X-RAY VARIABILITY OBSERVED WITH HEAO A-1

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The A-1 instrument was designed to extend the range of temporal variability that was observed in previous missions. In Figure 1, we indicate the variety of time scales that are covered, 10 msec to 40 sec in scanning data on single scans. We could go to microsecond time scales and high bit rate data, but only when the spacecraft was over a ground station capable of receiving telemetry in real time. High ecliptic latitude objects could be scanned for many days. Repeat sequences of scan were observed at 6-month intervals, over the 17 months of the mission. We have in hand data with which to complete an all-sky survey for X-ray pulsars in the high frequency range, and we can look for the detailed features of the temporal variations of the black hole candidates. The burst sources are especially interesting because, with the large areas of the A-1 instrument, we can get better profiles than previous missions have obtained and we can search them for evidence of pulsation or other variability intrinsic to the burst itself.

I shall start with an example of evidence for longer term variation in extragalactic objects. Figure 2 shows positional data on Pks 2155-304, a radio source, believed to be a BL Lac object, and illustrates how the various experiments in the mission combined to refine the error boxes. The A-3 experiment produces the diamond-shaped arrays of potential error boxes. A-1 and A-2 can then bracket these error boxes and A-1 particularly can select the one diamond which is the true position of the source. Figure 3 is a sample of flux measurements over a period of 6 days, which shows the degree of variability on this time scale. In the region around day 316, oscillations in the flux are observed on a time scale of the order of 6 hr, implying that the size of the source is less than 6 light hr. Such dimensions are comparable to the size of the solar system. Figure 4 fits a source identified with BL Lac object 3C 371. It shows the A-2 and A-1 error boxes; the suspected source lies on the edge of the A-1 error box, which is about 1/10 of a square degree. Figure 5 is a sample of the flux variations, which could be followed for about 60 days, because the source is very close to the ecliptic pole. Around day 238 we see what looks like a flare lasting on the order of a day, superimposed on a rather steady decline in the flux, and then a rise again around days 273 to 280. Optically, the source is observed to vary by about 1.2 visual magnitudes; the evidence here is for similar variations in the X-ray range of the spectrum. Such observations add significantly to the information that is gained optically for these sources. By comparisons of optical information and high energy information we can develop a more detailed model of the mechanisms that are operating in these very powerful sources.

So much for samples of what can be done with extragalactic sources. If we turn to the sources within the galaxy, perhaps the most interest attaches to candidate black holes. The leading candidate for a black hole is still Cygnus X-1. Interestingly, it was one of the earliest sources picked up in rocket surveys; we observed it in 1964 and again in 1965, and found that it had changed its intensity by about a factor of four. Uhuru quickly detected the very short term variability character of the source; it produces its emission in erratic, bursting fashion. Our chairman for this session, Marty Weisskopf, has been modelling the variability characteristics of this source, and has made a very good case for describing the emission as shot noise, random bursts of emission which have a typical time characteristic on the order of a fraction of a second (0.3 to 0.5 sec).

The top profile of Figure 6 shows a transit of Cygnus X-1 through the A-1 collimator; the passage takes approximately 10 sec from one corner of the collimator triangle to the other. Below it is a similar transit of GX 339-4, which Uhuru observed as a long term variable, but which HEAO shows is almost a duplicate of Cygnus X-1 in its short term variability. And there is a third source, Circinus X-1, which also shows this type of variability. The persuasive evidence for the black hole character of Cygnus X-1 comes out of the dynamics of the binary system in which it occurs. The evidence is that the mass of the compact object, Cygnus X-1, exceeds six solar masses. In theory, if the mass exceeds three solar masses, it cannot be a neutron star; it must be a black hole. We do not have similar evidence for GX 339-4 and Circinus X-1. They are candidate black holes only because their temporal variations so closely resemble Cygnus X-1.

Figure 7 shows integral chi-squared distributions for Cyg X-1; in the 30 to 300 msec range there is a very large deviation from a Poisson distribution. The discrepancy exists all the way down to the 1 to 10 msec range. Only in the 0.3 to 3 msec range do the data fit a Poisson distribution. In Figure 8 we show the autocorrelation; the upper curve is stretched out by a large factor (the bottom scale is 1 sec, while the scale at the top is 100 msec). Toward the origin there is a strong component at around 3 to 4 msec. It appears that, in addition to the approximately 0.5 sec shot noise pattern which has been confirmed by many observers, there is an additional component around 3 to 4 msec. One can speculate about the significance of this pattern in terms of black hole models. If Cygnus X-1 is a six solar mass black hole, the material at the edge of the accretion disc at the innermost stable orbit, would be circulating the black hole with a period of 3 or 4 msec. The approximately 0.5 sec shots may be associated with turbulence over a large portion of the accretion disc. Perhaps the 3 msec component is indicative of material which is tearing off the edge of the accretion disc and falling into the black hole, surviving less than one Keplerian orbit. That is just pure speculation, but the 3 msec effect is worthy of serious theoretical interpretation.

Figure 9 is a tabular summary of the rapid fluctuations in the 3 to 4 msec range. While the total count rate is approximately 1,000 counts per second, the time average of these bursts is approximately 50 counts per second; they represent a twentieth of all the luminosity. Individually each one of these fast bursts is about as luminous as one of the longer 300 msec bursts.

Figure 10 shows samples of data from GX 339-4, three transits through the scan collimators with 40 msec bins. Wide fluctuations are evident. Over a fraction of a second there are intensity excursions of factors of three or four above average. Figure 11 shows the integral chi-squared distribution against chi-squared; the solid line represents a Poisson distribution. In the ranges from 5 to 50, 40 to 400, 80 to 800, 160 to 1600 msec, there are very wide deviations revealing the shot noise character. We do not have data at the very short time scale end of the distribution because these were taken in our 5 msec timing mode and not the high bit rate data mode. Figure 12 is an attempt to summarize what we know about the three candidate sources, Cygnus X-1, Circinus X-1, and GX 339-4. In the case of Cygnus X-1 and Circinus X-1, we have clear evidence for binary orbital periods. A bimodal characteristic of the X-ray spectrum appears in all three sources. Extended off-periods exist for Circinus X-1 and GX 339-4. The strong resemblances in these three sources suggest a common model and they will be the object of much more detailed analysis with data that are in hand from the HEAO-1 mission.

We have had a few opportunities in the mission to look at bursters with the A-1 instrument. Figure 13 shows a burst from 1728-34. The rise time of the burst reveals a great deal of fluctuation. We have tried to search the data on this source at high frequencies to see if there is any evidence for rapid periodicity or quasi-periodicity in the source. The generally accepted model for a black hole and its accretion disc is that hot spots will form in the accretion disc as differential rotation winds up magnetic fields and eventually leads to a tearing mode instability resembling a solar flare. The flare becomes a hot spot which is carried around with the spin of the disc and because of gravitational focussing and doppler effects, the signal is likely to be strongly modulated. If the hot spot can survive several rotations, we should see the periodicity of the Keplerian motion; if it can not survive a few rotations, no periodicity will be observed. If it survives long enough, we might even observe the drift of the material as it spirals inward toward the black hole with decreasing Keplerian period. The evidence for 1728-34 has been very tantalizing. Although the statistical evidence is marginal, there appears to be a periodicity around 12 msec, in one strong burst. Off the burst, this source has a steady component of emission with no evidence of periodicity. Three other bursts have been observed with less statistical significance. In one of them there is a hint of pulsation closer to 10 msec, enough to make one wonder whether a black hole model for the burster ought to be considered seriously in competition with all the evidence for bursters being neutron stars. Of course, a fast spinning accretion disk model for a neutron star burster is not excluded.

