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HIGH RESOLUTION OBSERVATIONS OF CASSIOPEIA A AT METER WAVELENGTHS

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Abstract: Very long baseline interferometric (VLBI) observations of the supernova remnant Cassiopeia A, at 74 MHz with a 12,000-wavelength baseline and at 111 MHz with a 18,500-wavelength baseline, are reported. The fringe amplitudes are strongly varying on a time scale of about 15 to 30 minutes, which we feel can be explained by much the same complex structure as that observed at higher frequencies, plus one other compact source. Due to the poor (u,v)-plane coverage, we cannot isolate the location of the extra source unambiguously, but we can suggest possibilities. The source must lie outside the supernova remnant shell, possibly associated with a concentration of emission north of the shell, or lying outside the gap in

the northeastern side of the shell. The flux and spectral index deduced for the compact source depend on the assumed size, with a range of 100 Jy to 500 Jy at 74 MHz. If the source is associated with the supernova explosion, it must have been traveling at least 5000 km s^{-1}.

I. INTRODUCTION

The supernova remnant Cassiopeia A (Cas A) shows a very complicated brightness distribution at high radio frequencies. Various aperture synthesis maps have been made at centimeter wavelengths (Hogg et al. 1969; Rosenberg 1970a,b; Strom and Duin 1973) all showing the shell structure typical of supernova remnants, as well as a number of small "knots" of emission. It is of interest to have observations of comparable resolution at meter wavelengths for a number of reasons. First, differences in the spectra of various parts of the source might be distinguished over the wide frequency range provided. And secondly, Cas A could contain a compact source similar to the Crab Nebula pulsar (Hewish and Okoye 1964; Andrew, Branson and Wills 1964), which by virtue of its steep spectrum is detectable only at low frequencies. No pulsar searches have yet been successful in Cas A (e.g. Reifenstein, Brundage and Staelin 1969; Davies and Large 1970), but these surveys are generally not sensitive to very fast or very highly dispersed pulsars. For a supernova remnant as young as Cas A, the detection of a pulsar as a compact source rather than as a pulsating source might be more likely.

II. OBSERVATIONS

To obtain resolution comparable to the aperture synthesis maps at meter wavelengths, interferometers with 10 to 100-km baselines are necessary. Cas A had previously shown fringes on a 265-km baseline at 26.3 MHz (Cronyn *et al.* 1971; Hutton, Clark and Cronyn 1973), but only at one point in the (u,v) plane since the phased arrays used were essentially transit instruments. The source was therefore included in an extensive meter wavelength VLBI program utilizing the 300-ft. (94-m) telescope of the National Radio Astronomy Observatory in Green Bank, West Virginia and the 150-ft. (46-m) antenna of the Naval Research Laboratory at Sugar Grove, West Virginia (Clark and Erickson 1973; Vandenberg *et al.* 1973). They form a 50-km baseline, which amounts to 12,000 and 18,500 wavelengths at our observing frequencies of 74 MHz and 111 MHz, respectively. The data were taken in left circular polarization and recorded on computer tape using the Mark I VLBI system (Bare *et al.* 1967) with a bandwidth of 350 kHz. The observations were made between 1972 December 4 and 10, and between 1973 February 23 and March 1.

Although the 300-ft. telescope is normally a transit instrument, at these frequencies the use of the "traveling feed" allows a certain amount of hour angle range. Cas A, at declination +58°, can be tracked for nearly two and one half hours, so a number of points in the (u,v) plane were sampled. The Sugar Grove telescope is fully steerable and does not limit the mutual visibility. The resultant (u,v)-plane coverage is shown in Figure 1.

The data tapes were correlated using the standard GSFC-MIT VLBI reduction programs(Hinteregger 1973; Whitney 1974) on the IBM 360/91 and 360/75 computers at Goddard Space Flight Center. Fringe amplitudes were coherently averaged over three minutes, and expressed as a fraction of the geometric mean of the total system temperatures at the two stations. Since the antenna temperature due to the source alone accounted for over 75% of the total system temperature, the observed correlation coefficients were to first order true visibilities. Additional corrections were made on the basis of the total power data from both stations, but calibration errors were of little consequence due to the strength of the source. The resulting visibility curves at the two frequencies are presented in Figure 2.

III. ANALYSIS

The first step in the data analysis was to make as direct a comparison as possible with the existing higher frequency data. To accomplish this we used the map made at 2695 MHz with the NRAO interferometer (Hogg et al. 1969). "Observing" this map by computer on our baselines produced visibility curves of the shapes shown by the dotted curves in Figure 2. The reliability of this procedure was checked by also "observing" the map on the 2700-m baseline of the NRAO interferometer and comparing the results with the raw NRAO data. The normalization provided by this comparison revealed that the map accounts for about 40% of the total flux of Cas A at 2695 MHz, with the remaining flux being distributed in a broad plateau slightly greater than the shell source in size. (This plateau is not observable with the NRAO interferometer due to the lack of spacings less than 100 m, but is clearly seen on other maps, e.g. Rosenberg (1970a)). If the map is strictly extrapolated to the lower frequencies, assuming that it accounts for the same percentage of the total flux, then the normalization is that of the dotted curves in Figure 2. We see that, although the normalization appears to be reasonable, the correspondence between the models and the data is not good at either frequency.

