Lecture for summer students
July 1972

RADIO STARS

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Since about 1890 people have been trying to detect radio emission from stars, beginning with our own Sun. However, it was not until the 1940's that Reber, Southworth, and Hey independently detected radio emission from the Sun. Only during the last decade have any other radio stars been discovered. Between the 1940's and the early 1960's, radio astronomers had the habit of calling any new radio source a radio star. However, the data eventually showed that in all cases these sources were not single gravitationally bound bodies, as are all stars, by definition.

To appreciate the problem of detecting radio stars, let us consider the simple relationship between flux density, S_ν (in flux units, $10^{-26} Wm^{-2} Hz^{-1}$) and brightness temperature, T_B (in °K) for a uniform source of solid angle Ω_s (= $\pi\theta^2/4$ where θ is an equivalent disc diameter):

$$S_\nu = \frac{T_B\ \theta^2}{1970\ \lambda^2} \tag{1}$$

In equation (1) θ is measured in arcseconds.

One of the most sensitive radio instruments presently available is the NRAO interferometer for which the minimum detectable flux density is 0.005 flux units for eight hours of observing. Therefore, for a source to be detectable

$$S_\nu \gtrsim 0.005$$

and using equation (1)

$$T_B\ \theta^2 \gtrsim 9.9\lambda^2, \tag{2}$$

or

$$\left.\begin{array}{l} T_B\ \theta^2 \gtrsim 135 \text{ at } 3.7 \text{ cm} \\ T_B\ \theta^2 \gtrsim 1210 \text{ at } 11.1 \text{ cm} \end{array}\right. \tag{3}$$

The optical sizes of the stars with the largest apparent diameters (the red supergiants) are at the most 0."05, hence for these one needs

$$T_B \gtrsim 53{,}000°K \quad \text{at} \quad 3.7 \text{ cm}$$

$$T_B \gtrsim 484{,}000°K \quad \text{at} \quad 11.1 \text{ cm}$$

Normal process on the surfaces of stars easily produce $T_B \lesssim 10^6$°K, but it is difficult to produce larger values of T_B.

Some processes with larger T_B are known on the surface of the Sun

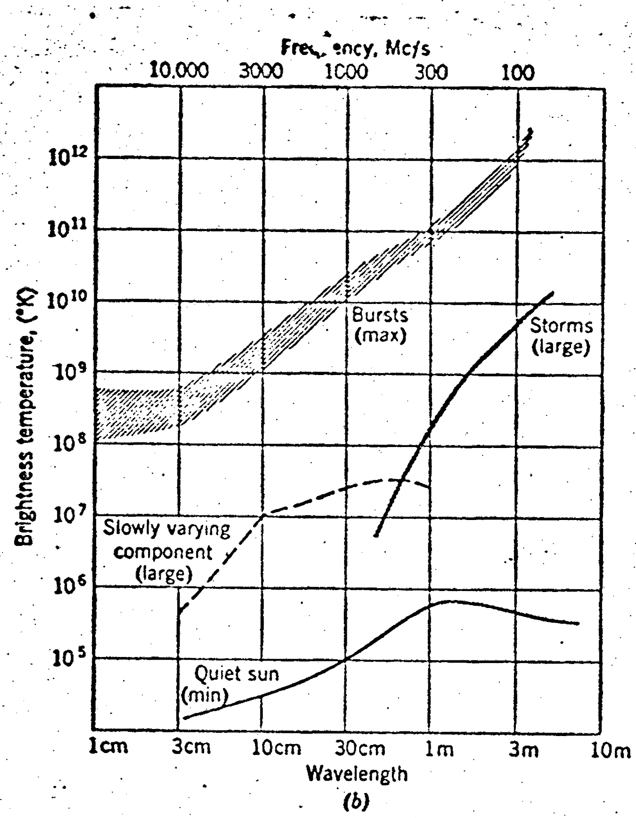


Fig. 1-1(b) The spectra of different components of solar radio emission, plotted in terms of brightness temperature. To calculate the brightness temperature, the source area is assumed to be as follows: the optical disk for the quiet sun; the sunspot area for the slowly varying component; and estimated mean areas based upon available observations for the bursts and storms (After Smerd 1964a).

The above figure shows the brightness temperatures for some of the major types of radio emission for the Sun.

Quiet Sun - chromosphere and coronal thermal emission

Slowly varying component - radio emission associated with sunspots or plages

Storms - non-thermal emission with time scales of hours to days. At sunspot maximum, in progress about 10% of the time

Radio bursts - short lived non-thermal events with time scales of a few minutes to hours.

Unfortunately, the quiet Sun at 10 cm could be seen only if closer than 0.07 pc, the slowly varying component could be seen only at less than 0.1 pc, and very strong bursts could be seen only within 2.5 pc.

The nearest star, Proxima Centauri, is only 1.3 pc away. You thus can see that only unusual processes are likely to produce a radio star. The worst problem with stars is that θ is always rather small, hence it takes a fantastic T_B to make up for this.

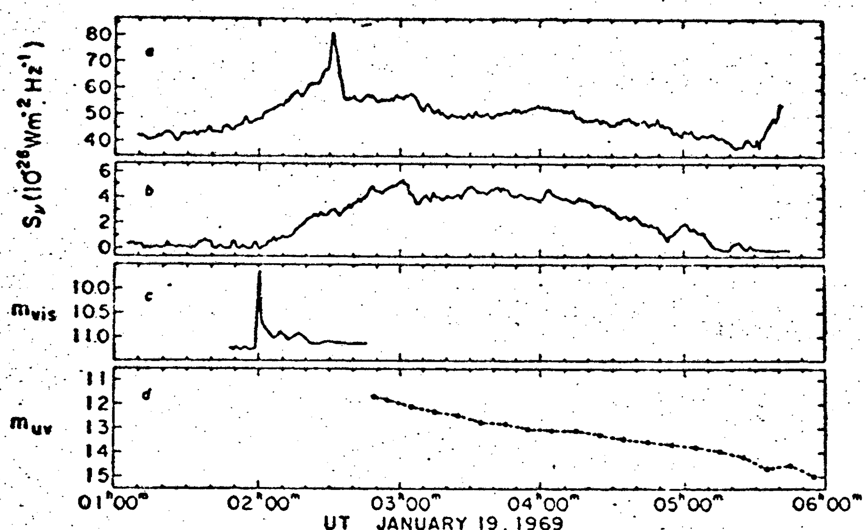
Despite all this, there are now five (or more) different types of radio stars.

FLARE STARS

Certain red dwarf stars are known to increase their brightness radically for brief periods of time (typically a few hours). These objects are called flare stars, and the flares they exhibit could be more intense versions of the well known solar flares. Since the solar flares are accompanied by intense radio bursts, the possibility of detecting these flare stars led British and Australian radio astronomers to monitor them extensively in the last decade. During several thousand hours of observing time, these investigators have found several cases of simultaneous radio and optical flares for a few stars, notably UV CETI, YZ CANIS MINORIS, and V371 ORIONIS. These were the first true radio stars.

One of the best examples is the flare of YZ CANIS MINORIS shown below.

The interpretation of radio flare stars is still quite uncertain. There have been attempts to attribute the radio emission to shock waves moving through a corona, or to non-thermal flare phenomena like the radio bursts on the Sun. There is the difficulty, however, that the brightness temperatures are at least 10^{15}°K in some cases. This is a few orders of magnitude greater than has been observed on the Sun.



