A-3 SCIENTIFIC RESULTS

Roger Doxsey
Massachusetts Institute of Technology

I would like to take this opportunity to thank the NASA personnel here at the Marshall Space Flight Center and Goddard and at NASA Headquarters for making the whole HEAO project happen. It has been quite a few years, and I guess I am a newcomer to the project since I have only been working on it since 1973. In fact, coming down here involves some nostalgia since it has been quite a while since I have been here. I can remember times when it seemed like we were coming down almost every month for various meetings and discussions during the hardware phase.

Dan and I are going to divide the discussion of A-3 results in half so I will end abruptly. I am going to discuss a little bit about the instrument and discuss results from our galactic observations and some of our results on active galaxies, and Dan will cover groups of galaxies, clusters of galaxies, and BL-Lac objects.

The purpose of the scanning modulation collimator experiment on HEAO-1 is to identify the optical counterparts of celestial x-ray sources. The optical identification and further studies at optical wavelengths can provide substantially more information about an x-ray source than is obtainable at x-ray wavelengths alone. Identification will reveal immediately whether the source is an extra-galactic object or a member of our own galaxy. The identification will usually indicate immediately whether the system is a stellar system, a supernova remnant, a galaxy, or a cluster of galaxies. Optical observations will usually lead to relatively good determinations of distance to the object and hence of the total luminosity, both at x-ray and optical wavelengths. The comparison of the x-ray and optical luminosities will tell you whether or not the x-ray emission from the source is a dominant characteristic of the source, as in the case of Sco X-1, or a minor part of the source's total emission, as in the case of our own Sun. In come cases, optical observations can provide a clue as to the age and chemical composition of the system. Detailed observation of complex sources, such as x-ray binary systems, can lead to determination of certain parameters of the system such as masses, radii, and separation of components in the binary. Probably one of the most important statements that an x-ray astronomer can make about any given particular x-ray source is to identify it with its optical counterpart.

The reason that the optical identification of x-ray sources has not been a completely trivial matter is shown in Figure 1. This shows the portion of the Palomar Sky Survey containing the x-ray source 2A1822-371.

This source was detected by both the Uhuru and Ariel 5 satellites, which were scanning missions using slat collimators. Both of these satellites determined error boxes for the source. The larger one is the Ariel 5 error box and the intermediate one is the Uhuru error box. These error boxes are typically 0.1 to several square degrees in area. It would be an impossible task for an optical astronomer to study, in detail, each of the stars in this error box to determine which is the counterpart to the x-ray source. Experience has shown, especially with galactic sources, that many of the optical counterparts are 18th, 19th, and 20th magnitude, which correspond to the faintest stars that you can see on this particular print. At high galactic latitudes one expects that the sources will be extra-galactic and hence begins by looking for cataloged, extra-galactic objects in the error boxes, as Kent Wood described the A-1 cataloging procedure. One looks for Seyferts, emission line galaxies, BL-Lac objects, clusters of galaxies, and other unusual objects. If one does not immediately find a cataloged object, one can begin doing optical studies of the galaxies in the box hoping to discover an as-yet unknown Seyfert or BL-Lac object. Many of the high latitude sources from the initial surveys, Uhuru and Ariel, have been identified in this manner. The error boxes are small enough and the surface density of unusual extra-galactic objects is low enough that the chance of getting an erroneous identification is fairly small. In particular, based on this method, Seyfert type 1 galaxies were identified as a class of x-ray sources. There are about 20 or so that were identified based on large error boxes. For any given one of them, there would be a possibility that the identification would be wrong but certainly for the class it was correct.

At low galactic latitudes the problem is more difficult because you really have to look at each individual object in the error box for unusual characteristics which would lead you to identify it as the x-ray source and, obviously, with boxes of this size, it is just not feasible to do that. From some of the original scans, astronomers began by looking at the few brightest stars in each error box to see whether they were unusual. They looked to see whether any of the brighter objects showed any unusual time variability because that is a characteristic of the optical counterparts of some x-ray sources. They especially looked for some time variability if the x-ray source had periodic variation. As you can see, what really is required is a survey with high angular resolution, one which provides relatively small error boxes. The small diamond in Figure 1 represents the HEAO A-3 error box that was obtained for this source. Phil Charles and John Thorstensen discovered a star, which is, in fact, the x-ray source, that has emission lines of Helium II λ4686 and CIII/NIII $\lambda\lambda$ 4640-4650 which are common lines to find in x-ray counterparts and very unusual in normal stars.