Since the 74-MHz data appears to present a more clear cut case of disagreement than the 111-MHz data, and is no doubt simpler due to the lower angular resolution, let us initially concentrate on the lower frequency. There is clearly "something extra" in the form of a quasi-sinusoidal variation of about 30-minute period in the data which does not appear in the model curves. Since a sinusoidal visibility function is what one expects from a pair of point sources, we see that we may have detected at least one such pair which is not present at higher frequencies. Because of the (u,v)-plane coverage, the north-south separation for the fastest variation is fairly well determined (about 4'), but the east-west separation is virtually unknown. The small knots of emission on the high frequency maps are immediately suspect; if one of these were enhanced at the lower frequencies, the beat pattern from it and the other knots could qualitatively produce the observed effect. The approximate north-south separation required is present between a knot on the north side of the remnant, outside the shell, and any one of the knots on the southern edge. The same effect could also be produced by an extra compact source, unrelated to those observed at high frequencies, beating with the knots in the shell.

To make the above analysis more quantitative, we used an iterative least squares routine (Bevington 1969) to fit the fluxes and relative positions of the NRAO map and one other point source (a total of four parameters). The program was provided with initial positions for the point source relative to the phase center of the NRAO map spaced 15" apart throughout the area within the dotted line in Figure 3. Convergent solutions which considerably improve the fit were found for point sources in the areas marked A,B and C, several solutions occurring in each. As would be expected, the individual solutions always occur in a series, spaced about one fringe apart in the east-west direction.

These regions were then grid searched by the same procedure at 111 MHz, yielding acceptable solutions in all three. The solutions are again arranged in a series, spaced about one fringe apart. None of the 111-MHz solutions correspond exactly in position to any of the 74-MHz ones, nor are the resulting fits exact at either frequency. However, such problems can probably be attributed to changes in the structure of the shell source with frequency. Figure 4 shows visibility curves typical of each of the three areas, along with the curves from the NRAO map alone for comparison. The solutions chosen are the ones with the closest coincidence in position between the two frequencies. Table 1 summarizes the parameters for each curve shown. The spectrum of the point source is very steep ($\alpha \approx -2.5$ where $S(\nu) \propto \nu^{-\alpha}$) in all three cases, perhaps explaining why it does not appear in higher frequency maps. The spectral index of the fraction of the total flux contained in the map (referred to as "map flux" in Table 1), between our frequencies and 2695 MHz, is generally consistent with the known spectral index of Cas A ($\alpha = -0.75$), even though the agreement between the 74-MHz and 111-MHz fluxes is poor in some cases.

All the above analysis assumes that the added source is a point source. On such a limited range of resolution we have virtually no information about the size of the extra source; larger sources simply require more flux. However, due to the difference in resolution, they require relatively more flux at 111 MHz than at 74 MHz and the spectral index changes. Least squares solutions similar to the ones just described, but using Gaussian sources of various fixed sizes, were performed for region C. The analysis showed that Gaussian sources with half power diameters greater than about 6'' have spectra flatter than the total flux of Cas A and therefore should have appeared on high frequency maps, provided that they have power law spectra. Such sources fit at about 500 Jy at 74 MHz, so we may tentatively consider this figure to be an upper limit. Table 2 summarizes the fluxes for sources of various assumed sizes. In any event, the compact source contains less than 10% of the total flux.

IV. SUMMARY

To summarize, we have succeeded in fitting visibility curves at 74 MHz and 111 MHz with a 2695-MHz map extrapolated directly to these frequencies, plus one other compact source. The compact source may be anywhere from 100 Jy to 500 Jy at 74 MHz depending on its size and its spectrum. The fact that we have had any success at all suggests that the SNR shell itself changes remarkably little with frequency, the changes being concentrated in one compact source.

From our data alone, the position of the compact source is ambiguous; we can at best suggest a few possible locations. The nature of the source is therefore only hinted at. The existence of solutions near the northernmost knot (region C) suggest that it may be responsible. No fits at either frequency are centered on the knot as it appears in the map, but again changes in the complicated structure of the shell with frequency may account for such problems. The consistency of the map fluxes for the region C solutions, as well as the more nearly coincident positions at the two frequencies, certainly speaks in favor of such an explanation. On the other hand, region B and perhaps even region A lie generally outside the gap in the shell. There are known optical filaments outside this gap (van den Bergh and Dodd 1970; van den Bergh 1971), although not as far as either of these regions, and as long ago as 1959 Jennison (1959) reported the existence of "something extra" on the eastern side of Cas A at meter wavelengths.