NOVAE

Some stars are subject to explosive activity in which they blow off part of their atmospheres. The mass which is ejected, perhaps 10^{-5} of their total mass, is thrown of violently with velocities which typically reach 1000 km/sec. These stars, called novae, were first detected as radio stars by myself and C. M. Wade in June 1970 with the Green Bank interferometer. Three novae: Nova Delphini 1967, Nova Serpentis 1970, and Nova Scuti 1970 have so far been detected.

Data for about 1-1/2 years of observations of Nova Delphini 1967 and Nova Serpentis 1970 are plotted as a function of t, the time since initial outburst. Most of the measurements are at 3.7 and 11.1 cm, but several measurements at 0.35, 0.95, and 1.95 cm were made at various times. The solid curves are the fits to a thermal model in which emission measure, E, and solid angle, Ω_s are varying as functions of time. The following are the solutions for the parameters:

Nova Serpentis 1970:

$$S_{3.7} = (0.08 \pm 0.1)\ t^{1.2 \pm 0.2}\ (1 - e^{-\tau})\ \text{f.u.}$$

$$\tau = (1.02 \pm 0.2)\ t^{-2.6 \pm 0.3}\ \left(\frac{\lambda}{3.7}\right)^{2.1}$$

i.e. $\Omega_s \;\alpha\; t^{1.2}$

$E \;\alpha\; t^{-2.6}$

Nova Delphini 1967:

$$S_{3.7} = (0.16 \pm 0.02)\ t^{0.4 \pm 0.2}\ \text{f.u.}$$

$$\tau = (6 \pm 1)\ t^{-2.5 \pm 0.3}\ \left(\frac{\lambda}{3.7}\right)^{2.1}$$

i.e. $\Omega_s \;\alpha\; t^{0.4}$

$E \;\alpha\; t^{-2.5}$

For free expansion of a nova shell

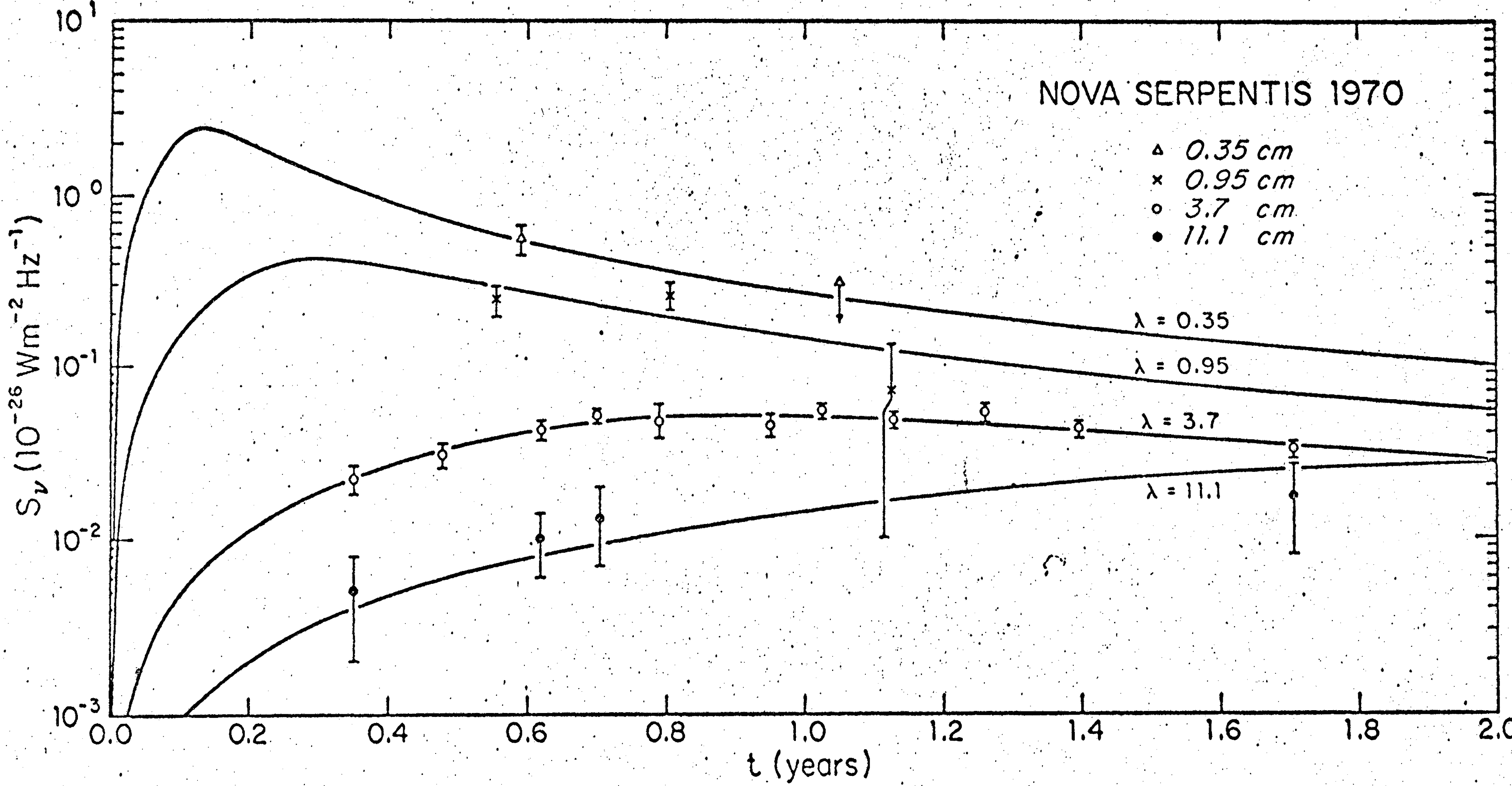
$$\Omega_s \;\alpha\; t^2$$

for one-dimension expansion

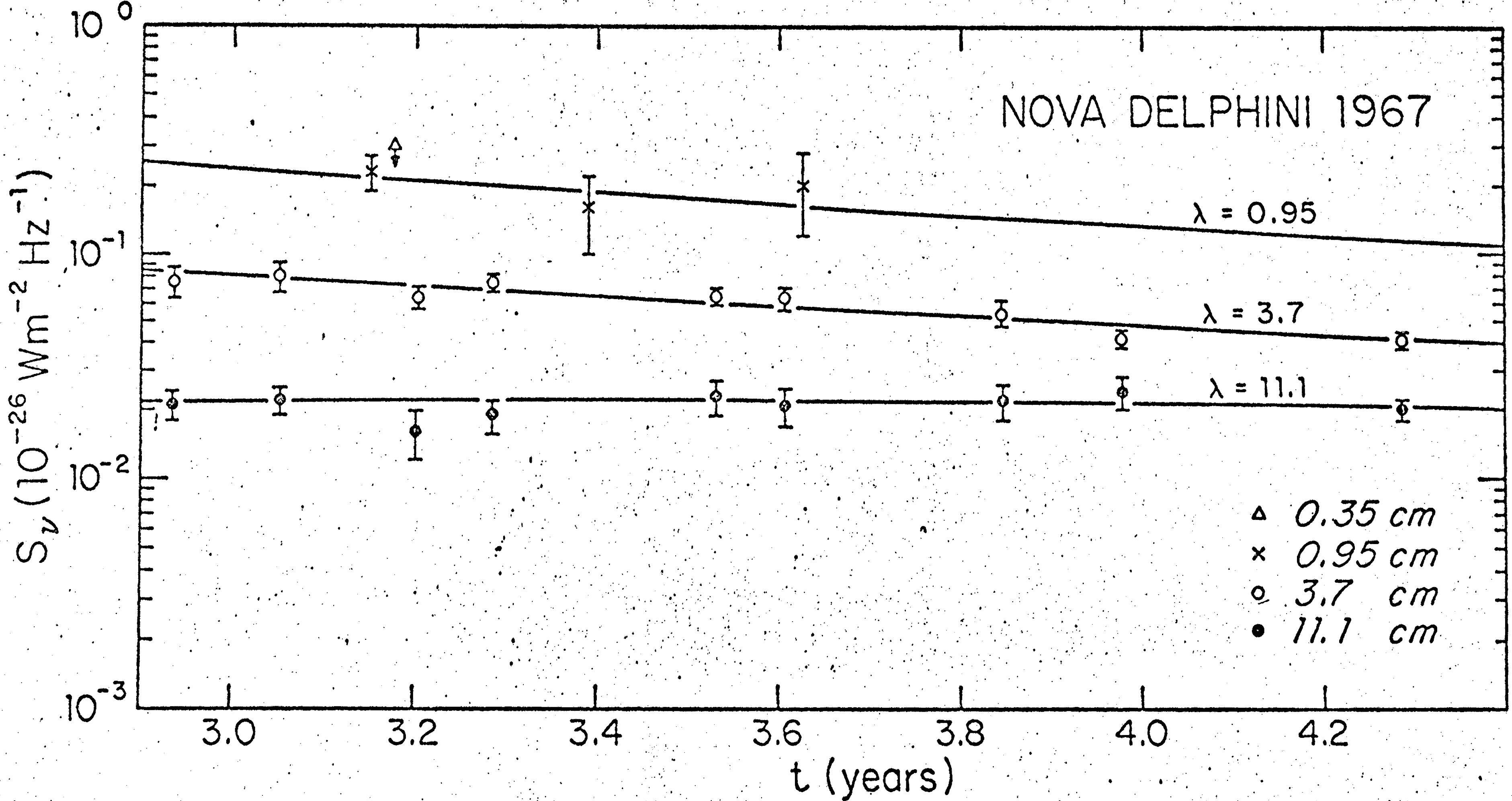
$$\Omega_s \;a\; t$$

hence we see that the expansion of Nova Serpentis 1970 is slightly confined in at least one dimension. However, Nova Delphini 1967 must be somewhat confined in its expansion for all directions.

Further analysis of this data is still underway. Recent data indicate both Novae may have become resolvable. If so, we will soon have distances determinable by the radio data.



NOVA SERPENTIS 1970
△ 0.35 cm
× 0.95 cm
○ 3.7 cm
● 11.1 cm
λ = 0.35
λ = 0.95
λ = 3.7
λ = 11.1
S_ν (10^{-26} Wm^{-2} Hz^{-1})
t (years)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0


NOVA DELPHINI 1967
λ = 0.95
λ = 3.7
λ = 11.1
Δ 0.35 cm
× 0.95 cm
o 3.7 cm
• 11.1 cm
S_ν (10^{-26} Wm^{-2} Hz^{-1})
t (years)
10^0
10^{-1}
10^{-2}
10^{-3}
3.0
3.2
3.4
3.6
3.8
4.0
4.2

RED SUPERGIANTS

This type of radio star must be placed in the maybe category. Kellerman and Pauliny-toth have reported a possible flare in the red supergiant called Betelguese (α ORIONIS). On February 21, 1966, they found a flux of (0.11 $\pm$ 0.03) f.u. at a wavelength of 1.9 cm. No signal was found, however, on eleven following nights.

In addition, Seaquist reported a possible detection of Π AURIGAE, another red supergiant. However, again the result is not reproducible.

This non-reproducibility is the curse of this subject. We know now that every known radio star is variable and some are erratically variable, hence it may be difficult to obtain a particular flare on a particular star.

ANTARES B

Extensive observations of Antares, another red supergiant, have produced an unexpected result and a new type of radio star. Observations at $11._1$ cm by myself and C. M. Wade on the NRAO interferometer have shown that in March, June and November 1970, Antares had a flux density of 0.005 $\pm$ 0.001 flux units. In June the flux at 3.7 cm was less than 0.003 f.n. On June 1, 1971 the Antares radio source was "flaring" at 3.7 cm to a level of 0.011 $\pm$ .002 f.u. A month later it was again less than 0.005 f.u. at this wave-length.

The surprise inherent in this data was that the radio source was not Antares A. the red supergiant, but rather was Antares B, a B3V blue companion 3".2 from the supergiant. The following table and a 3.7 cm map of the source proves this.

TABLE 1

FLUX-DENSITY MEASUREMENTS OF THE ANTARES RADIO SOURCE

DATE OF OBSERVATION	FLUX DENSITY (flux units) 11.1 cm	FLUX DENSITY (flux units) 3.7 cm	ANTENNA SPACINGS (meters)
1970 March 25..........	0.005±0.004	*	900, 1800, 2700
1970 June 4.............	0.006±0.002	<0.003	900, 1800, 2700
1970 November 12.......	0.005±0.001	*	900, 1800, 2700
1971 June 1.............	0.008±0.002	0.011±0.002	900, 1800, 2700
1971 July 8.............	0.007±0.002	<0.005	100, 1800, 1900

* Not observed at 3.7 cm on these dates.

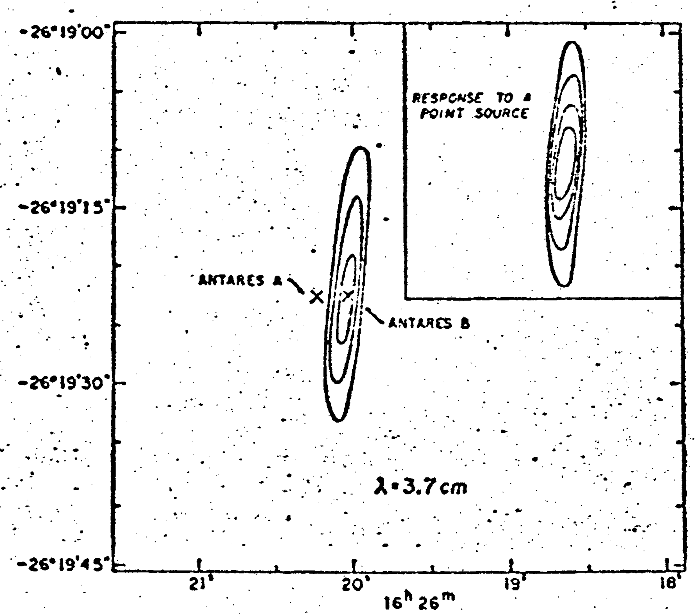


FIG. 1.—Aperture-synthesis map of the Antares radio source, derived from observations at 3.7 cm on 1970 June 1. The uncertainty of the placement of the radio contours is about 1″ in each coordinate. Coordinates are for the epoch 1950.0.

Whereas a red supergiant is very large, a B3V star is very small. Hence fantastic brightness temperatures are probably needed to produce the radio emission.

The variable radio source may also be related to a long known optical anomaly of the blue star: sharp forbidden emission lines of FeII and NiII with no other emission lines. This is physically very hard to explain because anything that excites these lines should excite hydrogen lines.

The answer to both anomalies seems to be unusual particle steaming in the atmosphere of the B star.

Radio Binary Stars

The most important contribution Antares B has made to the radio star business is the clue that matter streaming in binary systems might be important. Following up this clue, the eclipsing binary β Persei (Algol) was immediately detected in October 1971. Several days later another famous binary star, β Lyrae, was found to be a radio star. The following table shows the data obtained for these relatively weak radio stars.