The HEAO A-3 instrument is not the first experiment to have a high angular resolution. This problem was recognized a long time ago; in fact, one of the very earliest rocket experiments was the NRL experiment done by Dr. Friedman to use a lunar occultation to identify the Crab Nebula. There were lunar occultation measurements and some early rocket RMC flights which provided error boxes about this size for several of the brighter galactic center sources. The first high angular resolution survey that was conducted was done by the rotating modulation collimator experiment on SAS 3. This survey was primarily limited to observations of the galactic plane. This limitation was just a limitation in terms of the available observing time; it could theoretically have done the entire sky. On the scale of the HEAO instruments, it was a relatively small instrument so its sensitivity was not as good. In the galactic plane, the sensitivity of that survey was not quite as good as the Uhuru and Ariel 5 surveys. But, since it was the first high resolution survey that was carried out, it made quite a few identifications. There were many counterparts that had been proposed based on large error boxes which were either confirmed or denied by initial SAS measurements, and quite a few of the SAS circles led to new identifications and new suggestions of counterparts. There were a total of 15 to 20 of these galactic sources which were identified based on the SAS survey. The A-3 scanning modulation collimator takes advantage of the scanning nature of the HEAO-1 mission to obtain a fairly uniform all-sky coverage and it also takes advantage of the larger physical size of the spacecraft to get a larger area and hence better sensitivity, so that our survey typically gets to sensitivities comparable to the Uhuru and Ariel 5 limits of about 1 Uhuru count. In fact, in the pointed observations, we can get down to as low as a half of an Uhuru count.

Figure 2 shows a conceptual drawing of the experiment. The primary element which provides a high angular resolution is the 4 grid scanning modulation collimator. There are two of these collimators — one at the top and one at the bottom. The wires in the drawing are greatly exaggerated, the wires in the fine collimator are 5 mil diameter and in the coarse collimator they are 20 mils. The distance is about 3 ft from front to back. This provides an angular resolution for the finer of the collimators, of about 30 arc sec; and for the coarser, about 120 arc sec. The collimators basically work as shadow devices. At any instant in time, three quarters of the field of view is blocked from the proportional counter, so the counters will not detect x-rays from that part of the sky. The remaining quarter is divided into many narrow bands on the sky. The two collimators are tipped at ±10 degrees relative to the scan direction, so that one can detect the source in both collimators and then use the intersection of the bands in the sky to derive the position. The overall field of view is limited to 4 × 4 degrees to help reduce source confusion problems. The counters behind the collimators are fairly standard proportional counters operating in the range of 1.5 to 13 kV. The second primary element consists of the two image dissecting star trackers which are used in conjunction with the gyros on the spacecraft to obtain a 5 arc sec aspect solution. The accuracy is crucial to being able to derive small error boxes and hence make identifications.

Figure 3 shows the picture of one of the modulation collimators. The structure is brazed beryllium. One of the design problems with this experiment was the alignment that had to be maintained between the wires of the front grid and the wires in the back grid. This alignment tolerance was 1/10 mil and had to be maintained in all environments experienced by the spacecraft. The environments we were most worried about were the vibration of launch and the thermal cycling in orbit. The choice of beryllium in the design of the experiment was made to keep the thermal gradients as low as possible. We have no evidence of any on-orbit problems with distortions or misalignments.

Figure 4 shows the experiment as a whole, I should mention that the hardware is basically a result of the scientific direction from Herb Gursky and Dan Schwartz, originally at AS&E and then at the Center for Astrophysics, as well as Hale Bradt and myself at MIT. The hardware was built by AS&E under the direction of Phil Gray and Allen Ramsey. The experiment performed very well in orbit. We lost one of the eight proportional counters early and that reduced our sensitivity in one collimator by a small amount. We had a small problem with the thermal shields (not shown installed in the figure) which led to slightly increased gradients in the collimators, but not enough to create any distortions. Other than that the experiment worked perfectly.

Figure 5 shows how we determined source positions. The fields of view of the two collimators are shown projected on the sky. The wider triangles represent the coarser of the two collimators, which we call SMC2. There is a 16 arc min spacing between them and a 4 arc min spacing between the bands of the finer collimator, SMC1. As the collimators scan the sky, the source traverses a path across the various bands giving count rate profiles which are shown on the left. When one analyzes the data, putting it back on the sky, one gets diamonds for source positions, which are the intersections between the lines of position determined for the two collimators.