It is significant that no improvements to the fit were obtained by adding a point source inside the supernova shell (no pair can then produce the required 4' north-south spacing). Since the shell itself appears to be expanding at 5000 km s^{-1} (van den Bergh 1971), any object that originated in the supernova explosion and now lies outside the shell must have been expelled at a velocity greater than this. Although the point source spectrum is suggestive of a Crab-like pulsar, the velocities implied are certainly far greater than any "runaway" velocity yet reported.

Of course, the compact source may be a background source, not associated with the supernova at all. In that case, it might well have been one of the prominent sources in the 3C Catalogue, had it not had the misfortune of being too close to Cas A.

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Table 1: Parameters for Point Source Solutions

Region	Freq (MHz)	Position W (arc sec)	Position N (arc sec)	Map Flux (Jy)	Point Flux (Jy)	Map Spectral Index	Point Spectral Index
A	74	-431	76	14300	122		
	111	-430	57	3100	44	0.8	2.5
B	74	-200	69	13300	91		
	111	-197	85	2600	45	0.8	1.7
C	74	-19	99	6600	110		
	111	-21	93	6200	32	0.7	3.0

Table 2: Parameters For Gaussian Source Solutions

Point Size (")	74 MHz Flux (Jy)	111 MHz Flux (Jy)	Point Spectral Index
0.0	110	32	3.0
4.7	140	56	2.2
9.4	330	410	-0.54
14.1	1400	11000	-5.0

Figure Captions:

Figure 1. (u,v)-plane coverage for the meter wavelength observations. u and v are given in wavelengths and times are marked on the tracks in Greenwich Sidereal Time. Note that the longest baseline on the NRAO interferometer at 2695 MHz is 24,300 wavelengths.

Figure 2. Visibility curves observed on the meter wavelength experiment. The error bar is a 3-σ error bar estimated from the noise in fringe amplitude. The dotted curve is the visibility curve predicted from the 2695-MHz map alone.

Figure 3. Map of the Cas A region showing possible locations of the extra point source. The dotted line represents the area searched for solutions at 74 MHz. Distances are in seconds of arc.

Figure 4. Visibility curves obtained by the addition of the extra point source at the locations marked in Figure 3. The curves for the NRAO map alone are also shown for comparison.

References:

Androw, B., Branson, H., Wills, D. (1964), Nature 203, 171.

Bare, C., Clark, B.G., Kellermann, K.I., Cohen, M.H., Jauncey, D.L. (1967) Science 157, 189.

Bergh, S. van den, Dodd, W.W. (1970) Ap. J. 162, 485.

Bergh, S. van den (1971) Ap. J. 165, 457.

Bevington, P.R. (1969) Data Reduction and Error Analysis for the Physical Sciences (McGraw-Hill, New York), p. 238.

Clark, T.A., Erickson, W.C. (1973) Proc. I.E.E.E. 61, 1230.

Cronyn, W.M., Klemperer, W.K., Rufenach, C.L. Shawhan, S.D., Basart, J., Clark, T.A., Erickson, W.C. (1971) B.A.A.S. 3, 438.

Davies, J.G., Large, M.I. (1970) M.N.R.A.S. 149, 301.

Hewish, A., Okoye, S. (1964) Nature 203, 171

Hinteregger, H.F. (1973) Ph.D. Dissertation, M.I.T.

Hogg, D.E., Macdonald, G.H., Conway, R.G., Wade, C.M. (1969) A.J. 74, 1206.

Hutton, L.K., Clark, T.A., Cronyn, W.M. (1973) B.A.A.S. 5 ,35.

Jennison, R.C. (1959) I.A.U. Symposium 9 , 309.