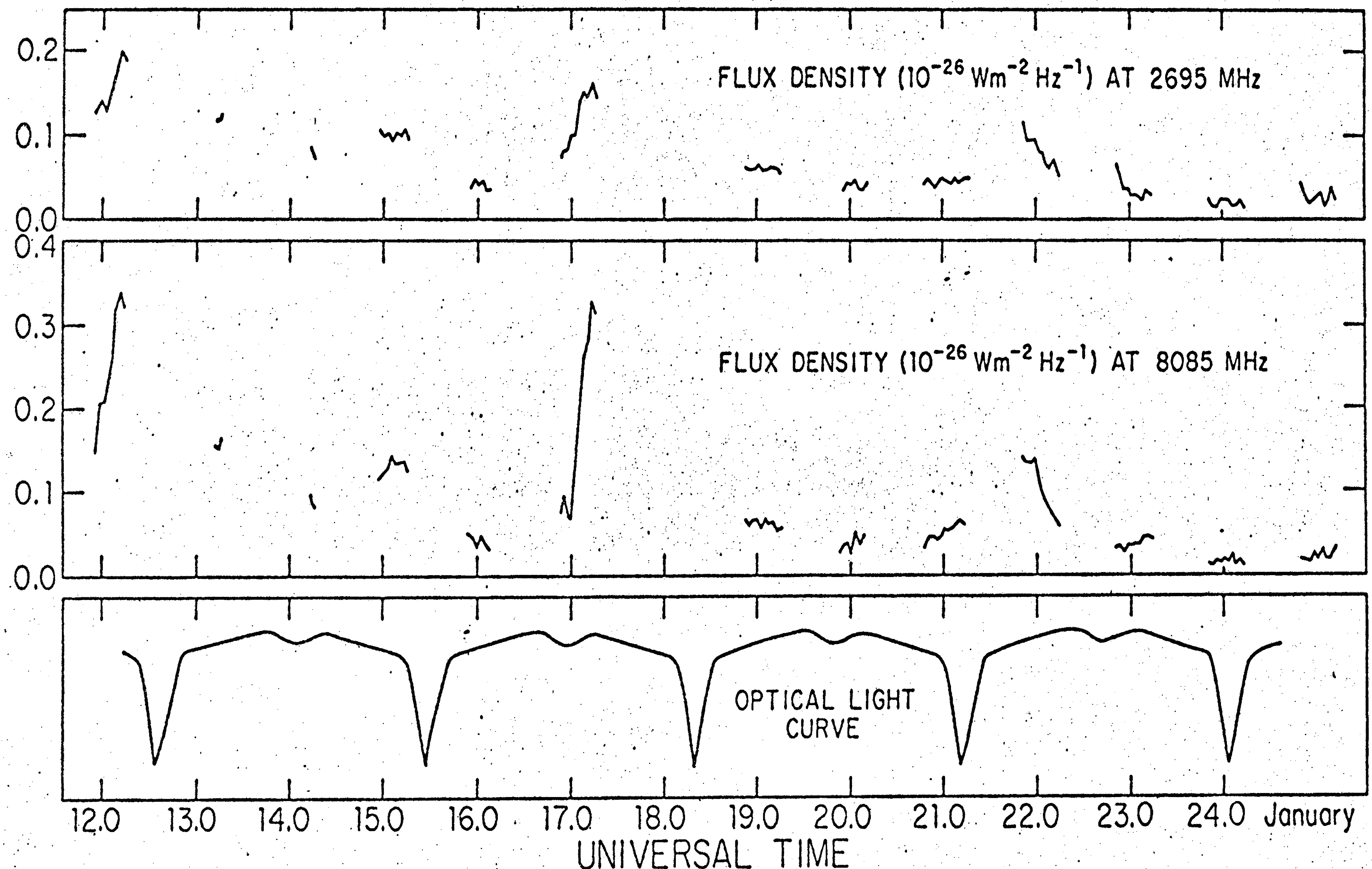
Table 2 Times of Observation and Flux Densities

Star	Date	UT	Flux density (10^{-26} W m^{-2} Hz^{-1}) 2,695 MHz	8,085 MHz
β Persei	Oct. 23, 1971	0543–1106	0.006 ± 0.004	0.015 ± 0.005
	Oct. 31	0445–0930	0.014 ± 0.003	0.019 ± 0.003
	Nov. 6	0026–1044	<0.004	0.010 ± 0.003
	Nov. 7	0247–1041	0.011 ± 0.003	0.012 ± 0.003
	Nov. 8	0244–1037	<0.005	0.015 ± 0.003
	Nov. 9	0239–0459	0.012 ± 0.005	0.006 ± 0.005
	Nov. 10	0235–0756	<0.005	0.010 ± 0.003
β Lyrae	Nov. 4–5, 1971	2240–0241	0.006 ± 0.004	0.015 ± 0.004
	Nov. 5–6	2239–0011	<0.005	0.020 ± 0.005
	Nov. 7	0018–0232	<0.005	0.015 ± 0.005
	Nov. 7–8	1547–1645 2352–0228	<0.005	0.011 ± 0.004
	Nov. 8–9	2343–0224	<0.005	0.013 ± 0.004
	Nov. 9–10	2125–0220	<0.005	0.015 ± 0.005

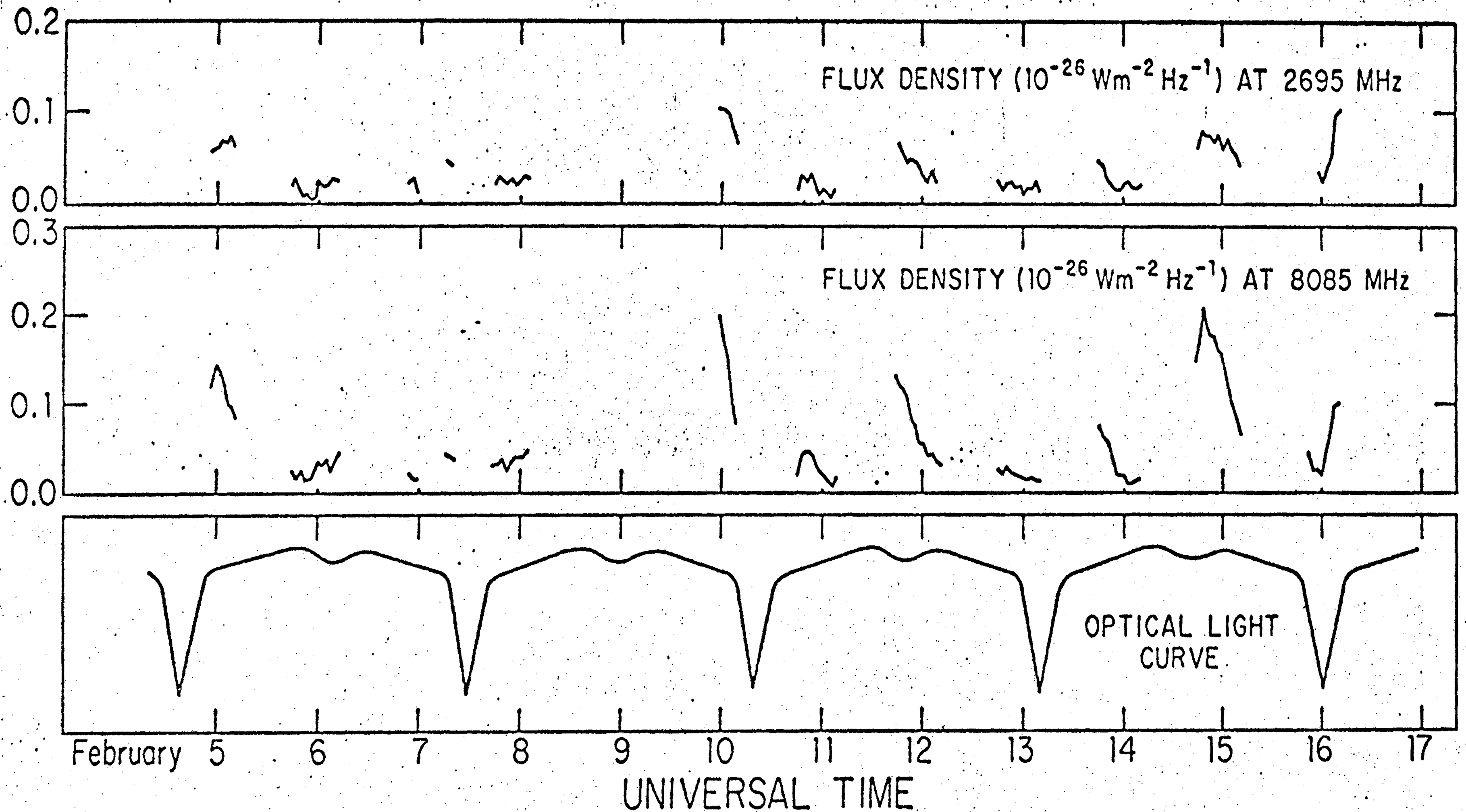
An extensive study of Algol, β Lyrae, and about 50 other similar binary systems in Jan.-Feb. 1972 produced the following results:

1. Algol was undergoing extensive flaring up to leves of 0.34 f.u.
2. β Lyrae weakened and went below the detection limit, thus proving it is variable.
3. No other binary, even though many are similar in every way, was detected.

The following two figures summarize the data for Jan.-Feb. 1972 and compare it with the optical eclipse cycle. No obvious correlation can be found.



FLUX DENSITY (10^{-26} Wm^{-2} Hz^{-1}) AT 2695 MHz
0.2
0.1
0.0
FLUX DENSITY (10^{-26} Wm^{-2} Hz^{-1}) AT 8085 MHz
0.4
0.3
0.2
0.1
0.0
OPTICAL LIGHT CURVE
12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0 21.0 22.0 23.0 24.0 January
UNIVERSAL TIME



0.2
0.1
0.0
FLUX DENSITY (10^{-26} Wm^{-2} Hz^{-1}) AT 2695 MHz
0.3
0.2
0.1
0.0
FLUX DENSITY (10^{-26} Wm^{-2} Hz^{-1}) AT 8085 MHz
OPTICAL LIGHT CURVE
February 5 6 7 8 9 10 11 12 13 14 15 16 17
UNIVERSAL TIME

The most interesting property of Algol as a radio star is the characteristic flare behavior, particularly in spectral index. The following two figures give details on some of the stronger flares and a schematic representation of a typical flare is shown.

The data can virtually all be fit by a thermal bremsstrahlung model. The frequent $\alpha = 0$ behavior is easily explainable only by an optically thin model. Further, during peak flares one can use a slightly optically thick model to find that