Figure 6 shows a transit through Sco X-1, normally the brightest x-ray source in the sky. The overall 4 × 4 degree collimator is readily apparent, as are the differences in resolution and spacing of the two modulation collimators. Observations of bright, identified sources are used to calibrate the collimators relative to the star trackers. For most sources, the intensity is many orders of magnitude less than Sco X-1. In fact, for most sources we are really interested in, you cannot see individual transits through planes of transmission. Since we know very accurately the angular spacing between the peaks, we can fold the data modulo that angular periodicity, taking all the peaks and superposing them on top of one another.

An example of that is shown in Figure 7. This was done for an observation of a rapid burster. These data were accumulated by folding a number of scans through the source. The superposition builds up peaks which can then be fit with triangles separately for the two collimators. Each triangle fit yields parallel lines of position, the intersections of which form the diamond shaped error boxes.

I would now like to discuss a few of the optical identifications which have been made for galactic sources. Figure 8 shows the first one, one which was very exciting at the time. This is Nova Ophiuchi 1977. There have been a number of x-ray novae in the history of x-ray astronomy. Typically, they go from being undetected or not previously known to being among the brightest x-ray sources in the sky. They rise very quickly in a few days, and then decay over time scales of months to a year or two. This particular nova appeared just prior to the HEAO-1 launch and was quite bright. HEAO-1 scanned across it in September 1977. HEAO A-1 data were used to limit which of our multiple intersections the source might be located in. The source was identified by astronomers collaborating with us in Australia. This is a "before" and "after" picture. The star which is quite bright, the brightest of the group in the "after" picture, is absent or at most barely visible on the "before" picture. One of the best ways of making optical identifications is by finding a temporal coincidence between the x-ray and optical events, as we had in this case. There are relatively few sources that are actually identified in this manner; however, most are discovered by making optical spectroscopic observations.

Figure 9 shows an optical spectrum, which happens to be of this source. Typically, one uses a relatively large telescope and a good spectral photometer and examines the optical spectrum of each star in a diamond. It turns out that there are a number of emission lines which are very characteristic of x-ray sources. In particular, the Helium II line at $\lambda 4686$, and the CIII/NIII blend at $\lambda 4640$-$\lambda 4650$ are very common. This technique has been used for most of the identifications that have been made on the basis of A-3 positions. Another way of getting a hint as to which star is the x-ray source, is to take plates at different colors; U, B, and V and to compare them looking for color differences, because x-ray sources also tend to be bluish or UV excess sources.

Figure 10 shows one of our identifications. This is the source GX339-4 which Herb Friedman discussed earlier as the one which is very similar to CYG X-1. The identification of GX339-4 was made by using an Uhuru box, an Ariel 5 circle, and our HEAO diamond. Identification was made by Josh Finley at Cerro Tololo in Chile. The star which is the candidate is a 16th magnitude star and it shows the standard emission lines which one sees from such objects.

Figure 11 shows MXB 1659-29, and again it was identified in the same way by making spectrographic observations in Chile at Cerro Tololo. This source is the burst source which for quite a while was thought not to have a DC component. The DC component appeared in the Spring of 1978 and this HEAO measurement was made which identified the candidate.

Figure 12 is a list of the stellar sources which have been identified primarily using the HEAO A-3 positions. Most of them are very faint. The brightest one is 14th magnitude and most of them are fainter than 16th magnitude, which means that you really do need the small error boxes to identify them. Two or three of them are of particular interest. One is 4U212947 which is the first of these faint UV excess, Helium II emission stars to show very clear evidence of a binary periodicity. This will be discussed in a later session by Richard Griffiths. There have also been several confirmations. These are sources that were previously believed to be x-ray sources, and with the HEAO A-3 boxes, we substantially reduced the error box area. In particular, for the U Gem types, it demonstrates before the time correlations were known, that the hard emission is, in fact, from the same star as the soft emission. We are expecting that quite a few more identifications will be made in the next couple of weeks or months. Right now is the season when the galactic center is visible from Cerro Tololo and from Kitt Peak. There are observers there now and will be over the next few months working on identifying sources based on our positions.

Figure 13 shows the Seyfert galaxy NGC 4151. Although it is outside both the Ariel and Uhuru error boxes, it is such an unusual object (it really does not appear that unusual in the picture) that it was identified with both of these sources by those catalogs. The diamond shows the HEAO A-3 position for that source.