These are some samples of the kind of information that we have from the mission and what we are trying to do with the data. I would like to end with some historical comments about the program. Dr. Lucas has already mentioned how far back the effort at Marshall goes, but it goes back considerably further than that. In 1965, at a meeting of the Space Science Board at Woods Hole, Riccardo Giacconi and I were the senior scientists (I wonder what we are now), and I pushed hard for large area detectors while Riccardo pressed for a mirror. Now we have seen both these approaches accomplished in the HEAO program. Here at Huntsville, Ernst Stuhlinger was my principal contact in the late sixties, and serious plans were made to carry very large arrays of detectors on left-over Apollo hardware. With Saturn V hardware it would have been possible to put a big fence of detectors on the moon (Fig. 14) looking over a lunar horizon to observe occultations of X-ray sources at the horizon. These drawings were made here at Huntsville. Figure 15 is a sketch of how one might put 100 ft^2 of detector modules on the LEM, or put a large folded array that could be deployed like solar panels on the service module (Fig. 16). You all know the history of what happened to the Apollo hardware, and how the HEAO concept was taken away from the manned missions and run as an unmanned program, how it went through one drastic reduction around 1973, and how it finally came to the successful launches of HEAO-1 and HEAO-2 in the last couple of years.

A-1 SURVEY OF X-RAY SOURCE VARIABILITY

- UTILIZE LARGE COLLECTING AREA AND WIDE RANGE OF ACCESSIBLE TIMESCALES

- 10 msec - 40 sec IN SCANNING DATA, SINGLE SCANS. LONGER TIMESCALES (UP TO 1 yr) BY COMPARING SCANS

- MICROSECOND TIMESCALES IN HIGH BIT RATE DATA

- QUASARS, BL LACERTAE, ACTIVE GALACTIC NUCLEI: 1 hr TO 1 yr

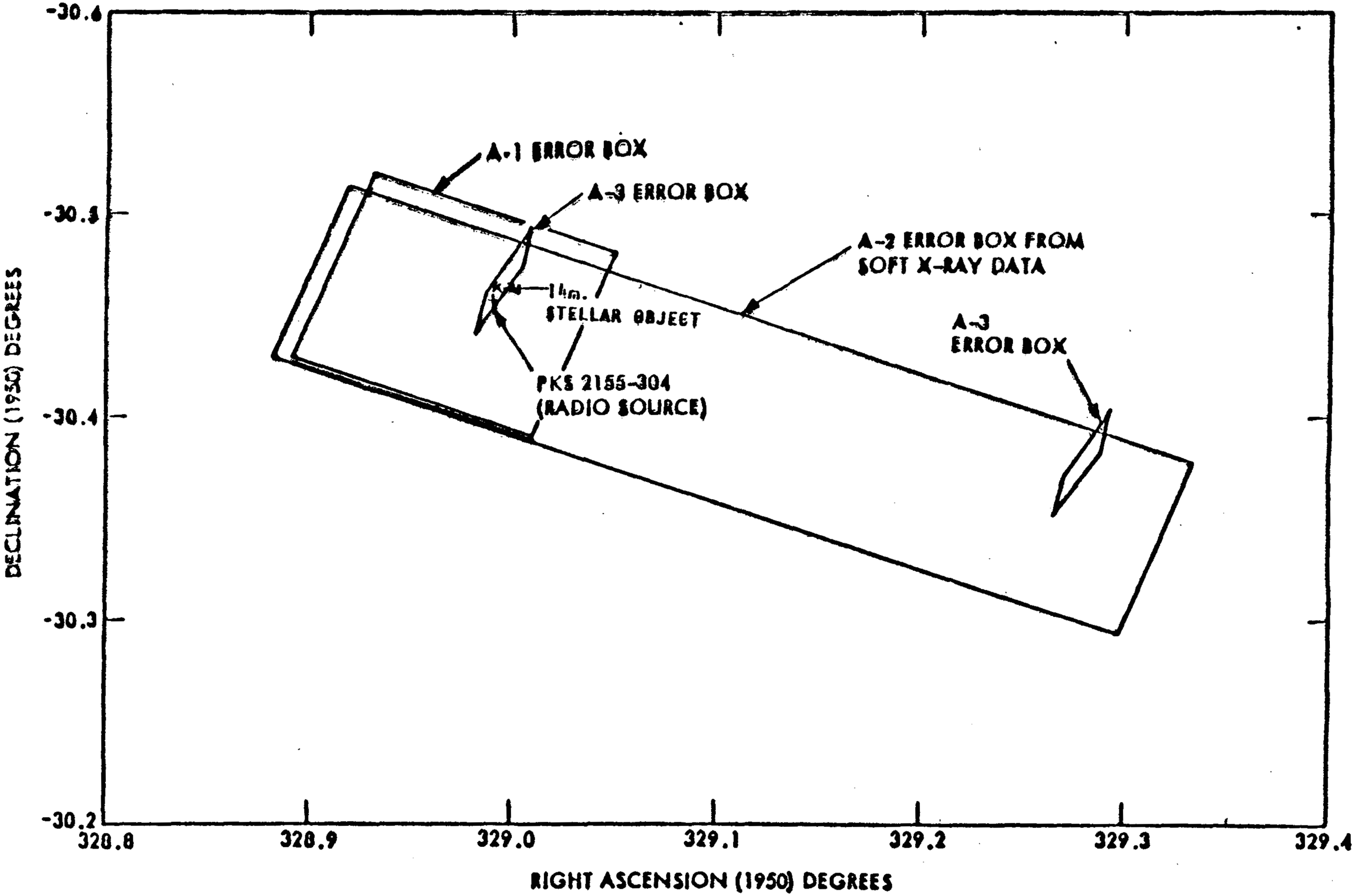
- HIGH-SENSITIVITY SEARCH FOR X-RAY PULSARS

- DETAILED STUDY OF KNOWN BLACK HOLE CANDIDATES
  - PERIODICITY SEARCH AT SHORT TIMESCALES
  - SHOT NOISE MODELING
  - SEARCH FOR SHORT DURATION SPIKES

- PERIOD FLUCTUATION STUDY IN BINARY PULSARS

- X-RAY AND GAMMA-RAY BURSTS

Figure 1



-30.6
-30.5
-30.4
-30.3
-30.2
328.8
328.9
329.0
329.1
329.2
329.3
329.4
DECLINATION (1950) DEGREES
RIGHT ASCENSION (1950) DEGREES
A-1 ERROR BOX
A-3 ERROR BOX
A-2 ERROR BOX FROM SOFT X-RAY DATA
14m.
STELLAR OBJECT
PKS 2155-304
(RADIO SOURCE)
A-3
ERROR BOX