$$T_e \sim 10^8 \,^\circ K$$

$$D \sim 0.3 \text{ A.U.}$$

$$N_e \sim 10^{10} \text{ cm}^{-3}$$

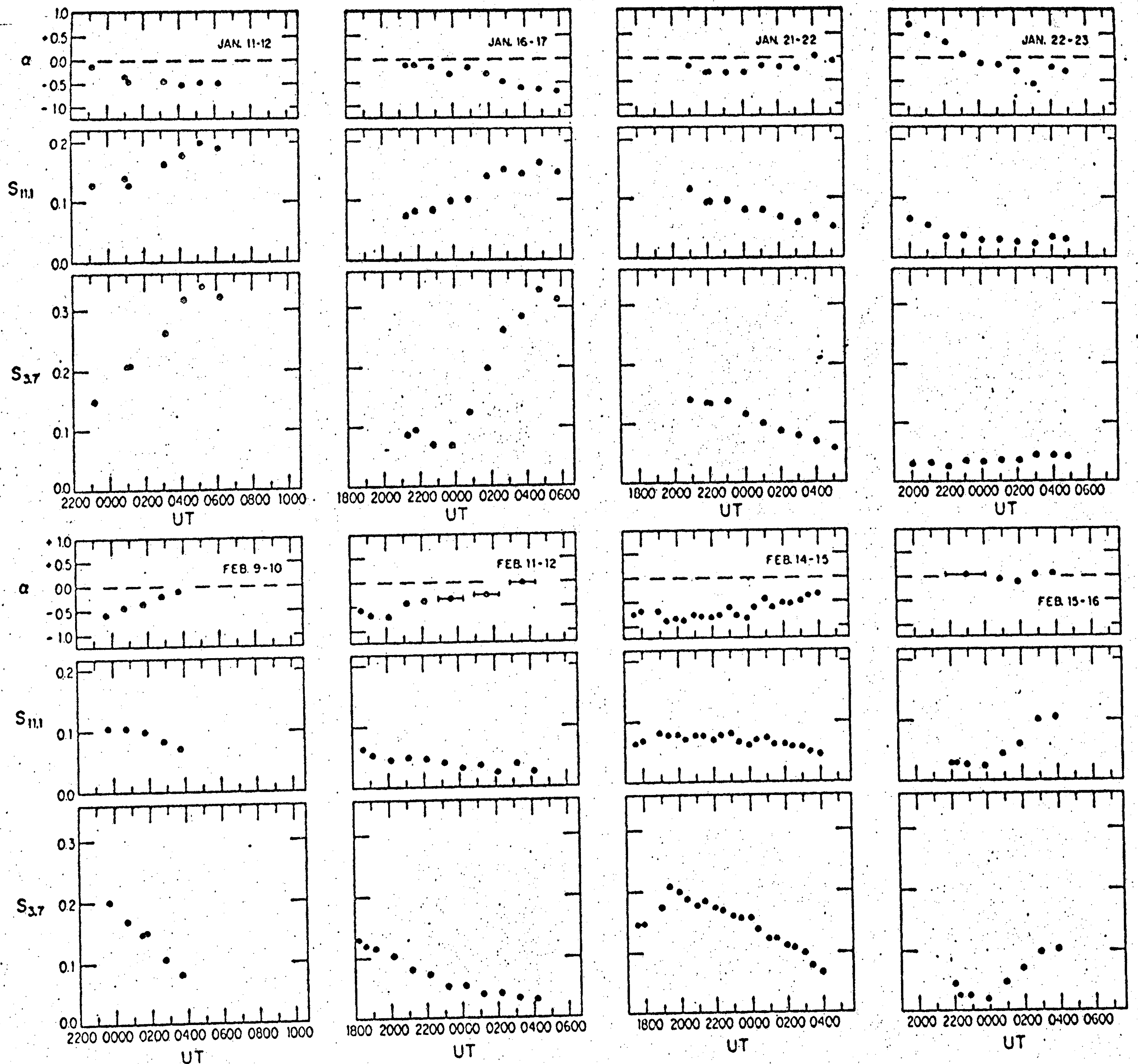
$$\theta \sim 0''.01$$

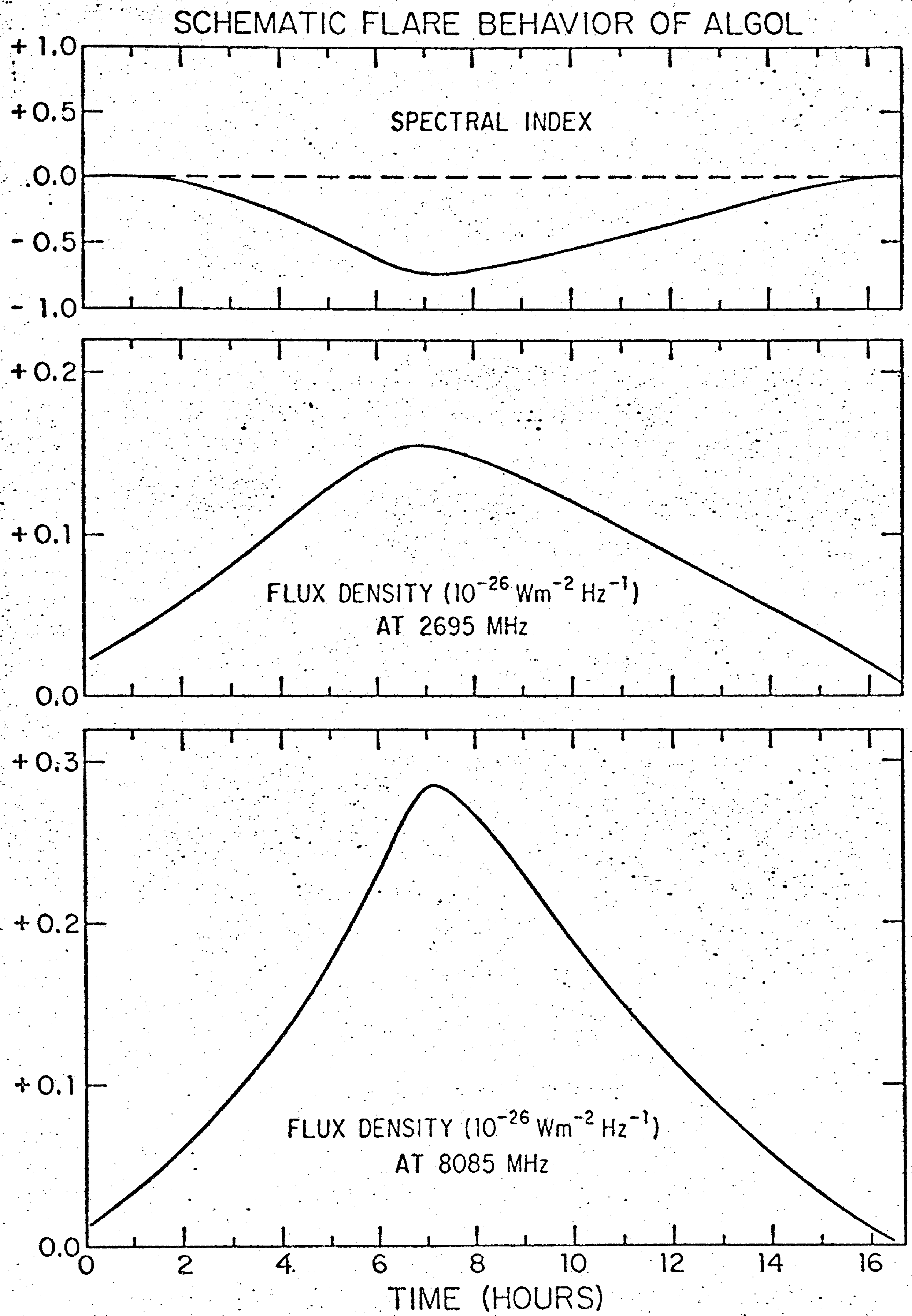
Thus Algol should be a transient X-ray source.

The above parameters imply a mass loss rate of the order of 10^{20} g/sec during peak flaring. With a duration of about a year, this means $\sim 10^{27.5}$ g mass loss. Since the mass in stars is $\sim 2 \times 10^{33}$ g, this is a few parts in 10^6 of the whole mass of the binary. This should produce a comparable change in period.

Interestingly, Algol is known to undergo period discontinuities of the order of a few parts in 10^6 roughly once every 30 years. Ths last known one was in 1942. Hence it was due this year.

ALGO


α
$S_{11.1}$
$S_{3.7}$
JAN. 11-12
JAN. 16-17
JAN. 21-22
JAN. 22-23
FEB. 9-10
FEB. 11-12
FEB. 14-15
FEB. 15-16
+1.0 +0.5 0.0 -0.5 -1.0
0.0 0.1 0.2
0.0 0.1 0.2 0.3
2200 0000 0200 0400 0600 0800 1000
1800 2000 2200 0000 0200 0400 0600
1800 2000 2200 0000 0200 0400
2000 2200 0000 0200 0400 0600
UT



SCHEMATIC FLARE BEHAVIOR OF ALGOL
+1.0
+0.5
0.0
-0.5
-1.0
SPECTRAL INDEX
+0.2
+0.1
0.0
FLUX DENSITY (10^{-26} Wm^{-2} Hz^{-1})
AT 2695 MHz
+0.3
+0.2
+0.1
0.0
FLUX DENSITY (10^{-26} Wm^{-2} Hz^{-1})
AT 8085 MHz
0
2
4
6
8
10
12
14
16
TIME (HOURS)

PULSARS

Pulsars are true radio stars. Because they have been a subject of special lectures this summer I will not discuss them.

X-RAY STARS

One of the most interesting developments of the last year is the coupling between X-ray astronomy and radio astronomy because of the fact that many X-ray sources are radio stars.

It all began with Sco X-1. In 1968 Andrew and Purton found it was a radio source and in 1969 Ables obtained data indicating it was a variable source. I and C. M. Wade entered the subject ~~last year~~ IN 1970 and have had a great deal of fun since then. The first thing we found, by using an interferometer which could accurately place radiation in the field of view, was that Sco X-1 is a triple radio source with the components arranged in a line. The next page shows a map of the source. This is reminiscent of one of the major unsolved phenomena in radio astronomy: why do double sources tend to be arranged on opposite sides of interesting objects.

