusters found.

The next source, Figure 9, is a very interesting case. This is the Ariel 5 source 2A0335+096. We have lines of position in the two collimators which locate the centroid of X-ray emission around a giant elliptical galaxy which has a very extended envelope. From the faintness of the galaxy (about 16th magnitude) and the size of the envelope, we can guess it is at a distance of 400 Mpc, giving this group an X-ray luminosity of about 6×10^{44} ergs per second — comparable with very rich clusters in Perseus and Coma (in fact, a factor of 2 or so less). We measure a finite size of about 1.5 arc min. That gives this group a rather small diameter of about 150 kpc.

I think one intriguing way to interpret emission from the groups of galaxies is in terms of the picture by Ostriker [19] whereby they represent an older stage in the evolution of clusters. In this picture, clusters with fewer galaxies evolve faster, and the central galaxy more easily accretes its neighbors and becomes a cD galaxy. The true signature if this is a valid picture of an older cluster should then be an advanced chemical age; for example, a very large iron abundance which could, in principle, be determined from X-ray measurements. Also, according to Ostriker's predictions, the group should show smaller velocity dispersions of their member galaxies since the fastest moving galaxies may have actually escaped from the group.

I would like to turn to another topic now, the so-called BL Lac objects [20]. These are named after a prototype object which had been known for a long time as a variable optical object in the constellation Lacerta. The overwhelming majority of the tens of thousands of such variable objects have turned out to be stars. However, some 30 such systems are distinguished by strong, variable optical polarization; by radio emission; and by the lack of any emission lines in their spectra. About 10 of the objects in this class are identified with distant galaxies so that we know the class does represent an extragalactic object. One of the conclusions from the X-ray discovery is that we could add an additional characteristic, namely, that they show strong and variable X-ray emission, to the definition of BL Lac objects. There are now two objects first discovered as X-ray emitters and subsequently proven to be of the BL Lacerta class.

The key interest is that these BL Lac sources appear stellar; that is, by definition they are quasi-stellar objects or quasars. Since they are so much closer and more numerous than the classical quasars, it is possible that they might be more amenable to detailed study and revelation of the internal energy conversion mechanism. In particular, if we just ask the questions, why are BL Lac objects different from quasars? why don't they have emission lines? we can look at a category of theories explaining the radiation of both quasars and BL Lac objects.

Figure 10 schematically categorizes various theories in the literature [21,22,23] as to why BL Lac objects are different from other quasars. In one class of models, it is simply a geometric difference of how the central black hole emits high energy cosmic ray particles and how those particles might intersect an irregular distribution of gas to ionize it or how the radiation transfer in this gas may present different aspects to us as we view it. The key features are that the emission from the central object is pictured as anisotropic — some sort of beaming or ejection, and that the gas is not spherically symmetric — either forming clouds as pictured or else an accretion disk. Another class of theories exploits the morphological characteristics. Seyferts and QSO's, which have many similarities, are pictured to be in spiral galaxies which are known to have gas. The N galaxies and BL Lac objects are pictured to be associated with elliptical galaxies which are deficient in gas. Perhaps a more interesting picture for future study is a very general evolutionary picture in which the clock can run in either direction, depending upon whether one considers an explosion or an accretion phenomenon. The start, for example, may be a condensed object with no gas around it and it might look like a BL Lac object. It may then explode to go through a quasar stage. Later, the gas may or may not dissipate to look like a BL Lac object again, with no gas to be ionized.

As in the case of groups of galaxies, the surveys for BL Lac objects were simply so sparse and irregular that statistical criteria for identification were not possible prior to HEAO-1. With an error box of a few tenths of a square degree, one could not be absolutely certain that a BL Lac object inside such a box was the true identification of an X-ray source. Figure 11 illustrates the source 4U 1651+39 which, in fact, was correctly identified in the Uhuru catalog [10] as X-ray emission from the BL Lac object Markarian 501. The three diamonds comprise about one-half percent of the area inside the larger box. We also used the NRL HEAO/A-1 data to select the line of multiple positions within the 4U box as the correct ones.

Figure 12 blows up this location on a Palomar sky survey. We see Markarian 501 as an elliptical galaxy. It has a measured redshift which places its distance at 200 Mpc [24]. Inside the galaxy is a variable optical nucleus, which varies by more than a factor of two on a time scale of years, and a compact radio source. It is this nucleus which is the BL Lac object itself.

As indicated in Figure 13, the source 2A1219+305 in the Ariel 5 catalog was studied by the Ariel 5 X-ray astronomers and their co-workers [25]. They obtained a revised, smaller location (denoted as 3A) and did a radio survey which found four relatively weak radio sources (denoted as numbered plus signs) in this region. They noticed that their radio source number 4 fell on a stellar object and suggested it to be the X-ray identification and the BL Lac object. In a pointed observation of the HEAO-1 satellite, we obtained the error box diamond coinciding with radio source number 4, and which contains about one percent of the total area. It is shown blown up in Figure 14 on the Palomar sky survey. It shows the stellar object which the Ariel observers picked out as the radio source, and the likely X-ray emitter. L. Chaisson of Harvard searched the Harvard Observatory plate collection from over the past 50 years and discovered that this object was in fact optically variable. Figure 15 shows about a magnitude and a half variation on a time scale of years. This is one of the key characteristics of BL Lac objects and, therefore, confirms its BL Lac nature. The A-3 team has another such case where we discovered an X-ray source and subsequently found it to be a BL Lac object. This is a more exciting one in many regards, PKS 2155-304. Richard Griffiths will discuss its properties this afternoon.