Figure 2

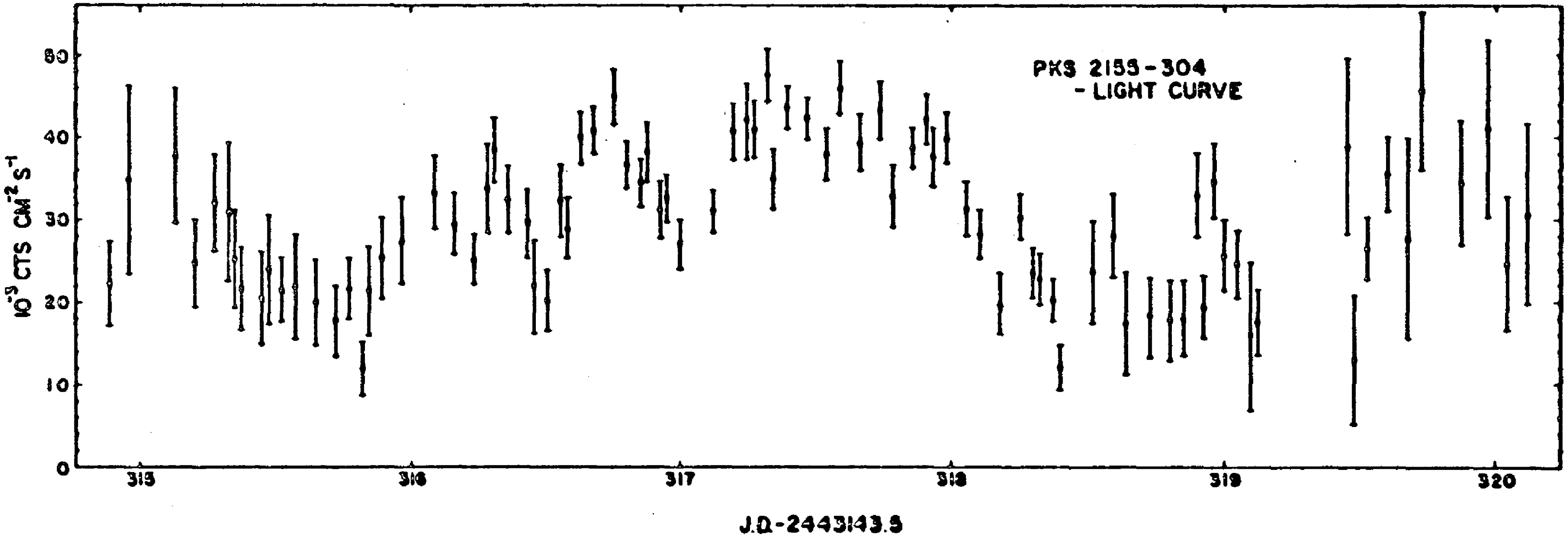

PKS 2155-304
- LIGHT CURVE
10^{-3} CTS CM^{-2} S^{-1}
0
10
20
30
40
50
315
316
317
318
319
320
J.D.-2443143.5

Figure 3

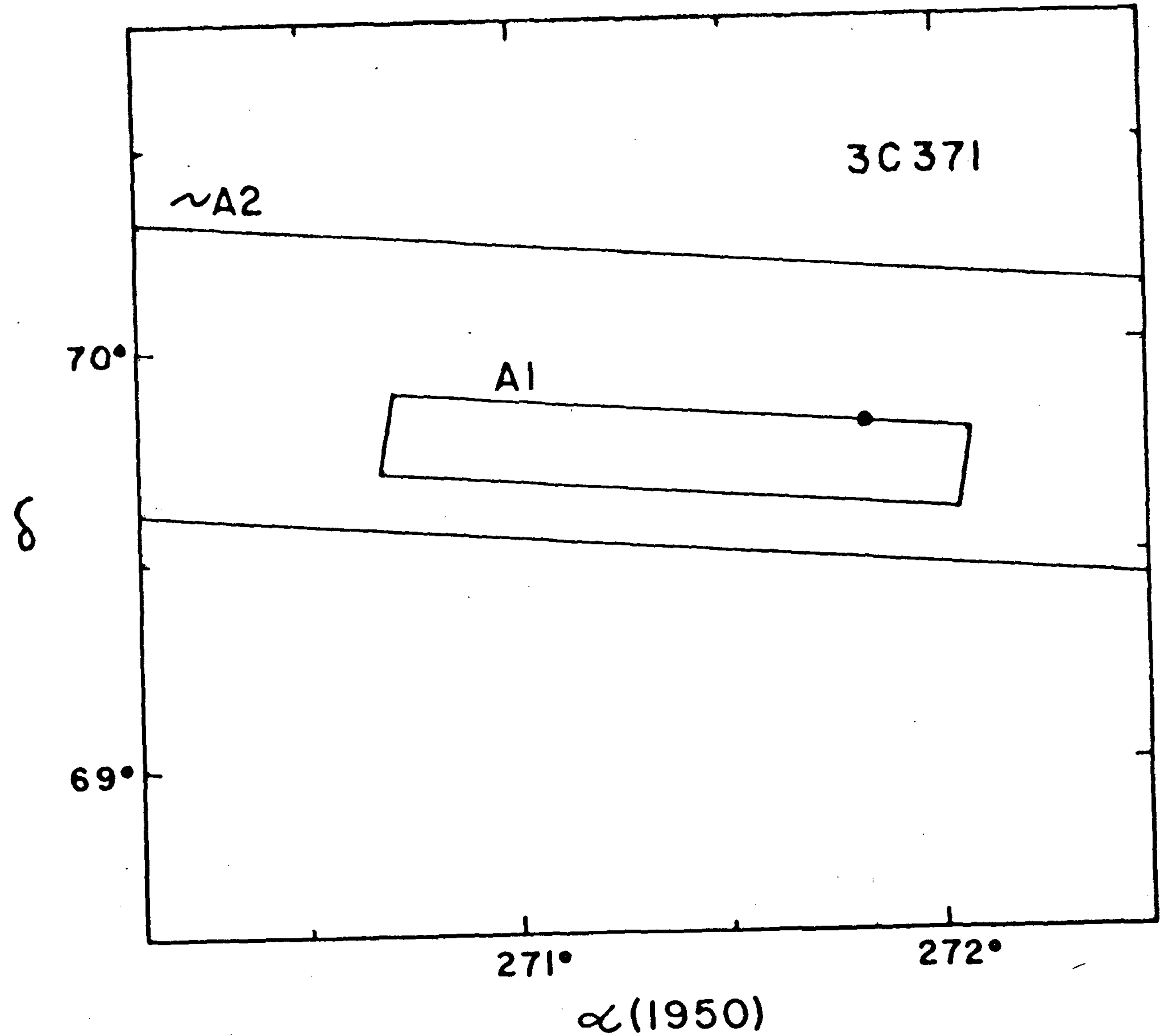


Figure 4

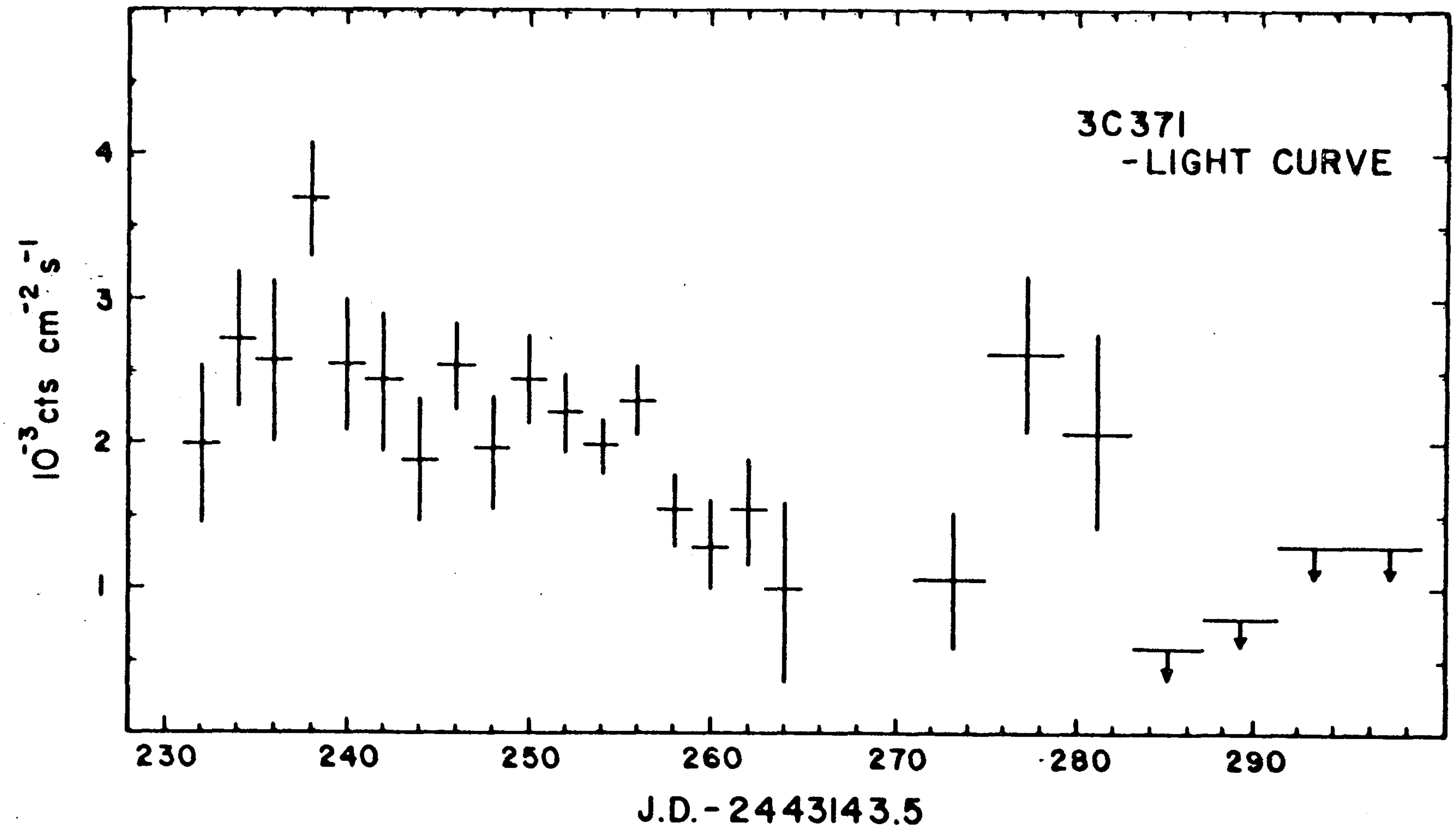