Reifenstein, E.C., Brundage, W.D., Staelin, D.H. (1969) Ap. J. Lett. 156, L125

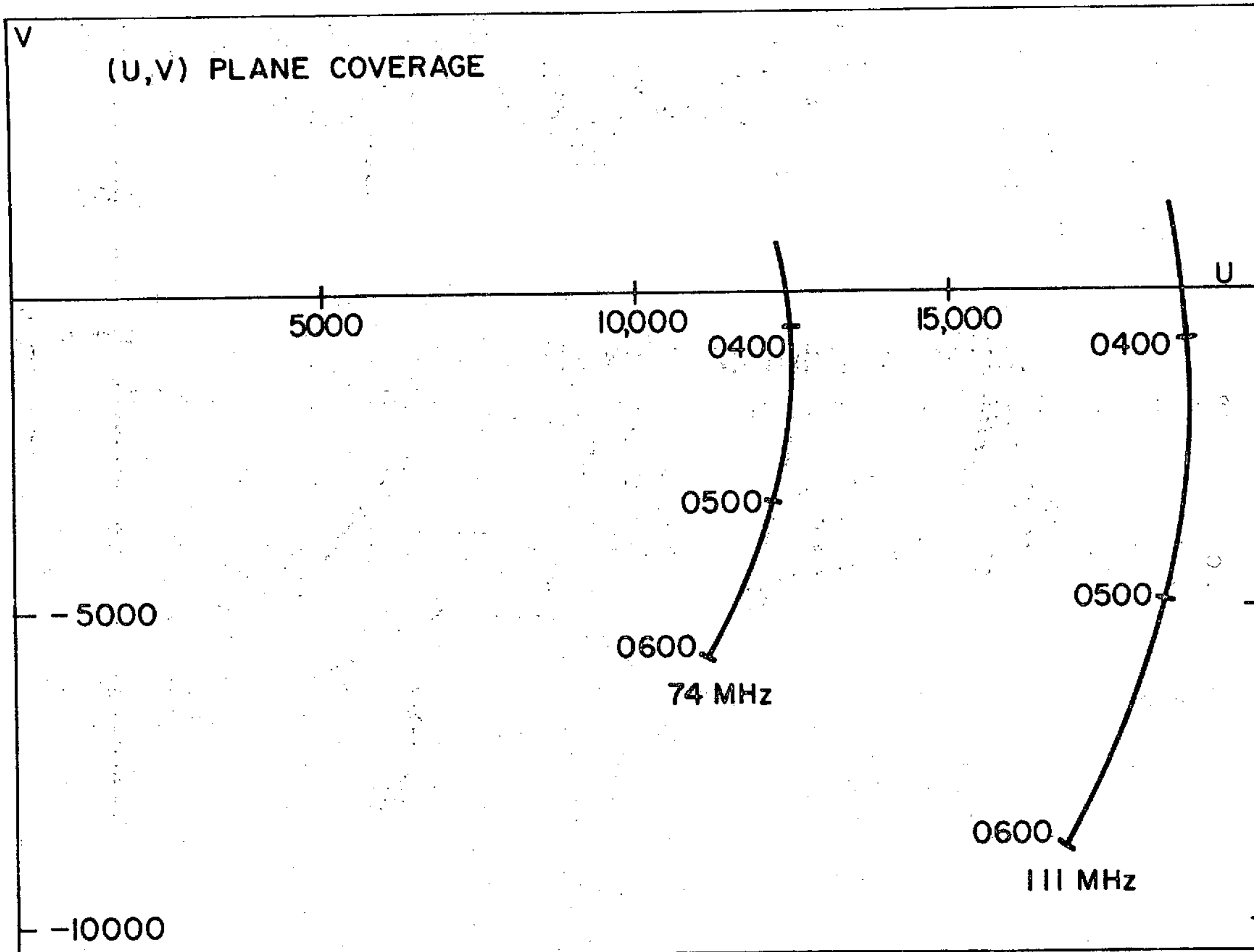
Rosenberg, I. (1970a) M.N.R.A.S. 147, 215.