Figure 16 is an overlay of four BL Lac objects in addition to Markarian 501. Mrk 421 and PKS 0548-322 are interesting in that they are both found in elliptical galaxies with measured redshifts. Together with Mrk 501, we can have an idea of the X-ray luminosity of these objects, namely 2×10^{44} ergs per second, 2-6 keV, for those with measured redshifts. These are just at the bottom of the range of luminosity of X-ray quasars, and near the top of the luminosity range of X-ray Seyferts. The two sources which were originally discovered in X-rays and subsequently found to be BL Lac objects appear on the Palomar sky survey prints to be stellar-like. They therefore might be much more distant objects where we cannot see the galaxy and they, therefore, might be very much more luminous in X-rays. This remains to be demonstrated.

What is the nature of the X-ray emission from the BL Lac objects? One clue we have is to look at their radio spectra. Referring to Figure 17, typical classical radio source spectra look something like the two cases on the lower left, increasing in flux toward lower frequencies. The turnover at lower frequency seen in many sources in the left side of Figure 17 is a somewhat unusual feature which is interpreted by the radio astronomers as a source which is so small that the radio photons actually are trapped and reabsorbed by the magnetic field before they can escape from the object. Many of the classical theories of radio sources would predict that in such objects the cosmic ray electrons which are making the radio emission will scatter off the radio photons and catastrophically explode as X-ray sources [27], at least at the one

Uhuru count or 2×10^{-11} ergs per cm^2 per second level. For the radio sources on the right side of Figure 17, which in fact are observed as X-ray sources, the spectra are somewhat less dramatic. In fact, one can construct such a model of so-called Compton self-synchrotron, or inverse Compton, for their X-ray emission. In view of the fact that the model does not work for the six sources at the top of the left column though, I would say that it is to be looked at somewhat askance. In particular, it seems that these sources are telling us that there is a self-regulating mechanism, perhaps by the X-rays, which destroys the simple radio theory geometry of uniform homogeneous point source ejection. Since we think that the ultimate energy sources of all these extragalactic active objects are gravitational accretion anyway, it is natural to look for accretion as the direct source of the X-ray emission.

We have some support for this in the A-3 data, and I know it is being exploited more fully by some of the other experiments. Figure 18 shows the spectrum of Markarian 421 as measured by the Goddard group on OSO-8 and by our pointing of HEAO-1 in June 1978, about a year after that measurement. We see very dramatic steepening of the spectrum. From a purely phenomenological point of view, it is very suggestive of both Cygnus X-1 and AM Hercules, which are in turn two very different kinds of galactic X-ray sources both of which nonetheless are well believed to be powered by accretion phenomena. I would just suggest that exploitation of the accretion disk or shock front explanation of the extragalactic sources may be very fruitful.

Let me summarize the overall results of A-3 experiment. Figure 19 shows a computer generated map showing all the X-ray sources known prior to the HEAO-1 launch. Mark Johnston and Rick Dower have this hanging in their office at MIT and diligently stick in a red push-pin for all the published HEAO/A-3 identifications, some of which are new, and some of which are confirmations, for example, of Seyfert galaxies. The blue colors represent sources for which we have accurate position from the scanning modulation collimator and which constitute the unidentified sources at present. The green colors represent some of the historical X-ray sources such as Sco X-1.

Finally, I think it would be appropriate to acknowledge the six real heroes of the A-3 data reduction effort. Figure 20 shows the data reduction and analysis support team information center, staffed by Mike Garcia, Wendy Roberts, Maureen Conroy, and Ellen Ralph, posed in front of our recent publications. Many of you receive these yellow preprints which are a joint MIT/SAO A-3 publication. And, finally, Figure 21 shows the real brains of the experiment.