The situation with Seyferts was that there had been more than 20 suggested identifications for Seyfert Type 1 galaxies. We have now observed and gotten positions for 20 of these and all of the ones that we see confirmed the initial identifications. There were also a few (one or two) BL-Lacs and high excitation emission line galaxies that had been suggested as counterparts for x-ray sources. By getting positions of 5 or 6 of these in each class, we established that they do represent classes of x-ray sources and that it is not a coincidence for an object of that type to be in an error box. We have seen a total of about 30 active galaxies so far and we expect to see a few more as we continue to analyze the data.

Figure 14 shows some of the Seyfert Identifications. Most of these are from the pointed observations between last May and December. In the case of IC4329A, the SAS 3 results indicated that perhaps the source is extended or perhaps both IC4329A and its companion IC4329 are x-ray sources. Our results are not consistent with either of those suggestions. There can be no more than 1/3 the flux from IC4329 as from IC4329A and there is no evidence of any extended component.

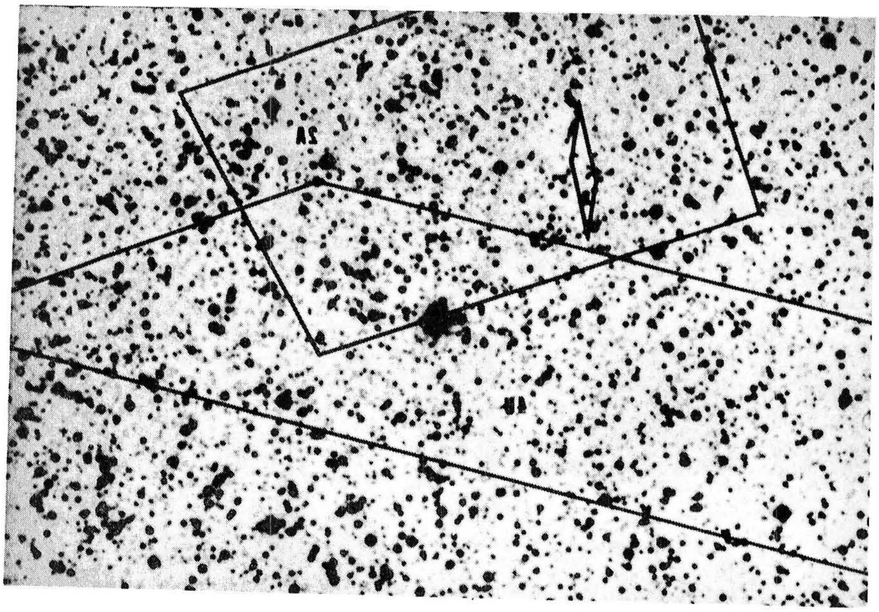

Figure 1

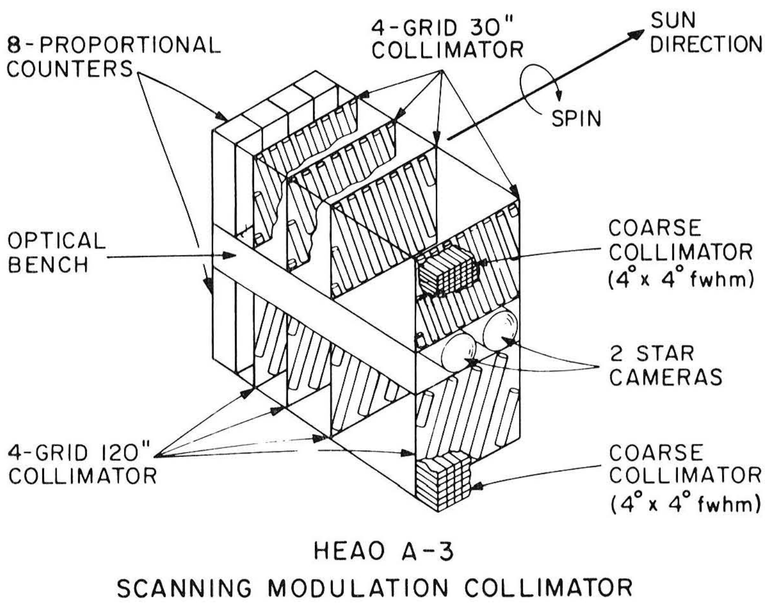

Figure 2

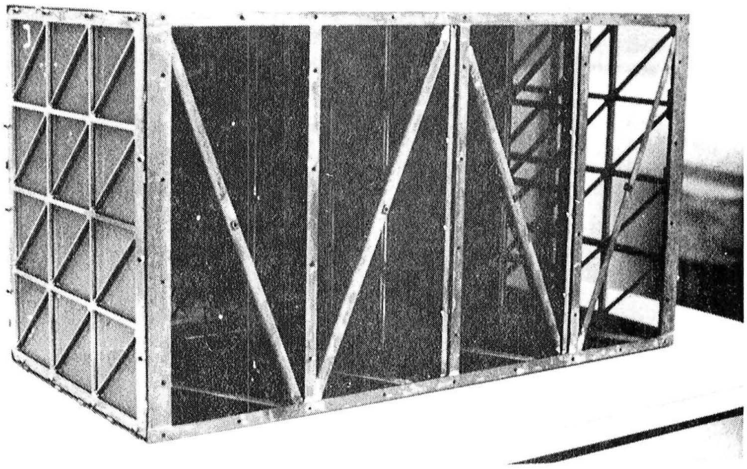

Figure 3

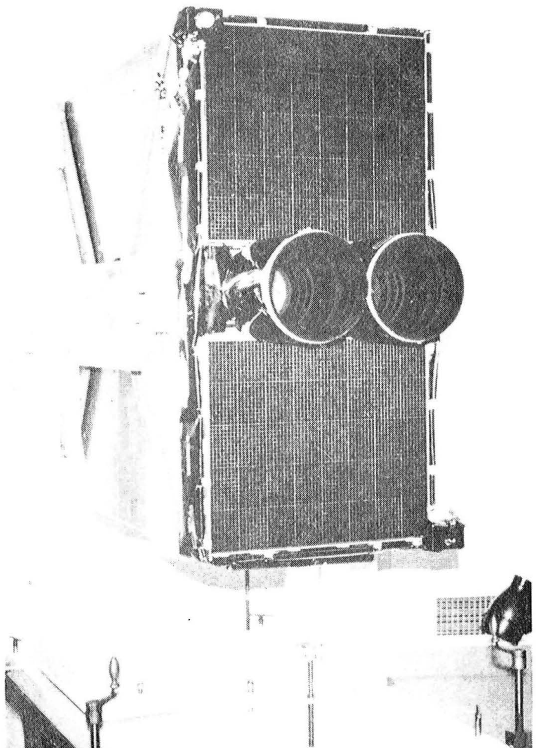

Figure 4

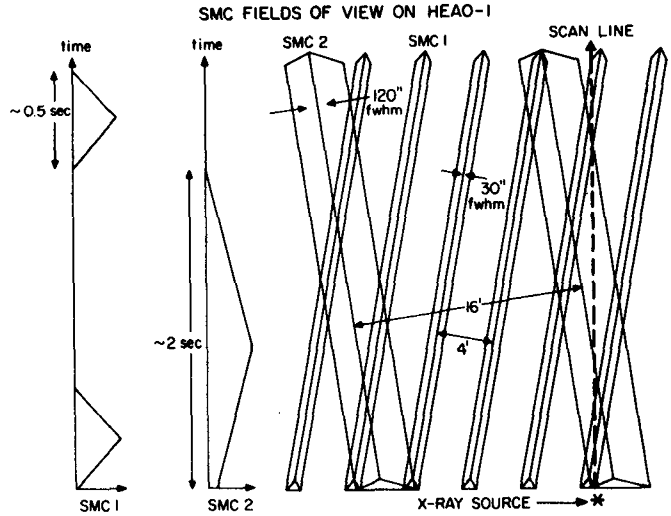

Figure 5

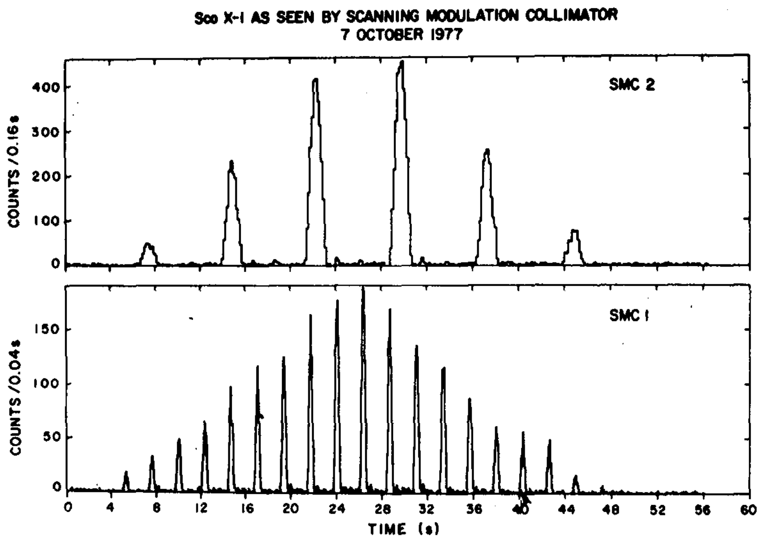

Figure 6

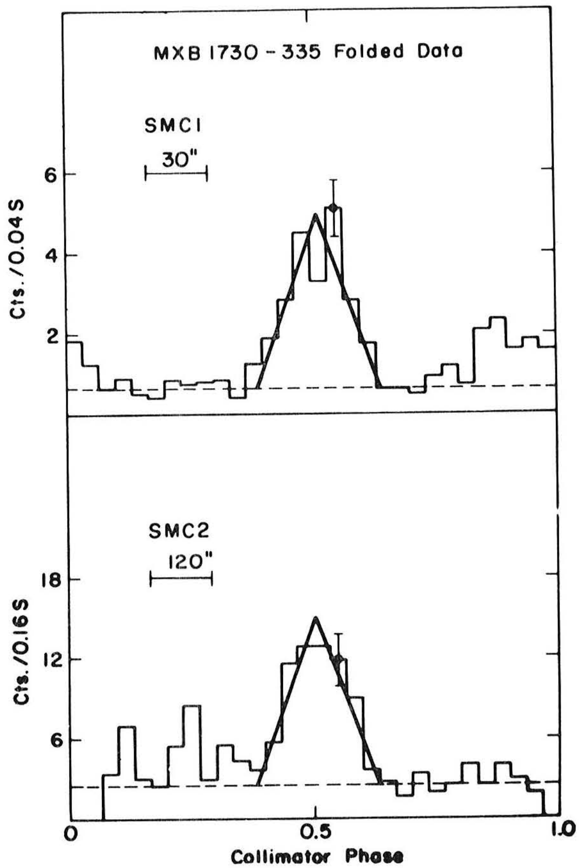

Figure 7

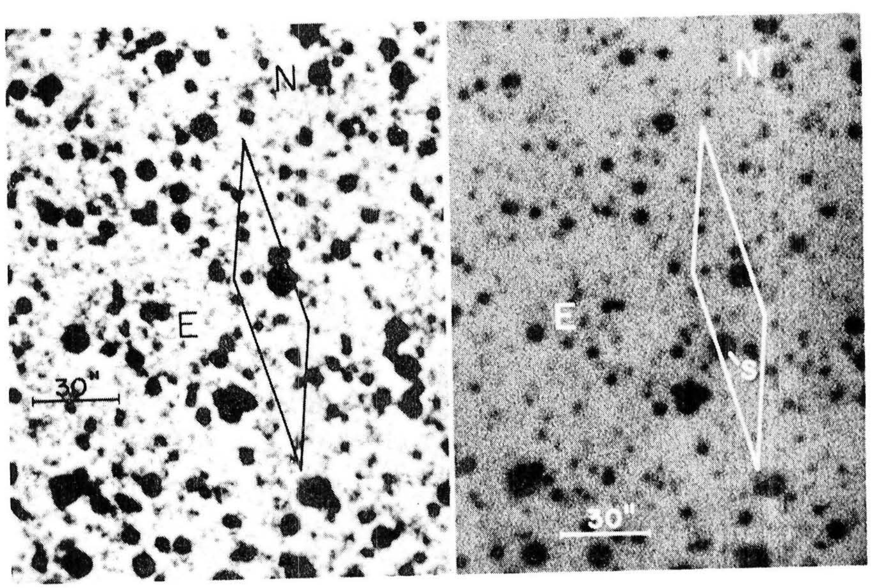

Figure 8

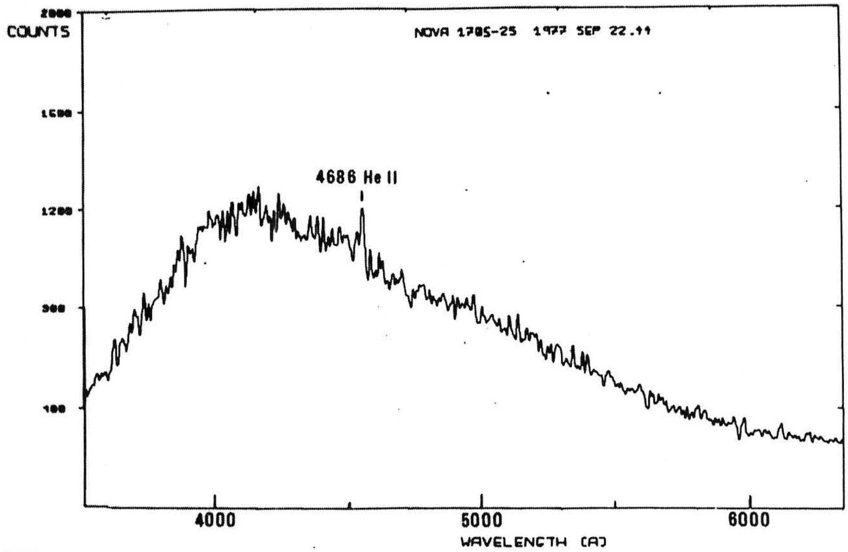

Figure 9

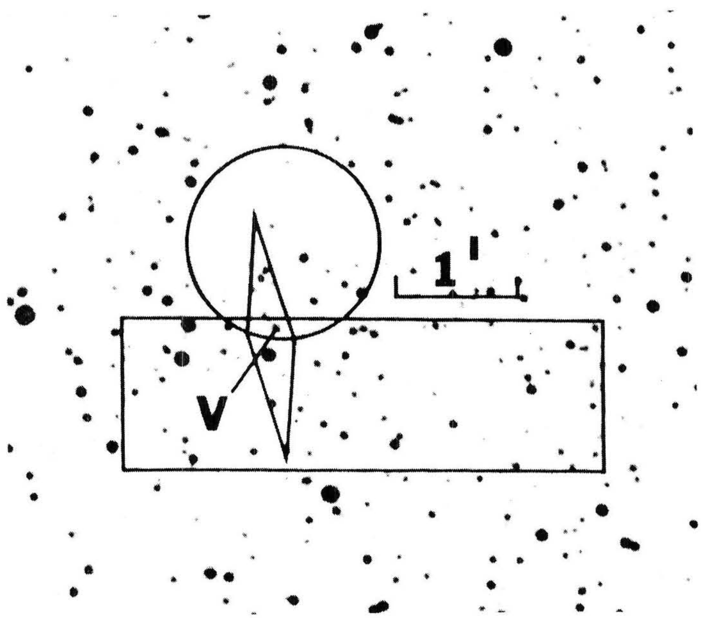

Figure 10

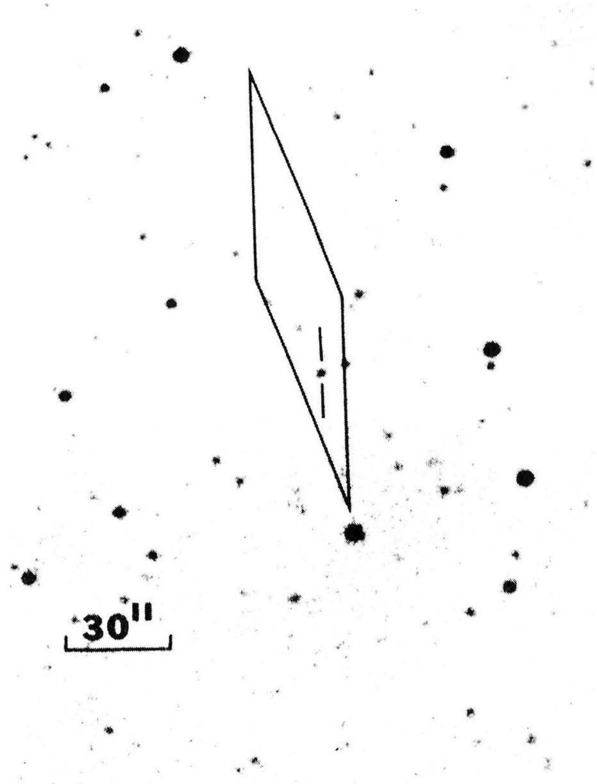