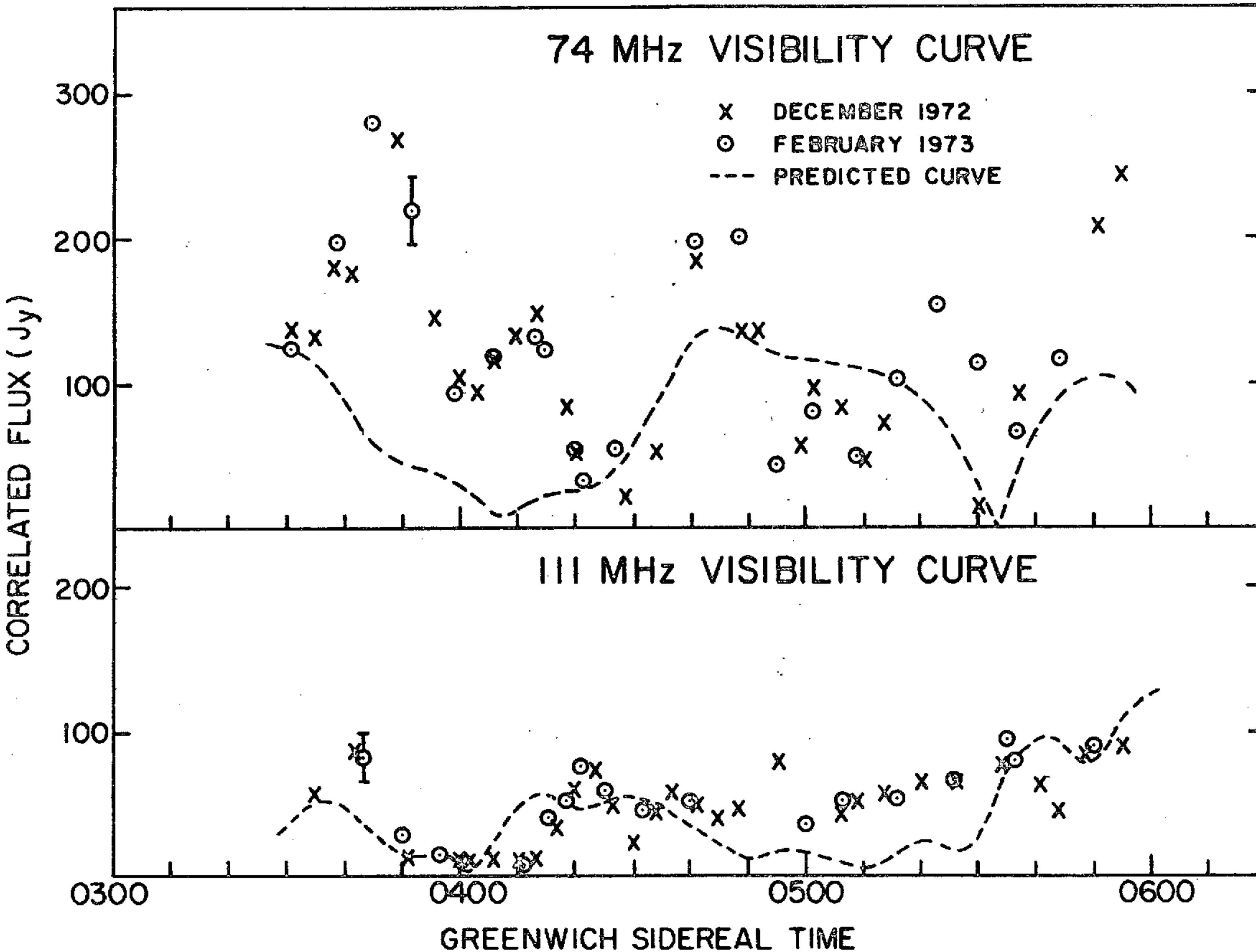
Rosenberg, I. (1970b) M.N.R.A.S. 151, 109.

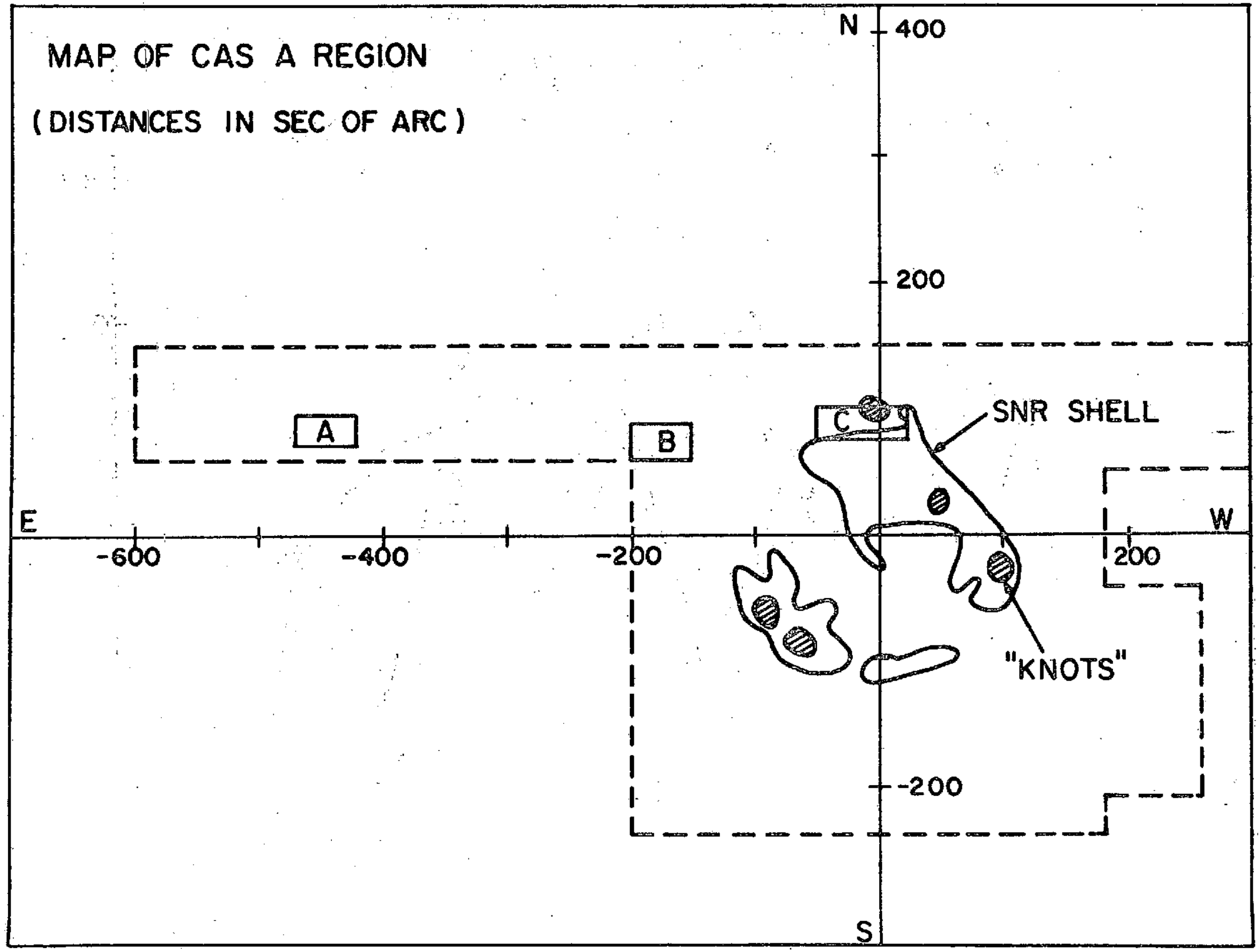
Strom, R.G., Duin, R.M. (1973) Astr. & Ap. 25, 351.