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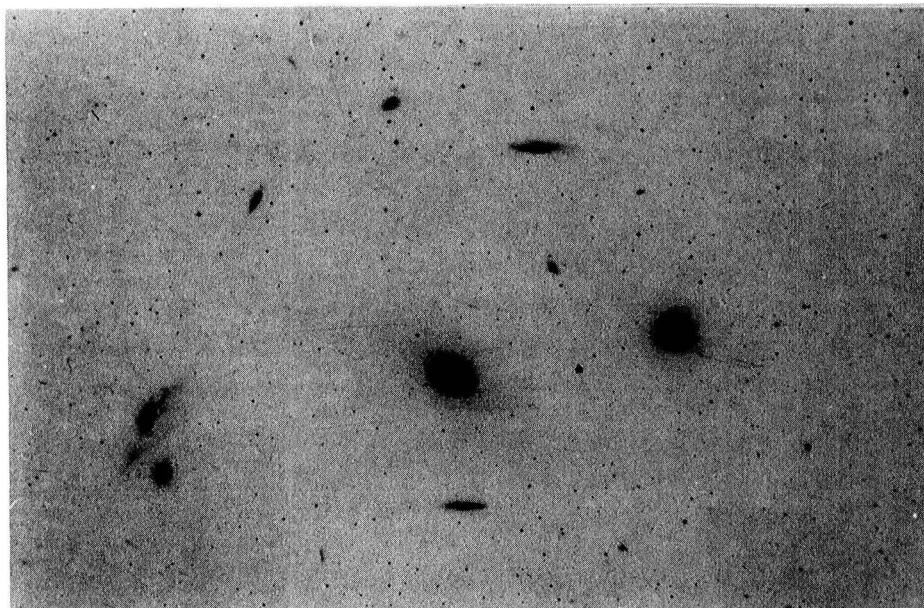
Figure 1. Central region of the Virgo cluster, showing elliptical and spiral galaxies. East is to the left and North is up on all figures.
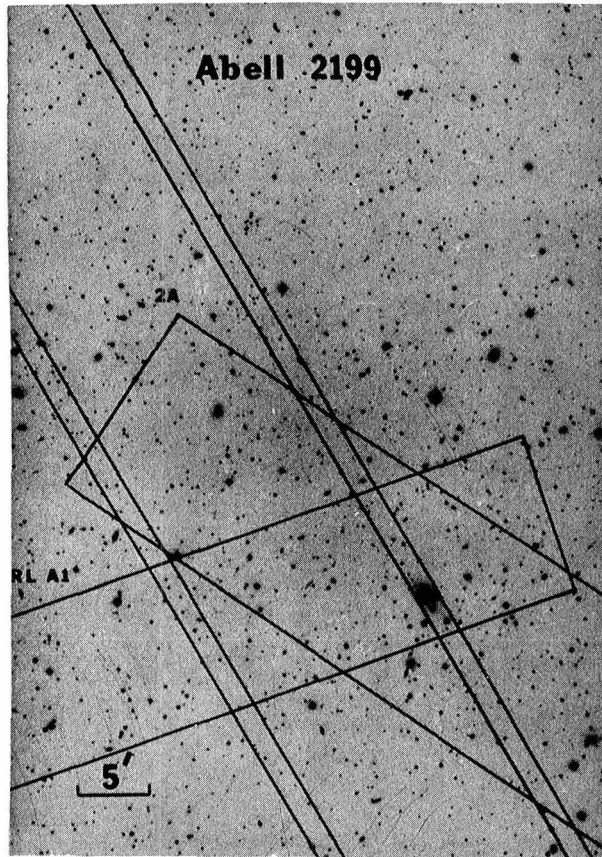
Figure 2.   Location of the X-ray source 2A1626+396 = Abell 2199 cluster.
The X-ray source centroid must be near the cD galaxy inside the 2A,
NRL HEAO/A-1, and out HEAO/A-3 (long parallel lines) boxes.
In this and all other figures we show only a portion of the
extent and multiplicity of the multiple A-3 lines, which by
themselves would cover a 4° x 4° FWHM area.
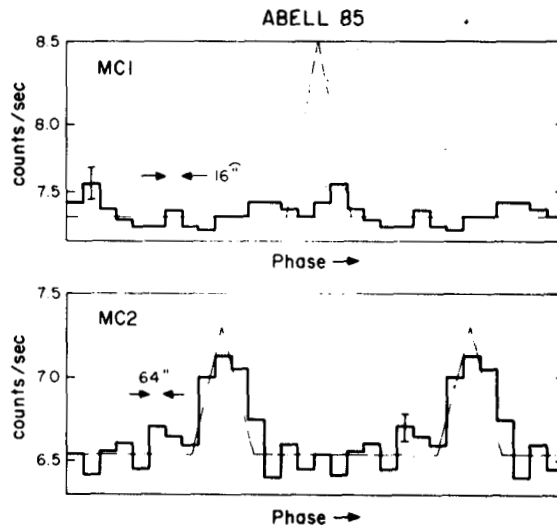
Figure 3. Response of MC2 (2 arc min FWHM) and MC1 (30 arc sec FWHM) to the X-ray source 2A0039-096 = Abell 85 cluster. Demodulation of the signal in MC1 indicates the source is extended by about 4 arc min FWHM.
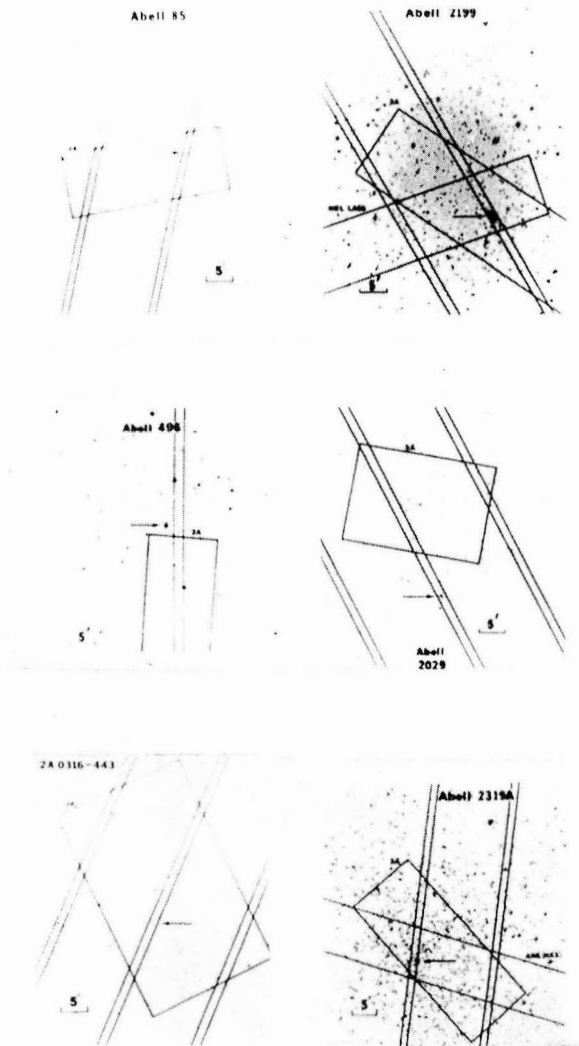
Figure 4. MC2 lines of positions for six clusters of galaxies, superposed
on the Palomar Observatory Sky Survey prints along with error boxes
obtained from the NRL HEAO-1 LASS, Ariel 5[9], and the ANS Hard
X-ray[28] experiments. In each case we identify the X-ray emission
as extended, and centered on the cD galaxy which is marked
with an arrow.