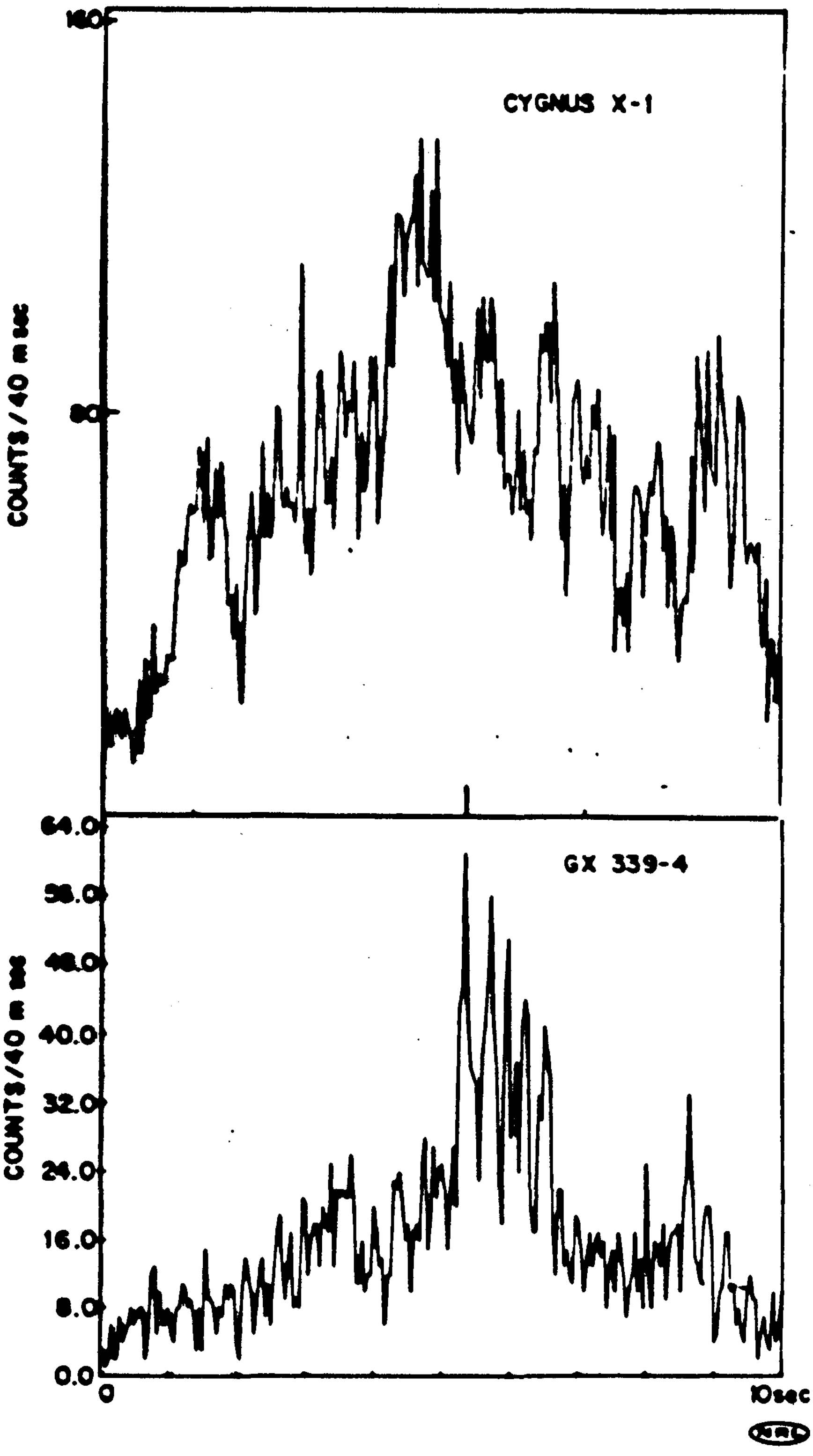

3C371
-LIGHT CURVE
10^{-3} cts cm^{-2} s^{-1}
1
2
3
4
230
240
250
260
270
280
290
J.D.-2443143.5

Figure 5



CYGNUS X-1
COUNTS / 40 m sec
160
80
GX 339-4
COUNTS/40 m sec
64.0
56.0
48.0
40.0
32.0
24.0
16.0
8.0
0.0
0
10sec