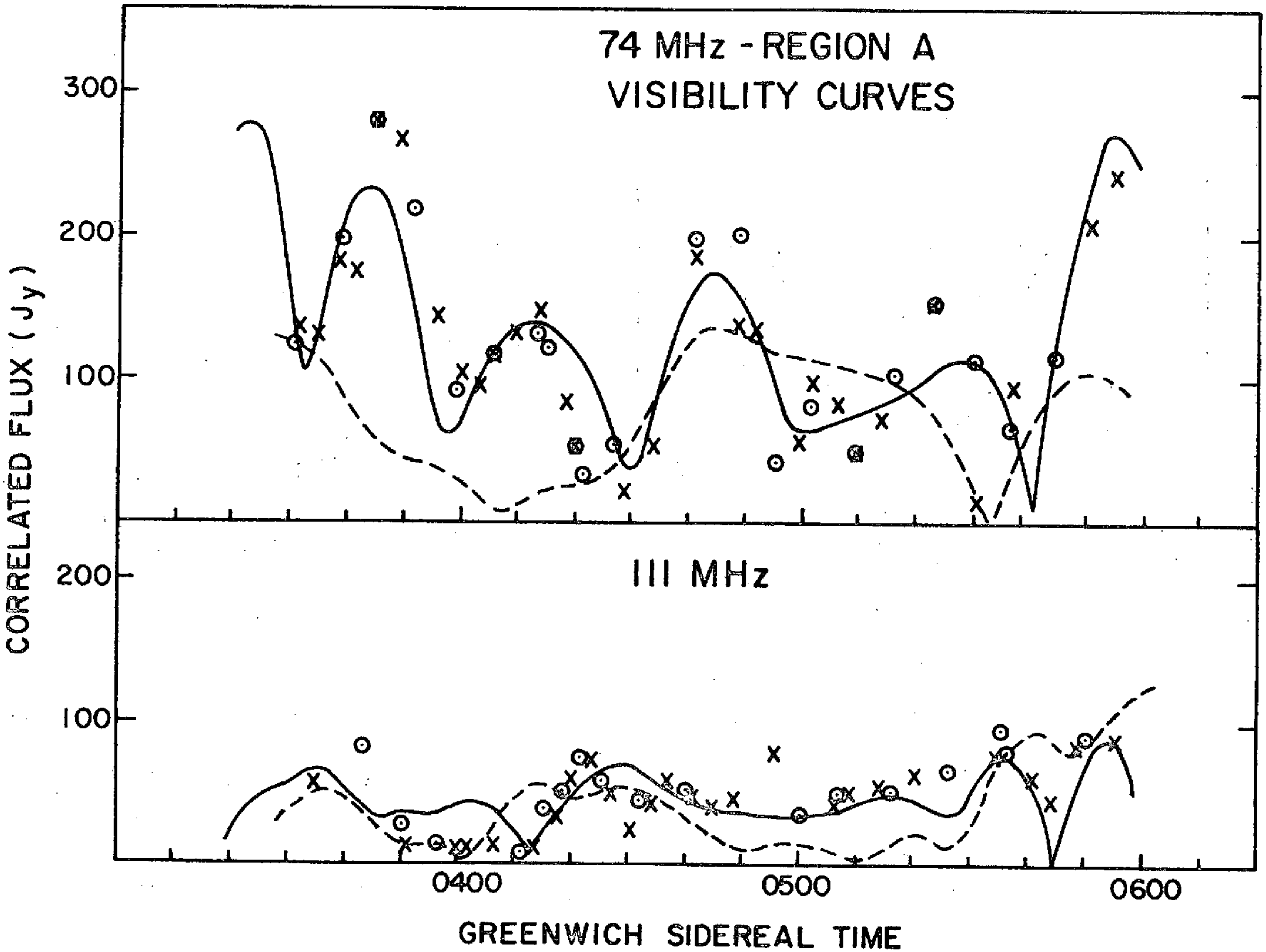
Vandenberg, N.R., Clark, T.A., Erickson, W.C., Resch, G.M., Broderick, J.J., Payne, R.R., Knowles, S.H., Youmans, A.B. (1973) Ap. J. Lett. 180, L27.