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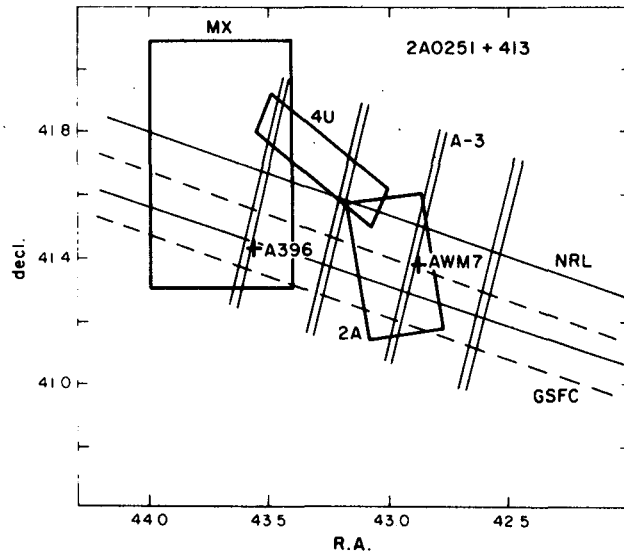
Figure 5. Locations of $2A\,0251+413$[9] $= 4U\,0253+41$[10] $=$ AWM7[15] group. The source $MX\,0255+41$[14] is a distinct, variable source.
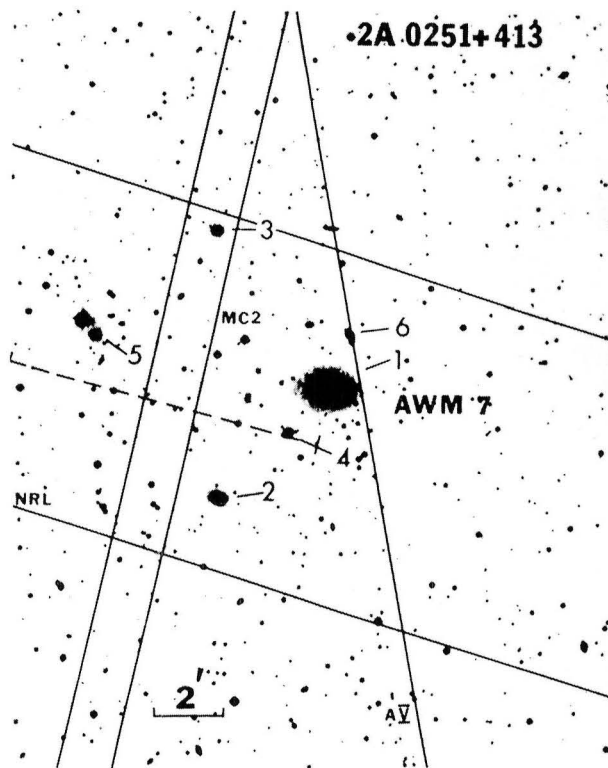
Figure 6. Appearance of the AWM7 group on a Palomar Sky Survey enlargement. The numbered galaxies are the group members[15], number 1 is the cD galaxy NGC 1129. Because of the large extent (shown as dashed) our X-ray centroid location depends on the assumed profile, and does not yet exclude NGC 1129.
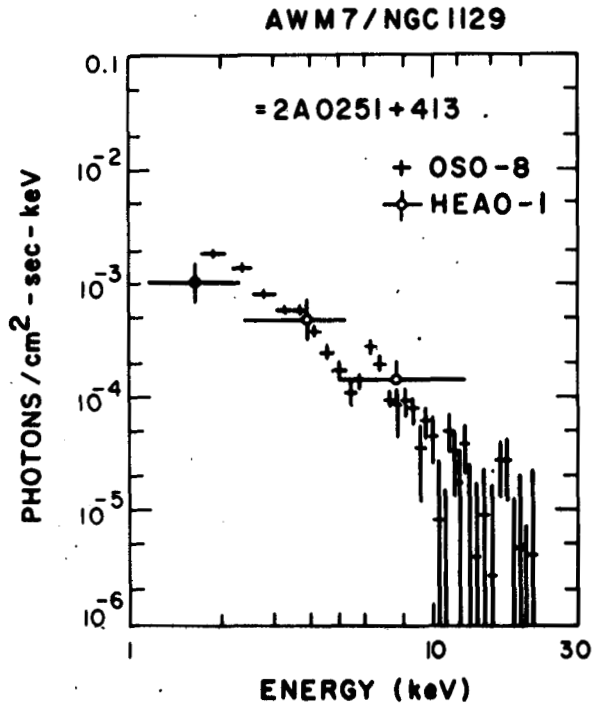
Figure 7. The X-ray spectrum of AWM 7. The OSO-8 points are from reference 16, the HEAO-1 points are our 3-channel spectral data. The iron line emission at 6.7 keV, ubiquitous in clusters of galaxies and the signature of hot gas, is clearly seen.
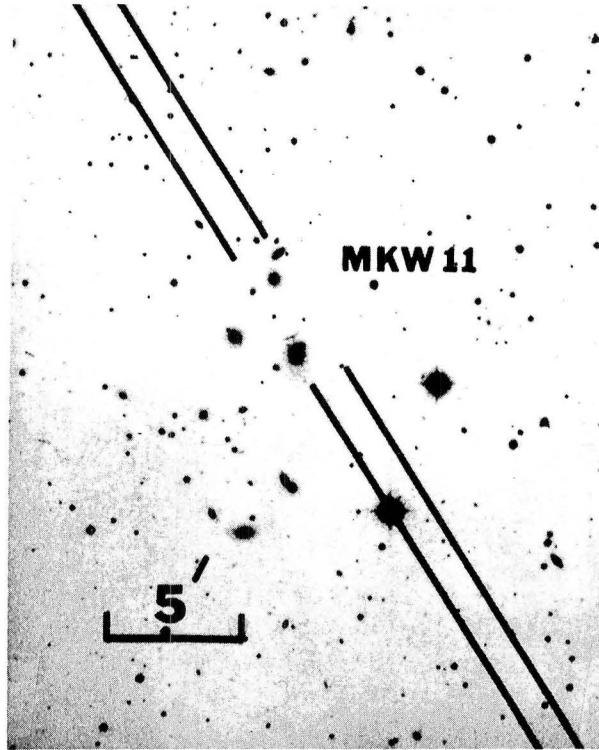
Figure 8.   A portion of the MC2 line of position for the X-ray source
4U1326+11, identifying it with the group of galaxies MKW11[17].
The brightest member is NGC 5171, a D galaxy, which appears
just above the break in the lower left line.
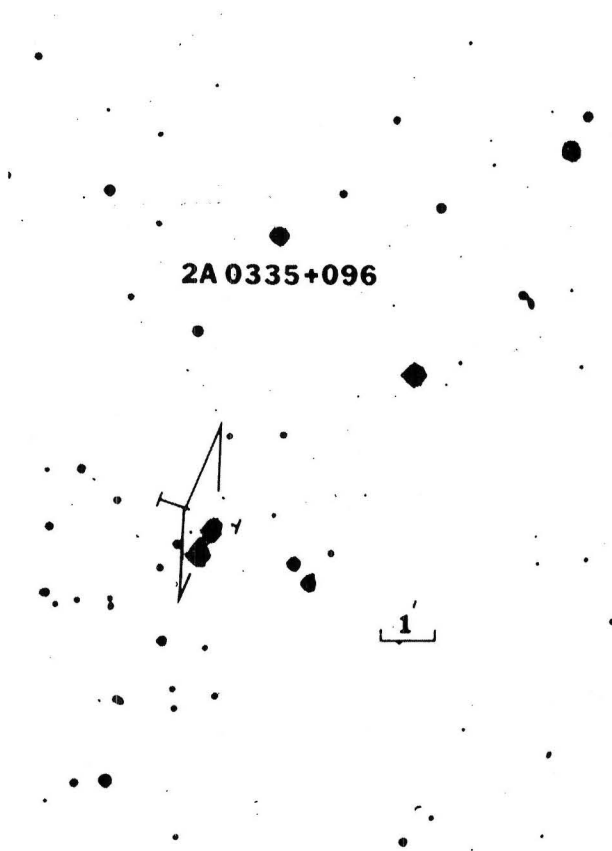