Figure 6

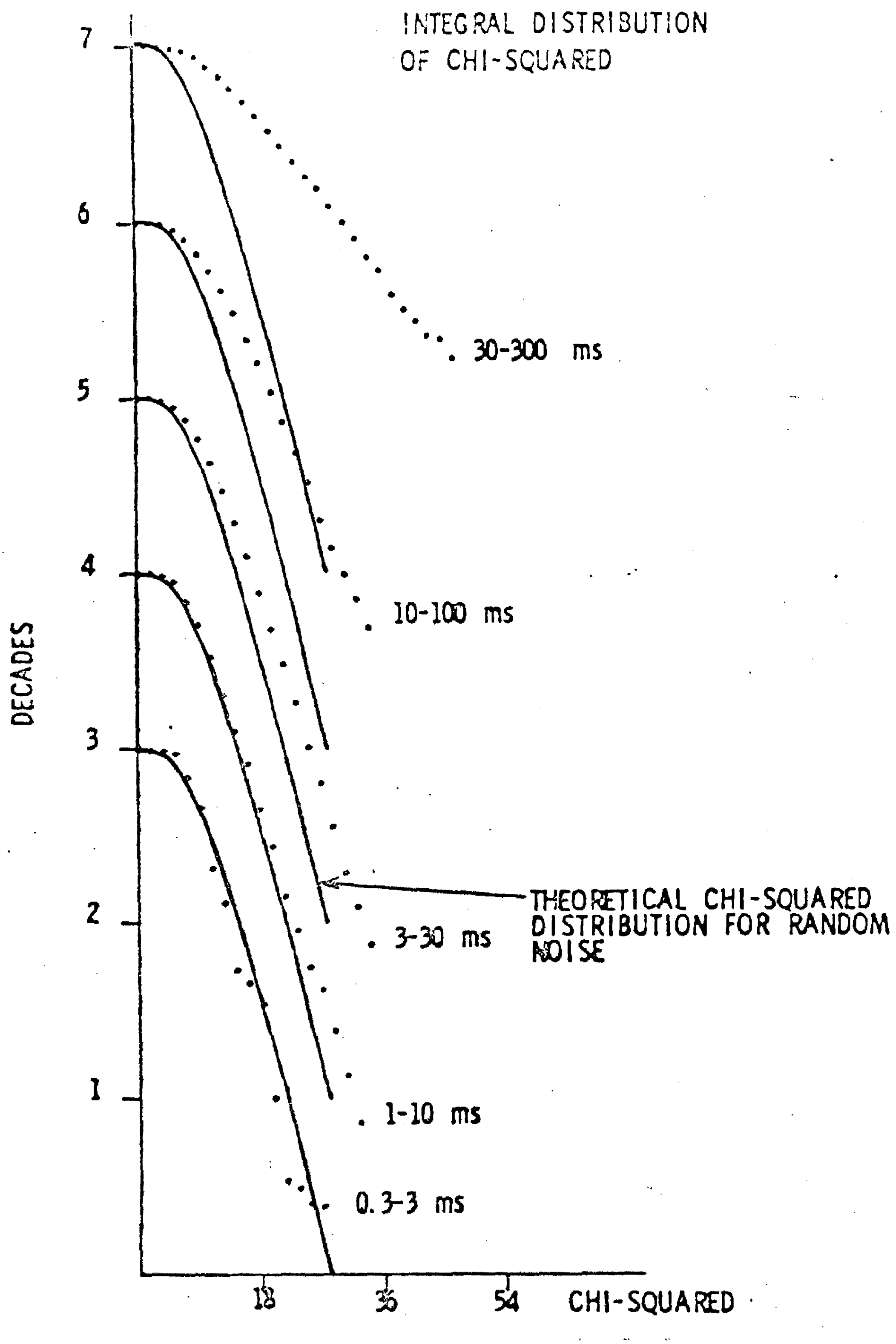

INTEGRAL DISTRIBUTION
OF CHI-SQUARED
7
6
5
4
3
2
1
DECADES
30-300 ms
10-100 ms
3-30 ms
1-10 ms
0.3-3 ms
THEORETICAL CHI-SQUARED
DISTRIBUTION FOR RANDOM
NOISE
18
36
54
CHI-SQUARED