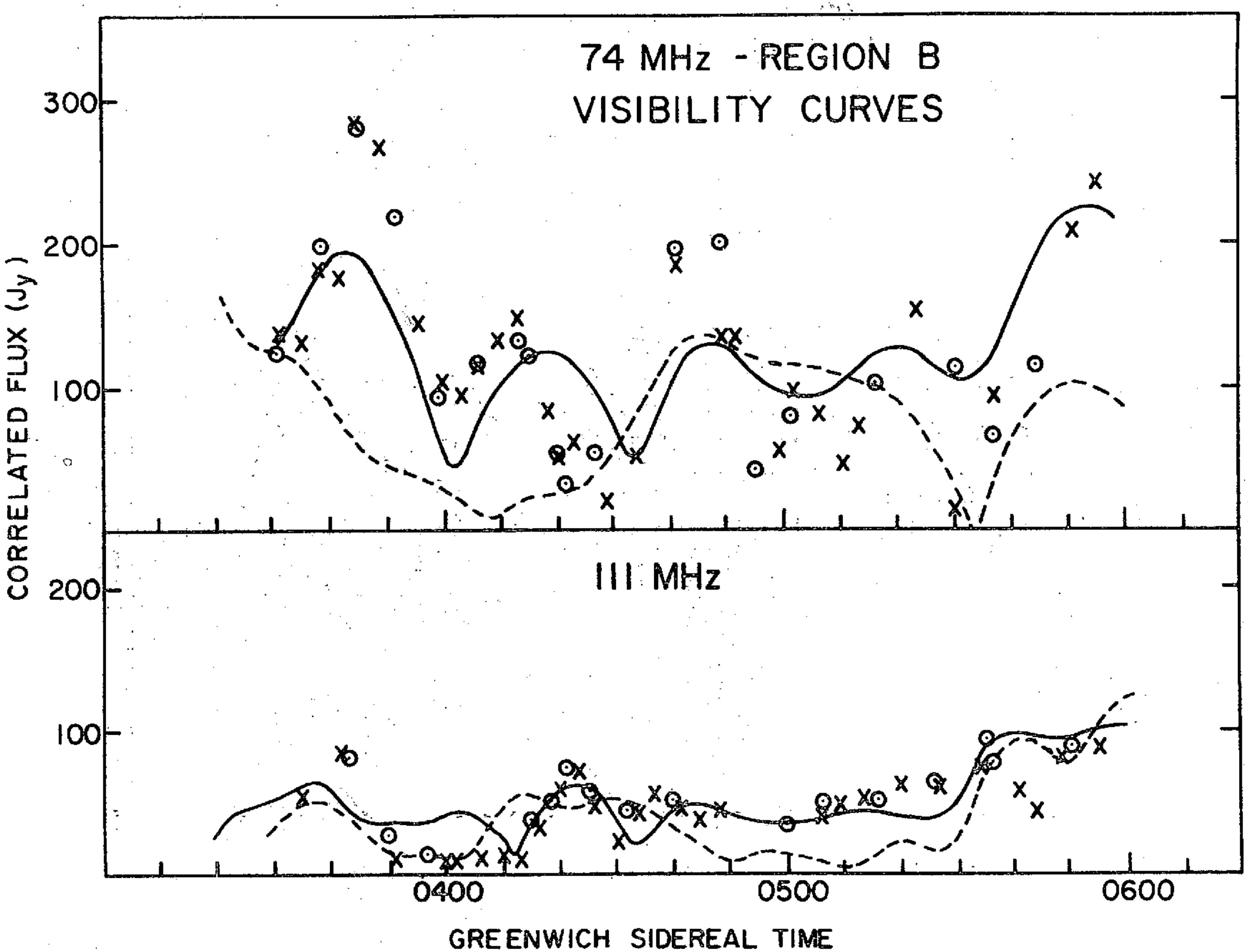
Whitney, A.R. (1974) Ph.D. Dissertation, M.I.T.