Figure 9. The A-3 location of 2A0335+096 is centered on a cD galaxy in a sparse group. The bar through our error box indicates the finite size, 1.5 arc min FWHM, inferred for this source. A foreground star of magnitude 12.2 is superposed on the SE.
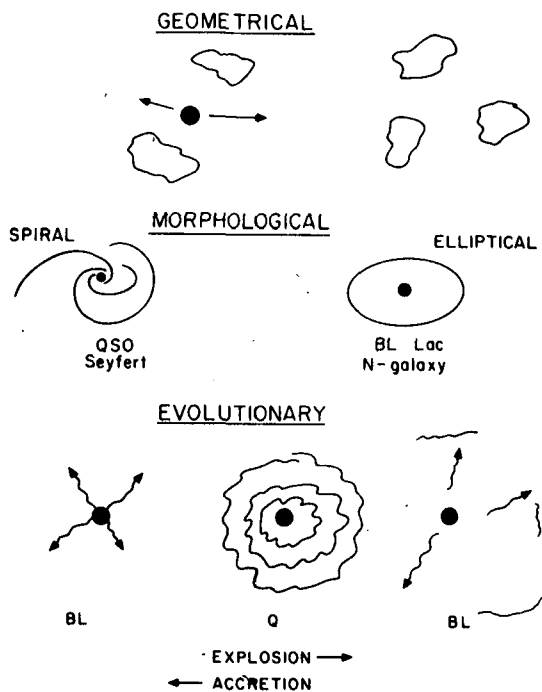
Figure 10.   A schematic classification of different kinds of theories to explain the specific properties of BL Lac objects in contrast to the more general category of quasi-stellar object to which they belong. Black dots represent the ultimate energy source (black holes?). Lines with arrow heads represent particle or photon emission. Wavy lines, contours, and clouds represent gas.
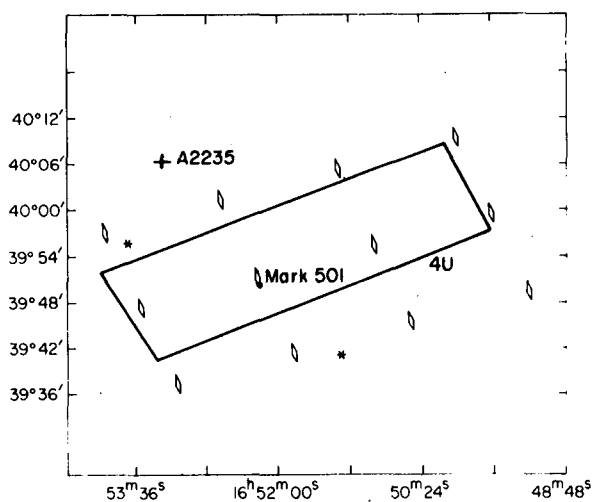
Figure 11.   Location of 4U1651+39, identifying it with the BL Lac object in Markarian 501.
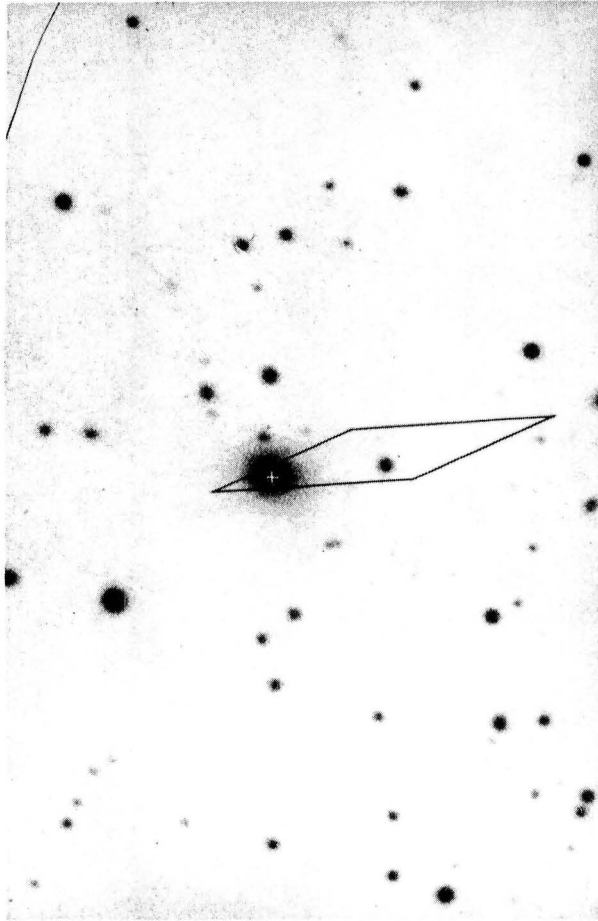
Figure 12. Superposition of one of our error diamonds on the Palomar
Survey print. The white cross denotes the radio source B2
1652+396, which is the BL Lac nucleus.
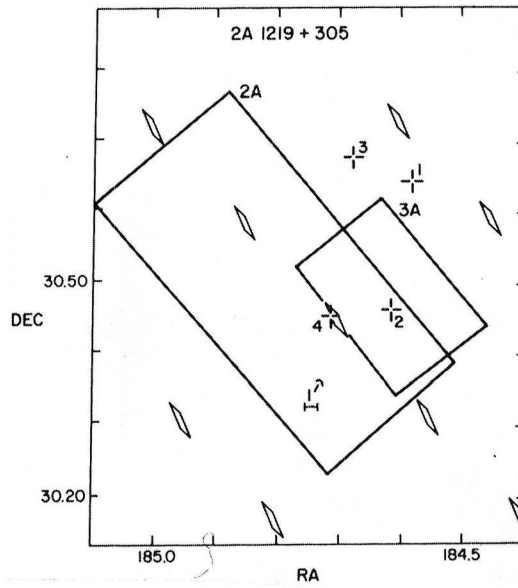
Figure 13. Locations of 2A1219+305. The only modulation collimator position allowed by the revised Ariel 5 position [25] contains the the radio source 4 suggested as the counterpart. [25]