Figure 7

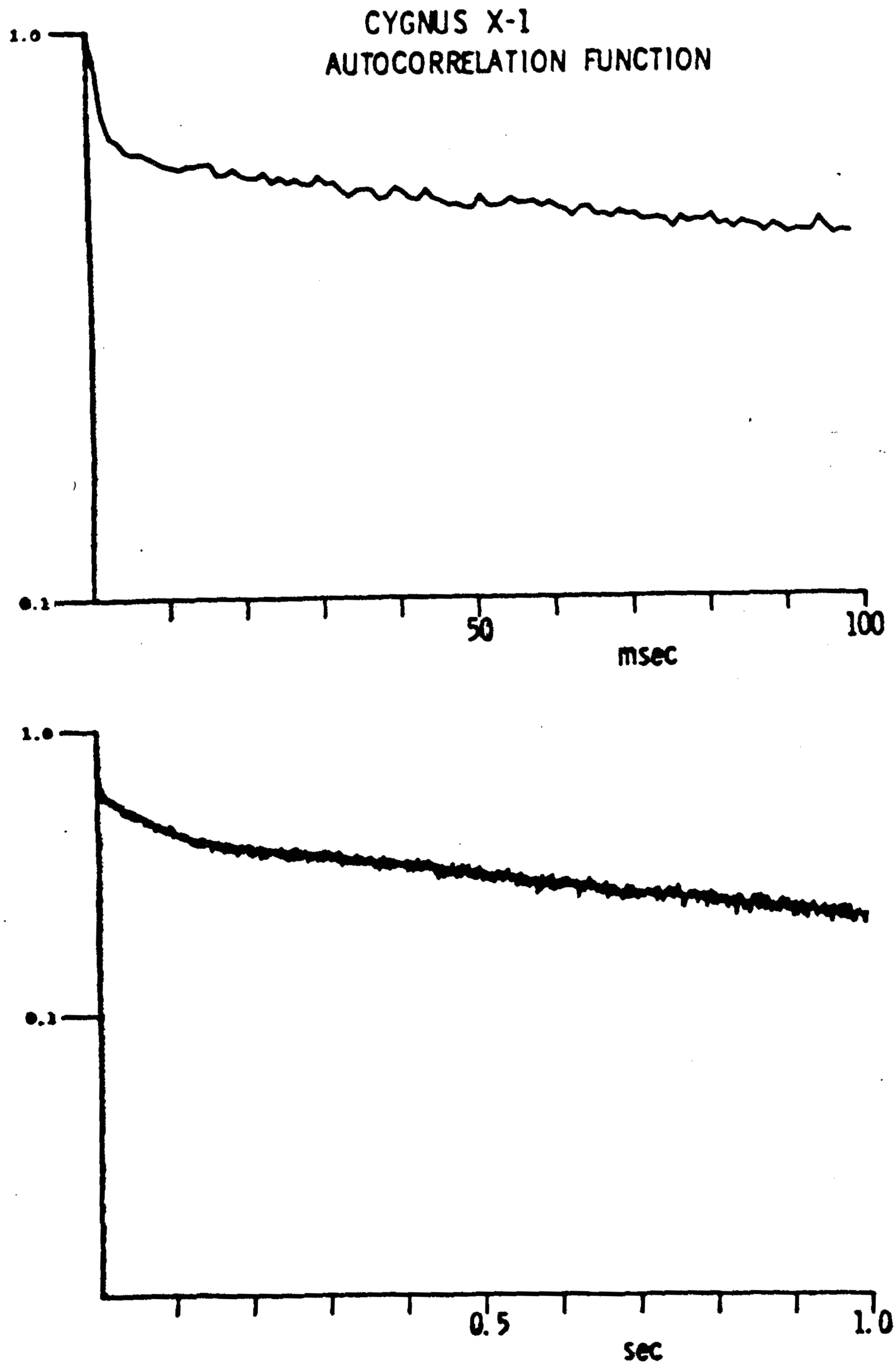

CYGNUS X-1
AUTOCORRELATION FUNCTION
1.0
0.1
50
100
msec
1.0
0.1
0.5
1.0
sec

Figure 8

CYGNUS X-1 RAPID FLUCTUATIONS

- STATISTICALLY SIGNIFICANT EXCESS OF EVENTS ON TIMESCALES 1 - 10 msec

- FREQUENT SMALL-AMPLITUDE EVENTS RATHER THAN A SMALL NUMBER OF LARGE EVENTS

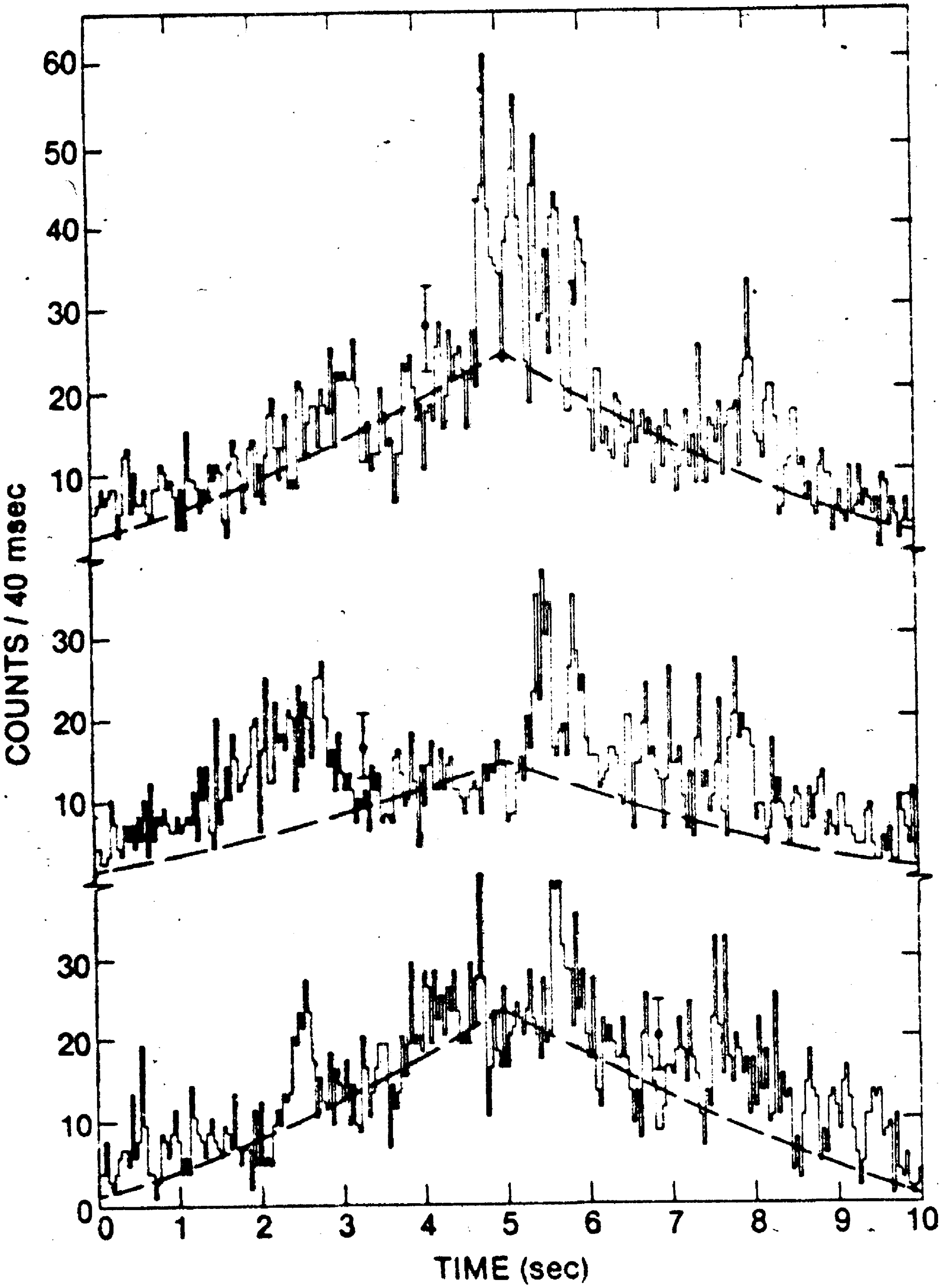
- AUTOCORRELATION FUNCTION GIVES MINIMUM CHARACTERISTIC TIMESCALE: 3-4 ms

RATE OF OCCURRENCE: $\geq$ 10 EVENTS: /s

	EVENT	TIME-AVERAGE
FLUX	1 ct/cm^2 s	3×10^{-2} ct/cm^2 s
LUMINOSITY	10^{37} ergs/s	3×10^{35} ergs/s
COUNT RATE	1500 cts/s	50 cts/s

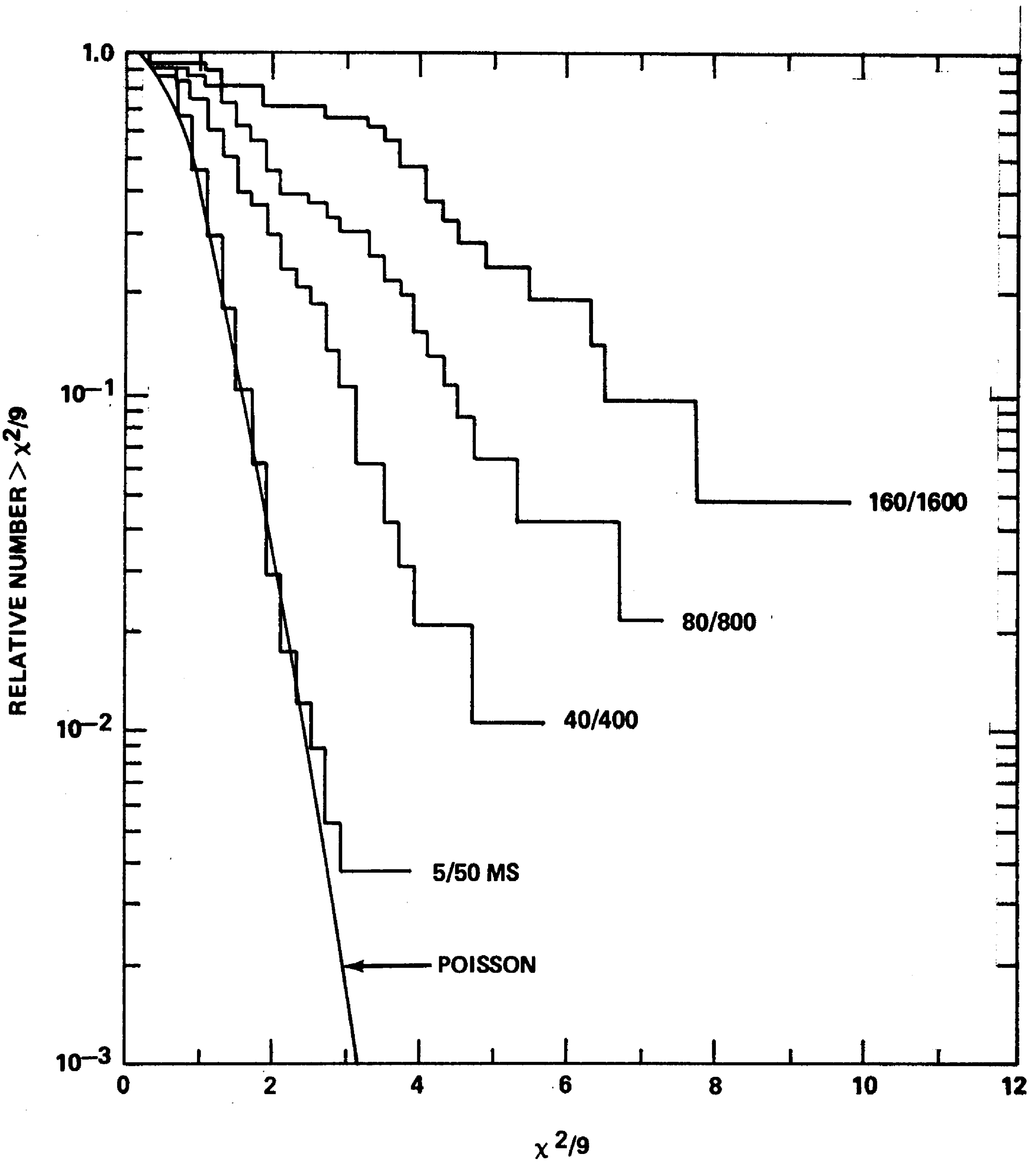
(TOTAL SOURCE COUNT RATE IS 1000 cts/s)

Figure 9



60
50
40
30
20
10
30
20
10
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
COUNTS / 40 msec
TIME (sec)