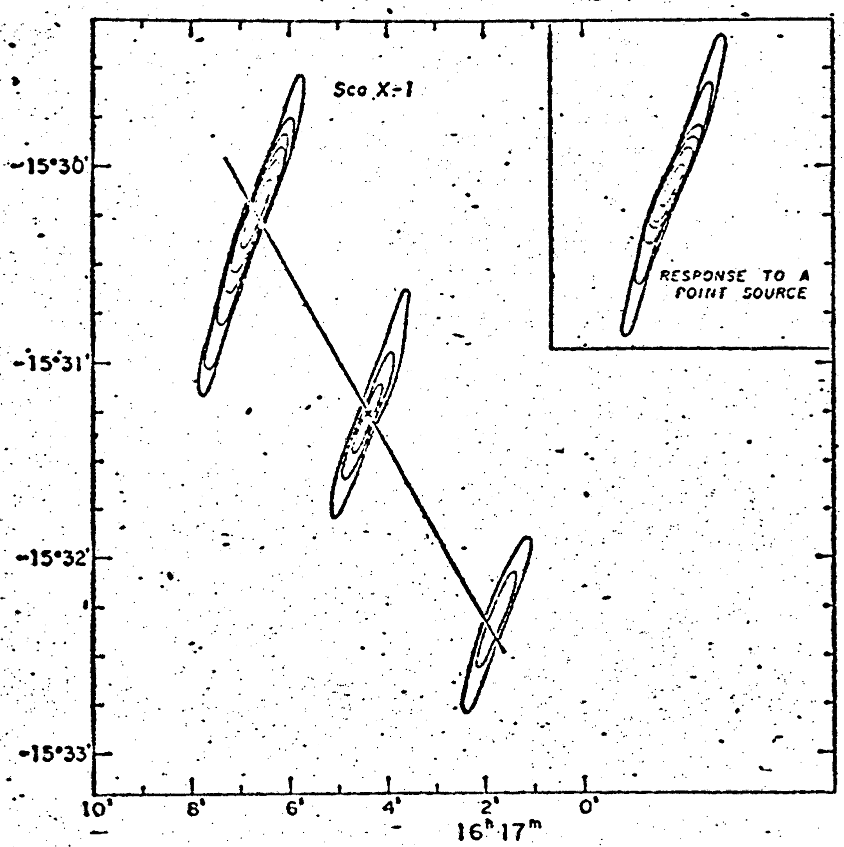
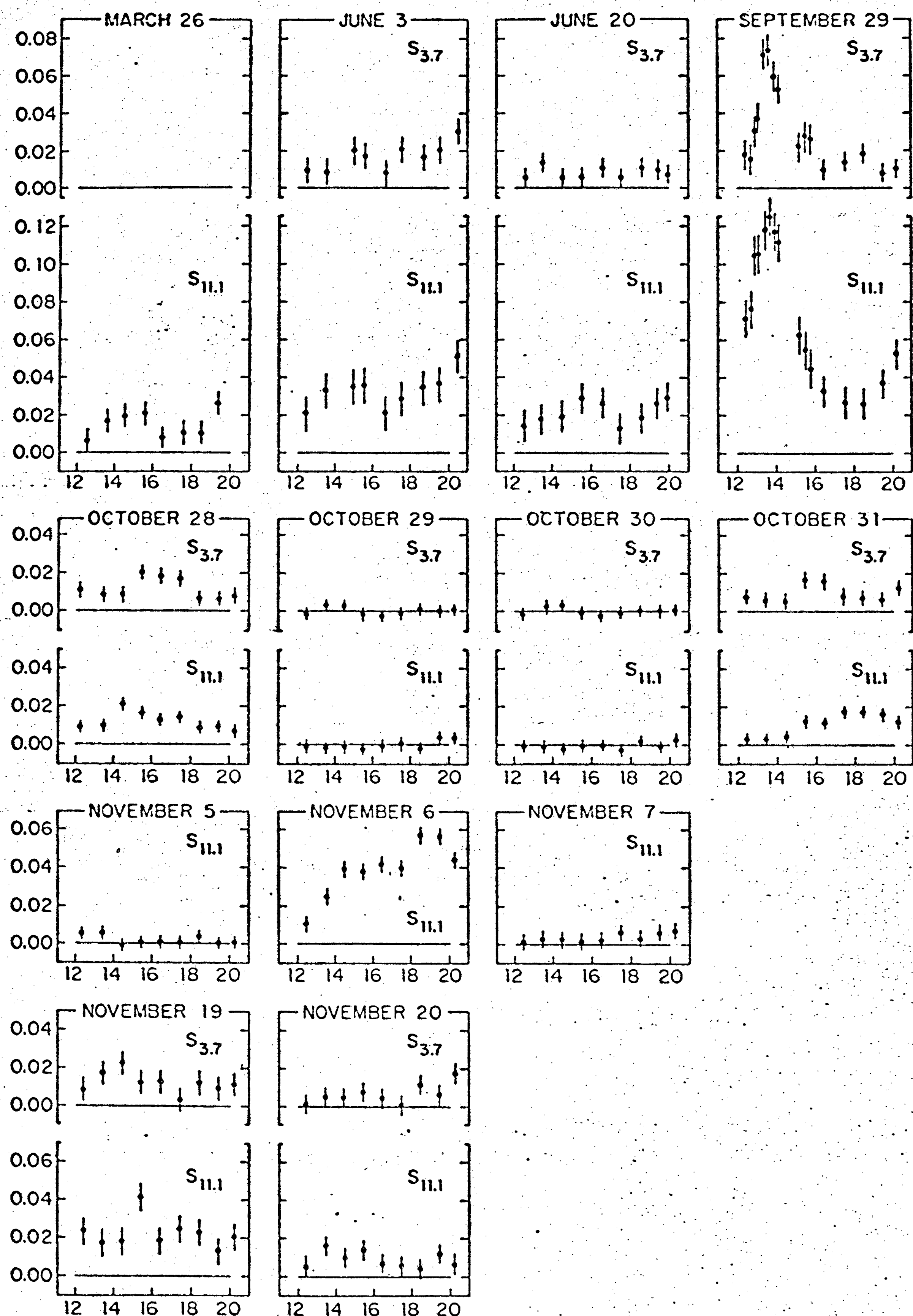


FIG. 2.—Map of the Sco X-1 field, derived from observations during 1971 February, March, and April. Position of the X-ray star is shown by an X. Diagonal line through the component sources is at position angle 29°. The coordinate grid is for the epoch 1950.0.

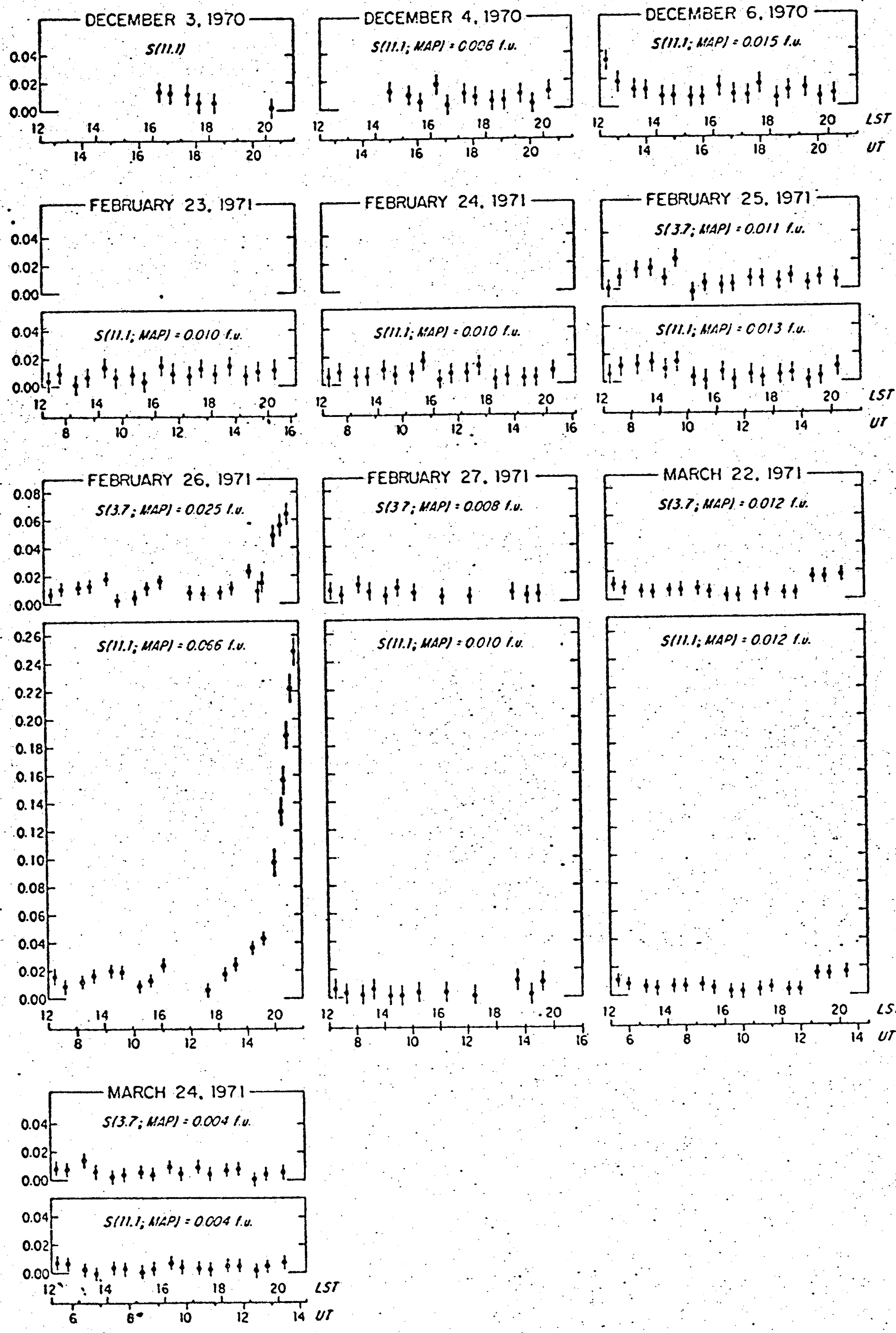
Indeed the central source sits exactly on the peculiar star identified as the X-ray source. Furthermore, the central source varies in flux by as much as two orders of magnitude in a few hours. Nobody yet understands this radio source, which appears to be non-thermal with a very variable spectral index.