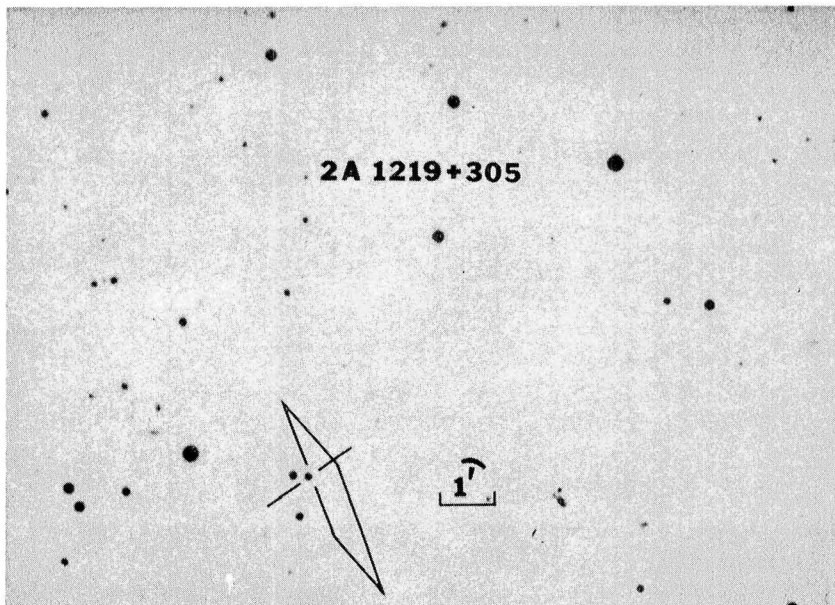
Figure 14. Superposition of the allowed MC for 2A 1219+305 superposed on the Palomar Sky Survey. The bars mark the position of the BL Lac object – the first object recognized as a BL Lac subsequent to its recognition as an X-ray source. [25]
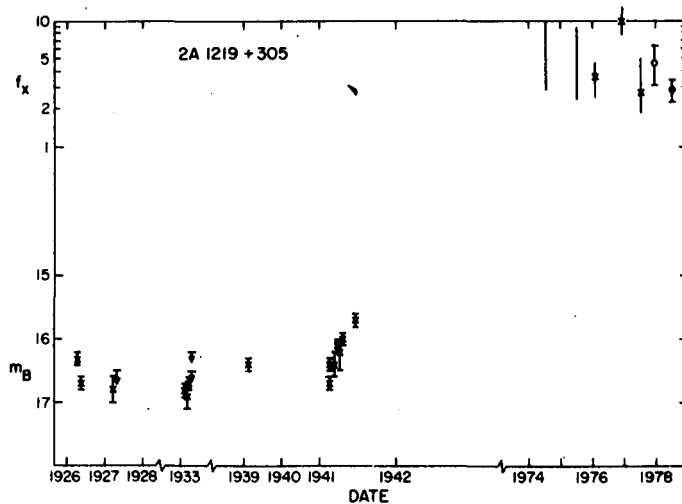
Figure 15.   X-ray[25] and optical light curves of the BL Lac object
2A1219+305.   For the X-ray fluxes, in 10^{-11} ergs/cm^2 s, the straight
lines give ranges observed by Ariel 5 over 6 month intervals, and
the circles with error bars give our A-3 measurements.   (The
horizontal scale has been broken and distorted for clarity.)
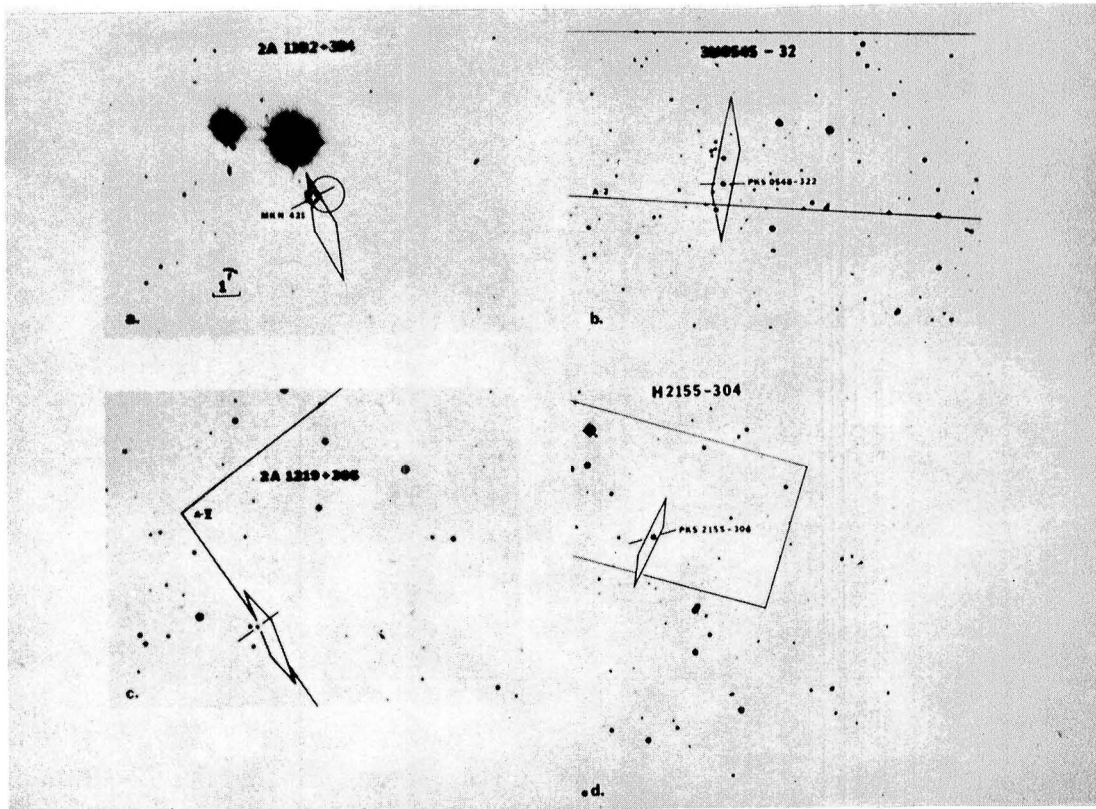
Figure 16. MC locations of 4 X-ray emitting BL Lac objects are given by
the diamonds superposed on enlargements of the POSS red prints.
Portions of previous X-ray locations are also shown.
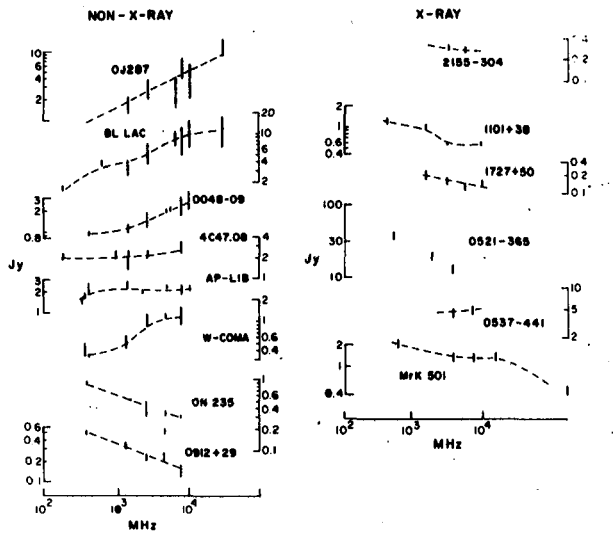
Figure 17.   Radio spectra of BL Lac objects (mostly from reference 26) which do (right hand column) and do not (left hand column) emit X-rays above a threshold of about 1 μJy at 4 keV.
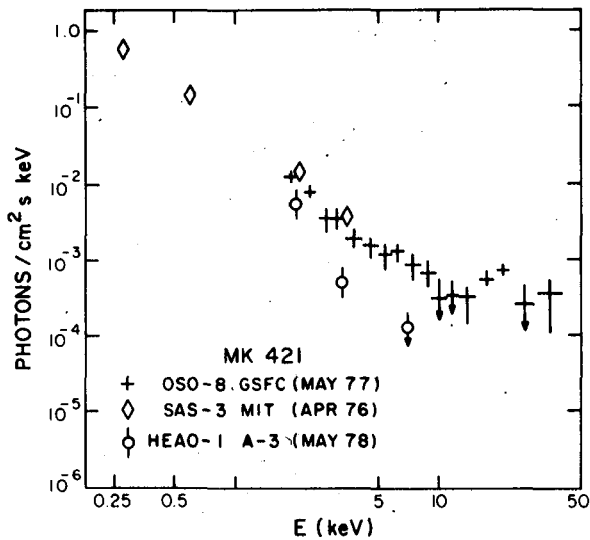