Figure 10



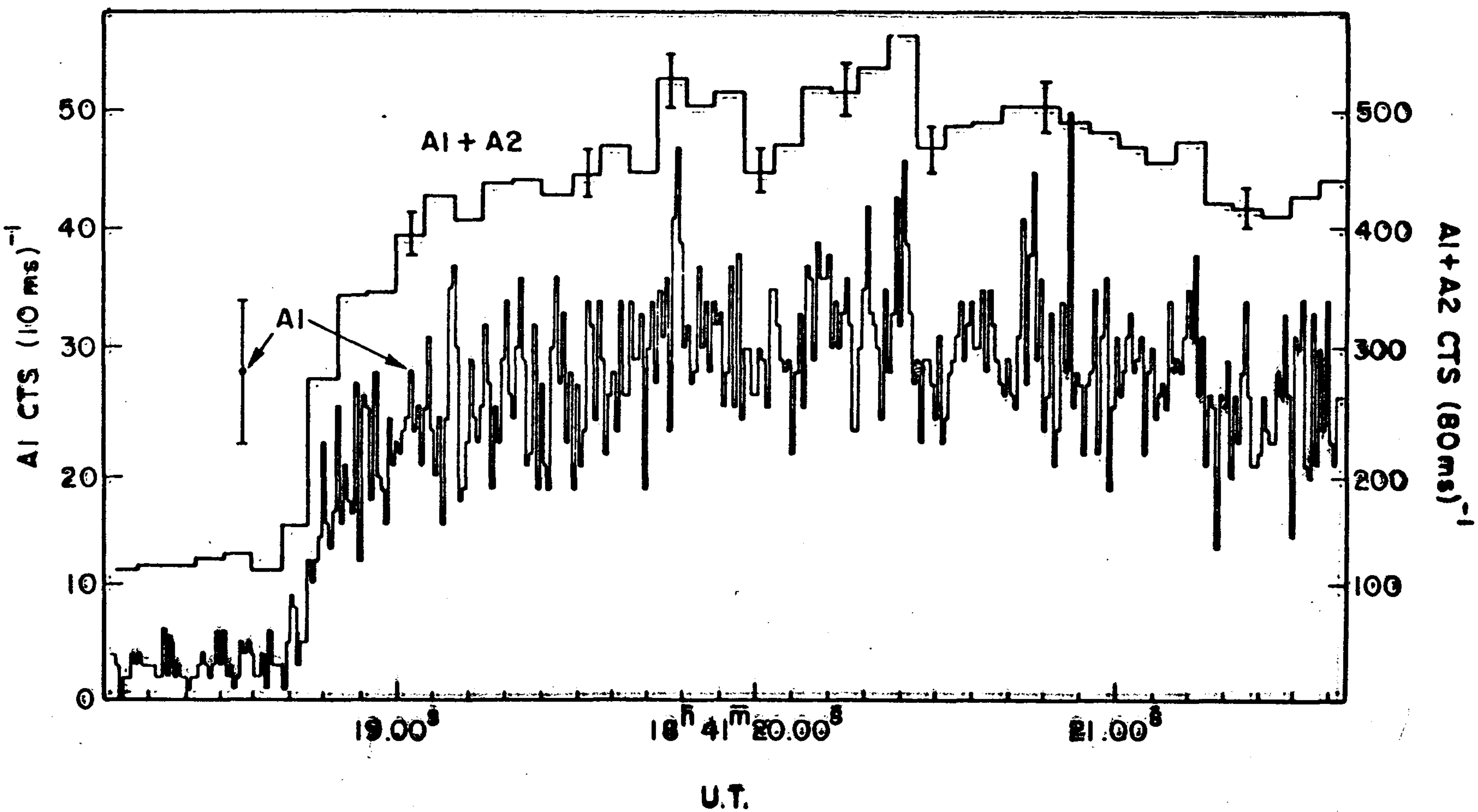
1.0
10^{-1}
10^{-2}
10^{-3}
RELATIVE NUMBER > $\chi^2/9$
160/1600
80/800
40/400
5/50 MS
POISSON
0
2
4
6
8
10
12
$\chi^2/9$

Figure 11

CHARACTERISTICS OF BLACK HOLE CANDIDATES

		CYG X-1	CIR X-1	GX 339-4
1.	VARIABILITY			
	ORBITAL PERIOD	5.60 d	16.6 d	—
	BIMODAL X-RAY SPECTRUM	YES	YES	YES
	EXTENDED "OFF" STATES	NO	YES	YES
	CORRELATION TIME	0.5 s	VARIABLE	0.3 - 0.6 s
	SHORTEST TIME SCALE	$\gtrsim$1 ms	$\gtrsim$1 ms	$\gtrsim$10 ms
2.	OPTICAL COMPANION/ EMISSION LINES	HD 226868 09.7 lab	FAINT HIGHLY REDDENED $m_R = 16$	$m_V = 16.6$
		$M_V = 8.9$	STRONG He AND H_EI	
3.	MASS FUNCTION	0.22 $M_\odot$	—	—
	M_x	$\gtrsim$ 10 $M_\odot$	—	—
4.	DISTANCE	~2.5 kpc	$\gtrsim$8 kpc[14]	$\gtrsim$4 kpc
5.	MAXIMUM LUMINOSITY ergs/s	$\sim 2 \times 10^{37}$	$\gtrsim 10^{38}$	$\gtrsim 2 \times 10^{37}$
6.	OTHER EMISSION	RADIO, IR	RADIO	—

Figure 12



A1 + A2
A1
A1 CTS (10 ms)$^{-1}$
A1+A2 CTS (80ms)$^{-1}$
50
40
30
20
10
0
500
400
300
200
100
19.00^s
18^h 41^m 20.00^s
21.00^s
U.T.