Figure 11

TABLE 1 - A-3 STELLAR OBSERVATIONS

Source	Optical Counterpart	X-ray Properties
H1705-25	Nova Oph 1977	transient
4U0115+63	B type	pulsing binary transient
4U1538-52	BOI	pulsing binary
2A1052+606	early K subgiant Hα emission	$\lesssim 10^{32}$ ergs/s
4U1254-89	m_V = 19 HeII emission	
2A1822-371	m_V = 16, HeII emission	
MXB1659-29	m_V = 16, HeII emission	burster
GX339-4	m_V = 16, HeII, Hα	black hole?
4U2129+47	m_V = 16-18, HeII 5-hr binary	
A1916-C5	m_V = 19, flat spectrum	burster
LMC X-1	B5I	$\gtrsim 10^{38}$ ergs/s
LMC X-2	M_V = 18.5, HeII emission	
LMC X-3	OB	$\gtrsim 10^{38}$ ergs/s
A0538-66	B2 Iab	recurrent transient in LMC
A1907+09	m_V = 16, Hα emission	
2A0311-227	m_V = 15, many lines	AM Her type
2A0526-326	m_V = 14, HeI, HeII emission	
CONFIRMATIONS:		
4U1543-624	m_B = 20, UV excess	
4U1755-33	m_B = 19, UV excess	
4U1608-52	variable m_B = 18 to >20	transient, burster
U Gem	U Gem type dwarf nova	
SS Cygni	U Gem type dwarf nova	
EX Hydrae	U Gem type dwarf nova	
MXB1730-335	cluster core, Liller 1	rapid burster

Figure 12

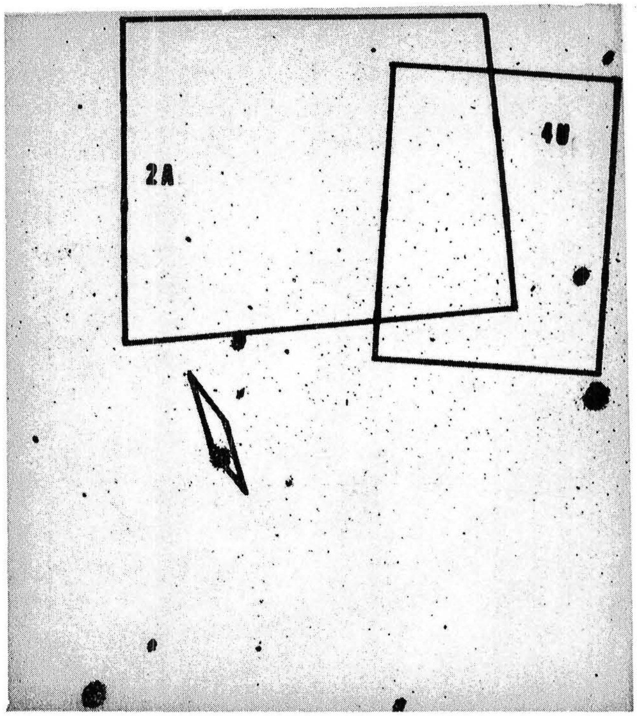

Figure 13

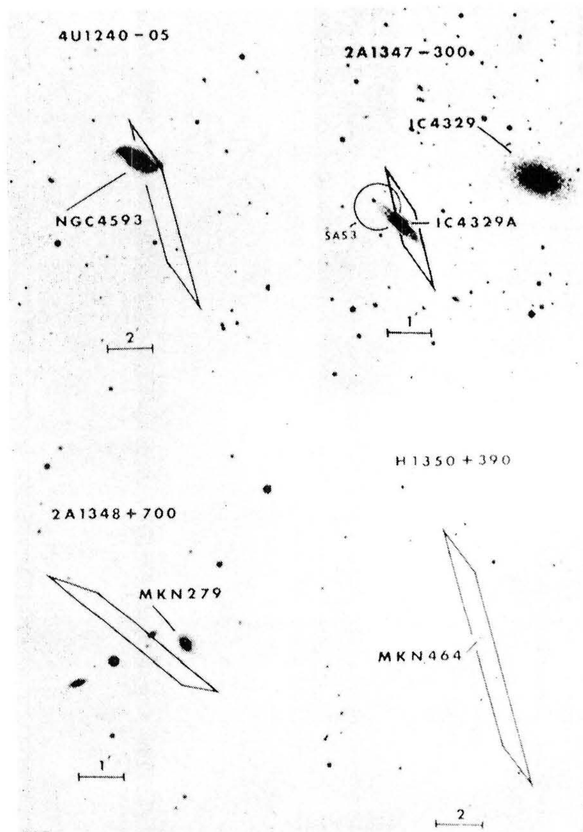

Figure 14