Figure 18.   X-ray spectra of Markarian 421.   The HEAO-1 MC data fit a power law slope 3 ± 1, in contrast to the slope 1 ± 0.5 measured above 3 keV by OSO-8[29] one year previously.
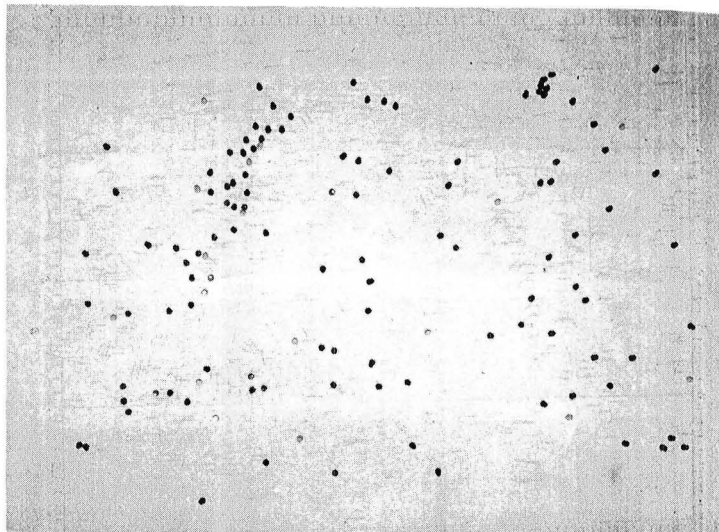
Figure 19. Computer map of all X-ray sources known prior to HEAO-1.
Red pins indicate new identifications, confirmations, or structure
measurements by the A-3 Scanning Modulation Collimator
Experiment. Blue push-pins indicate MC locations for
sources currently unidentified. Green pins are
sources firmly identified prior to the HEAO-1 launch.
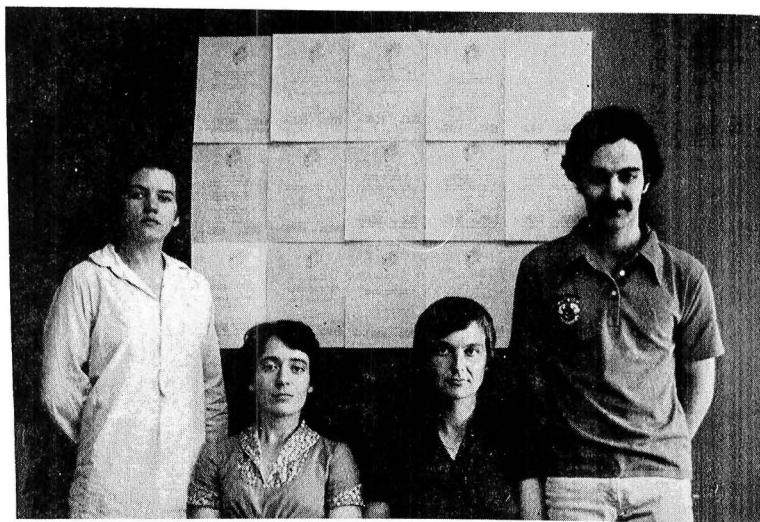