Figure 13

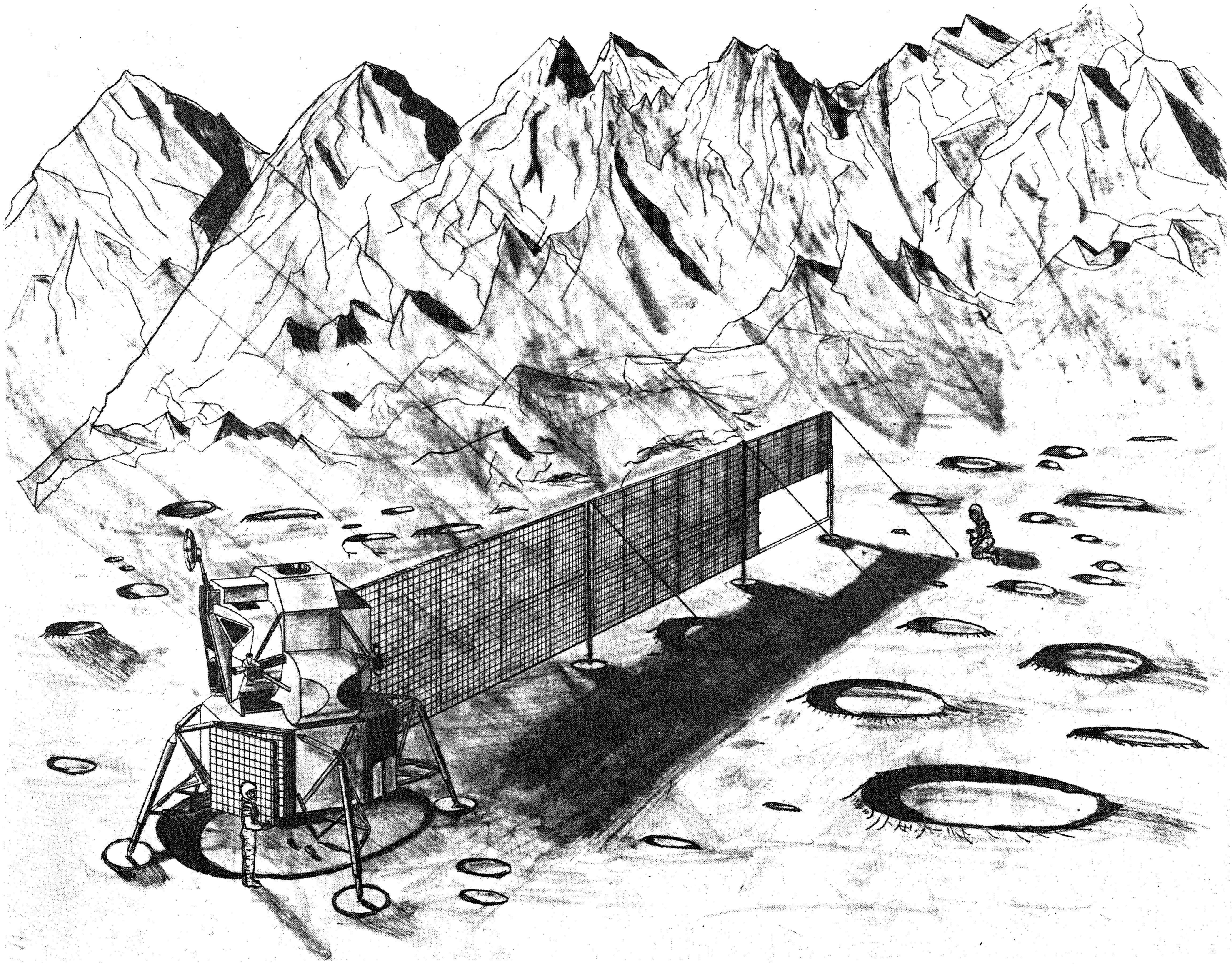


Figure 14

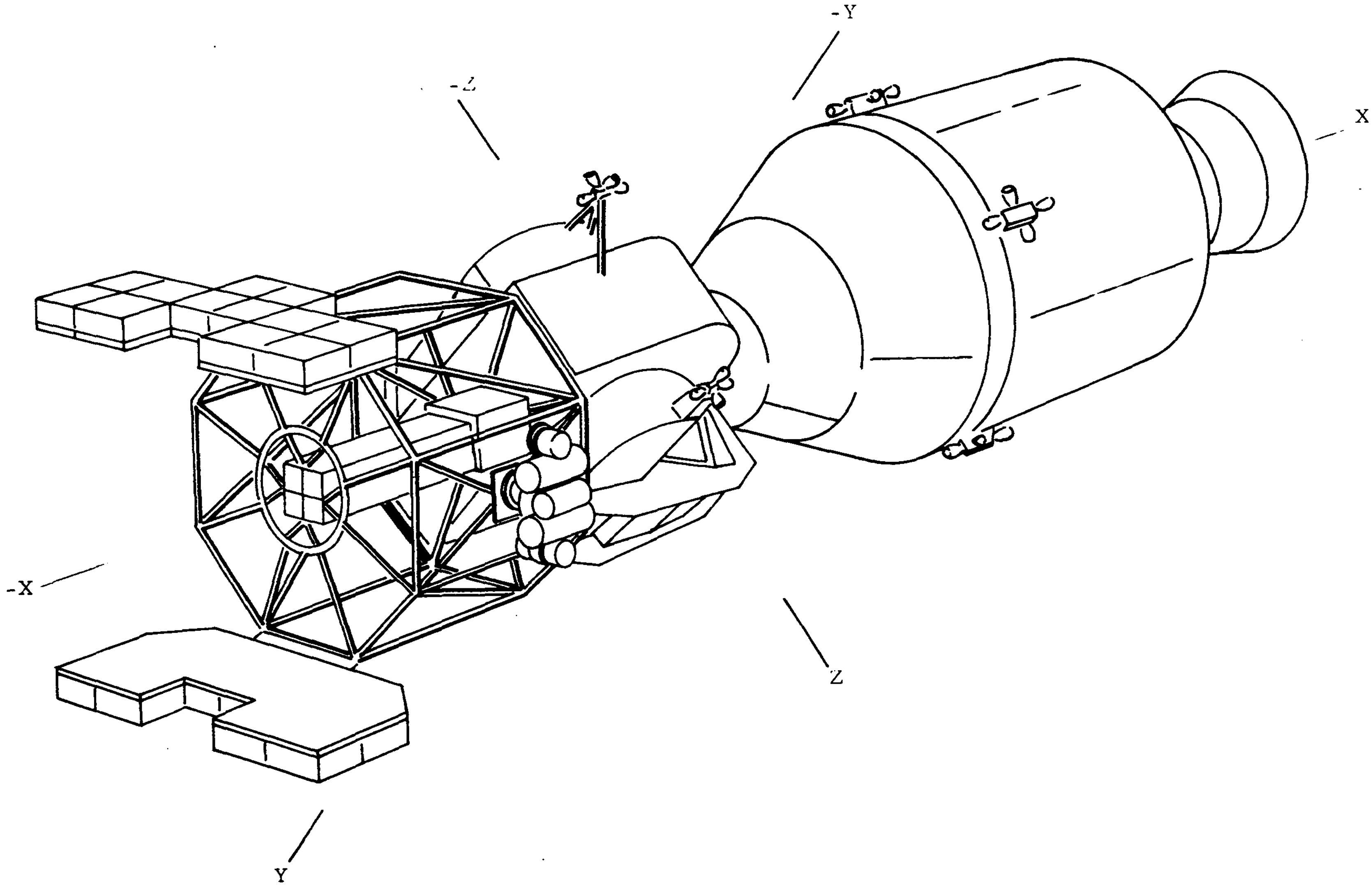


Figure 15

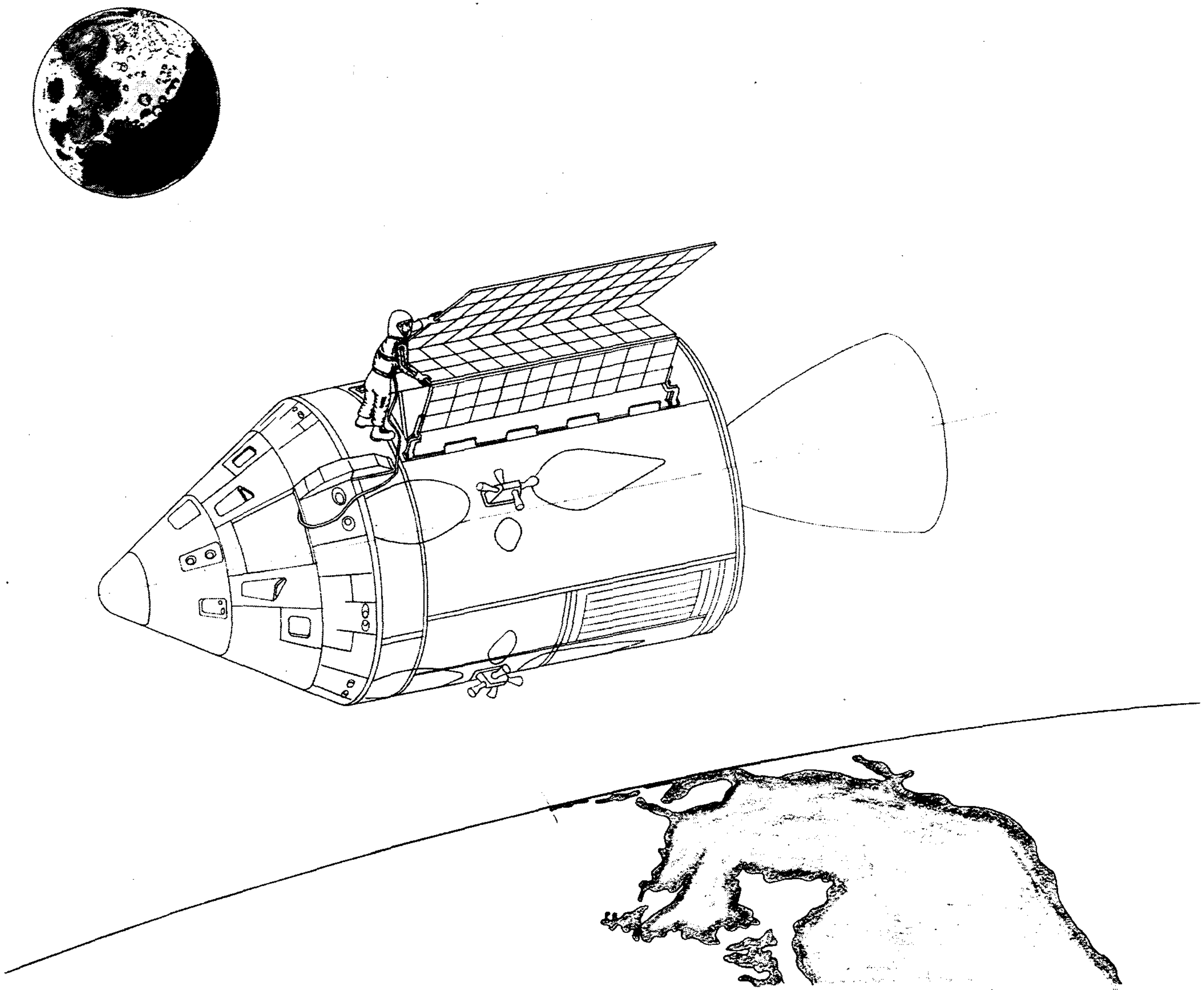


Figure 16