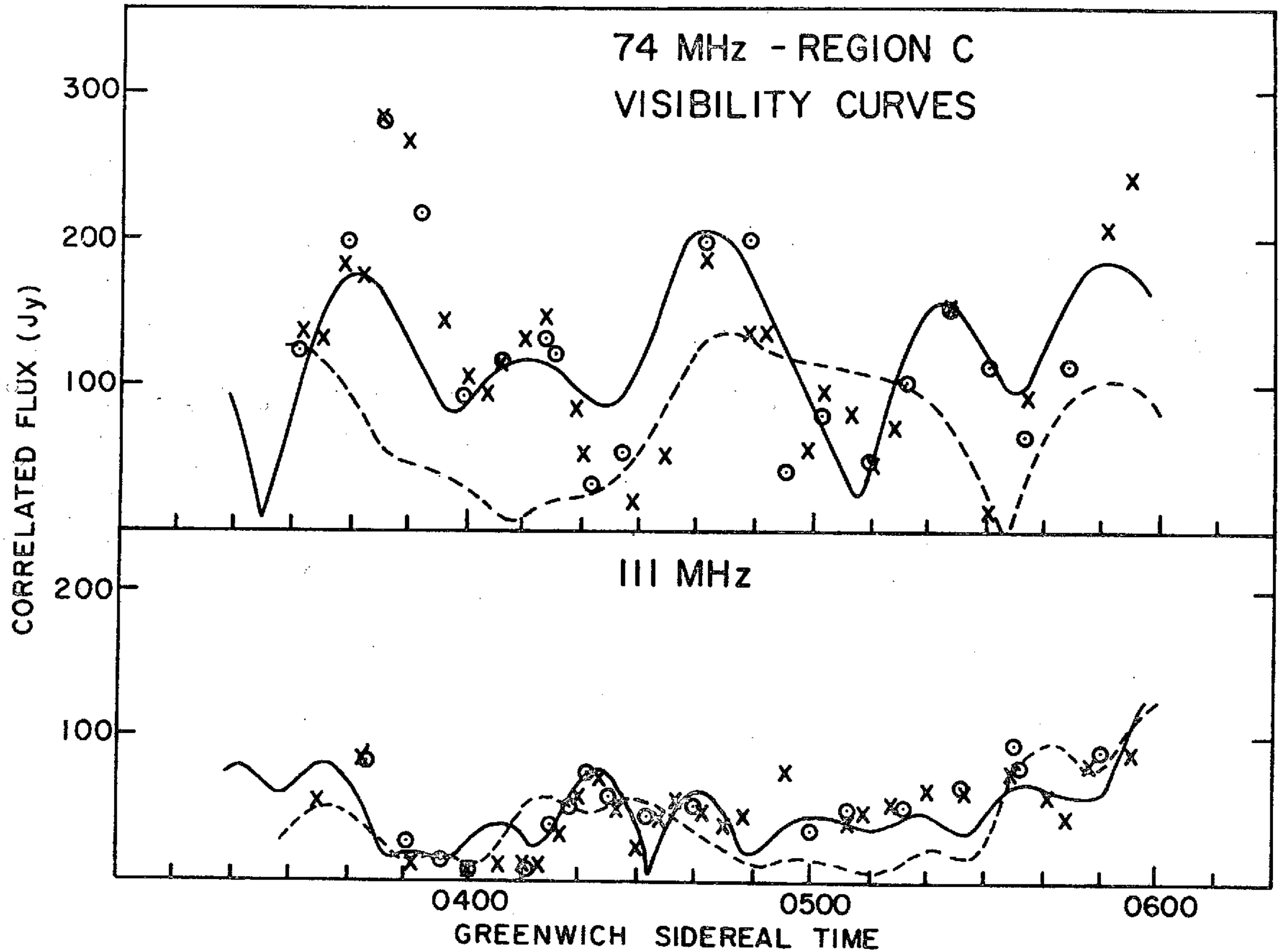

V
(U,V) PLANE COVERAGE
U
5000
10,000
15,000
0400
0500
0600
74 MHz
0400
0500
0600
111 MHz
-5000
-10000


74 MHz VISIBILITY CURVE
X DECEMBER 1972
⊙ FEBRUARY 1973
--- PREDICTED CURVE
300
200
100
III MHz VISIBILITY CURVE
200
100
CORRELATED FLUX (Jy)
0300
0400
0500
0600
GREENWICH SIDEREAL TIME


MAP OF CAS A REGION
(DISTANCES IN SEC OF ARC)
N
S
E
W
400
200
-200
-600
-400
-200
200
A
B
C
SNR SHELL
"KNOTS"


74 MHz - REGION A
VISIBILITY CURVES
111 MHz
CORRELATED FLUX (Jy)
300
200
100
200
100
0400
0500
0600
GREENWICH SIDEREAL TIME


74 MHz - REGION B
VISIBILITY CURVES
III MHz
CORRELATED FLUX (Jy)
300
200
100
200
100
0400
0500
0600
GREENWICH SIDEREAL TIME


74 MHz - REGION C
VISIBILITY CURVES
III MHz
CORRELATED FLUX (Jy)
300
200
100
200
100
0400
0500
0600
GREENWICH SIDEREAL TIME

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