Figure 20. The Data Reduction and Analysis Support Team Information
Center, staffed by (right to left) Mike Garcia, Wendy Roberts,
Maureen Conroy, and Ellen Ralph, posed in front of a few of
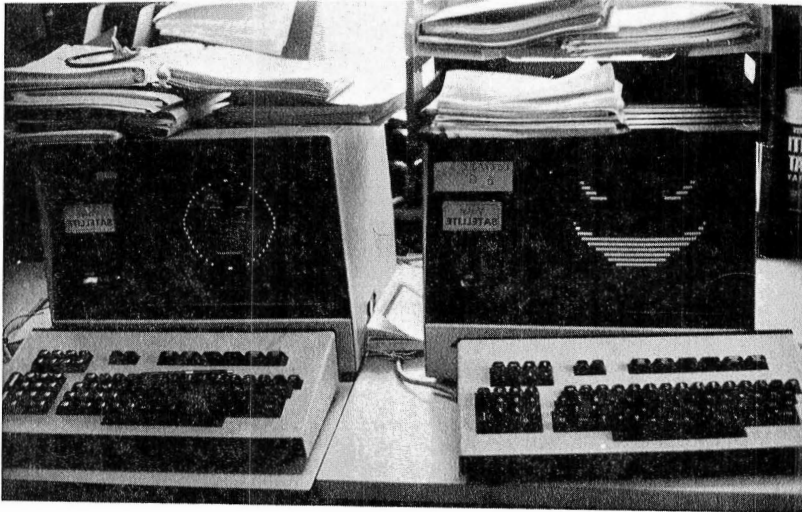our recent publications.

Figure 21.   The A-3 computer terminals prepare to give
the scientists orders for the day.