Some pages of data on the time variations of this source follow.

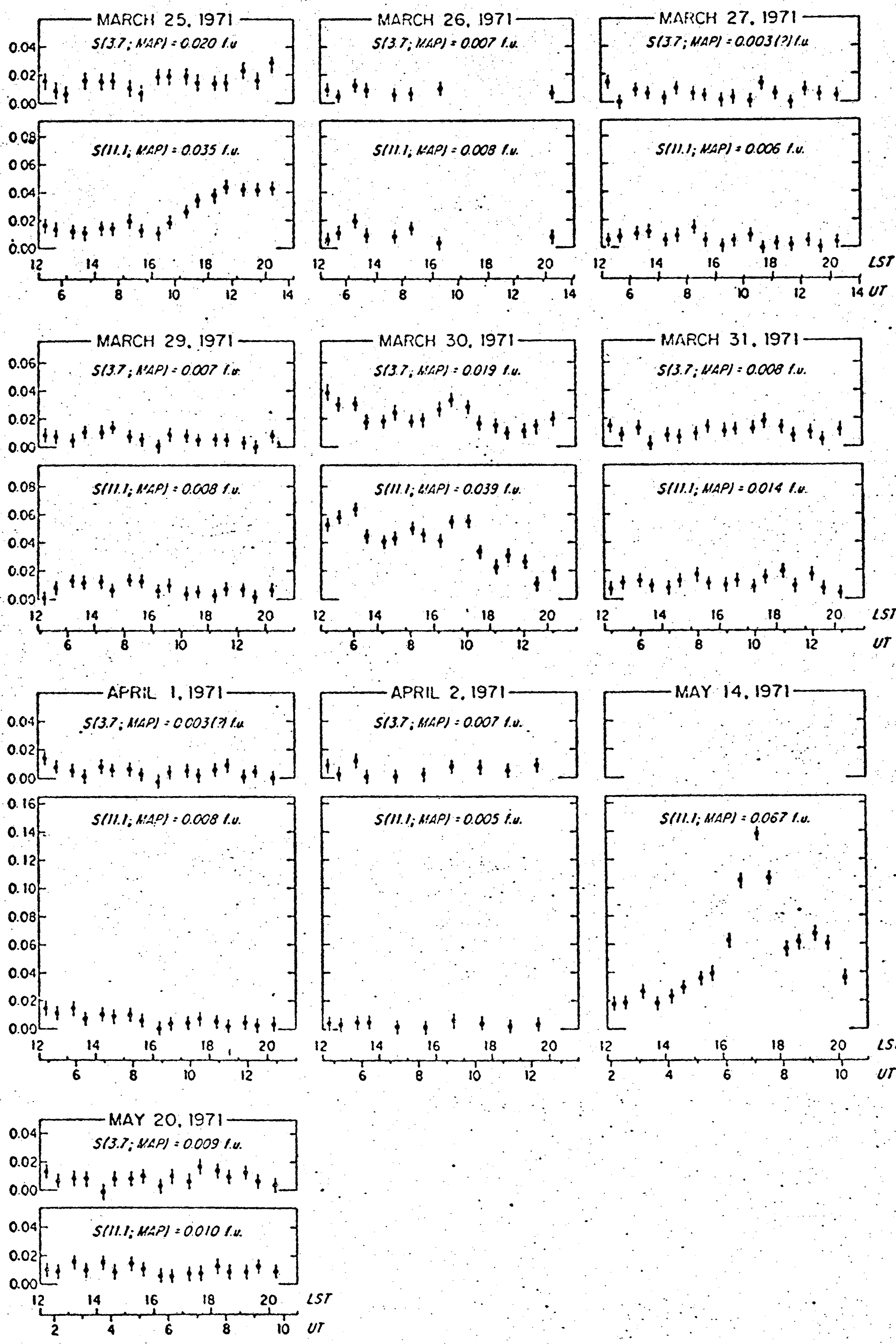
Sco X-1 Central Component



Sco X-1 Central Component



Sco X-1 Central Component



The idea of hunting for other X-ray sources by looking for radio variables in the relatively large X-ray error boxes has lead to a number of successful detections and one important identification.

GX17+2: A lovely Sco X-1 like flare was detected for this object May 27, 1971. The fact that it appeared and disappeared is shown beautifully by, not only the map, but by the amplitude and phase data for two different days.

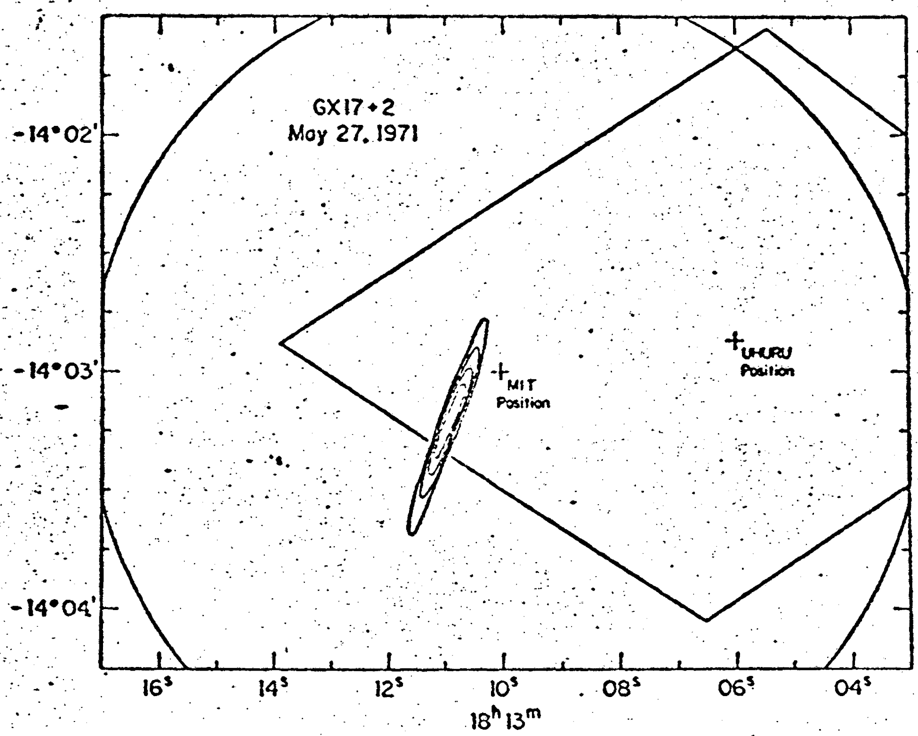
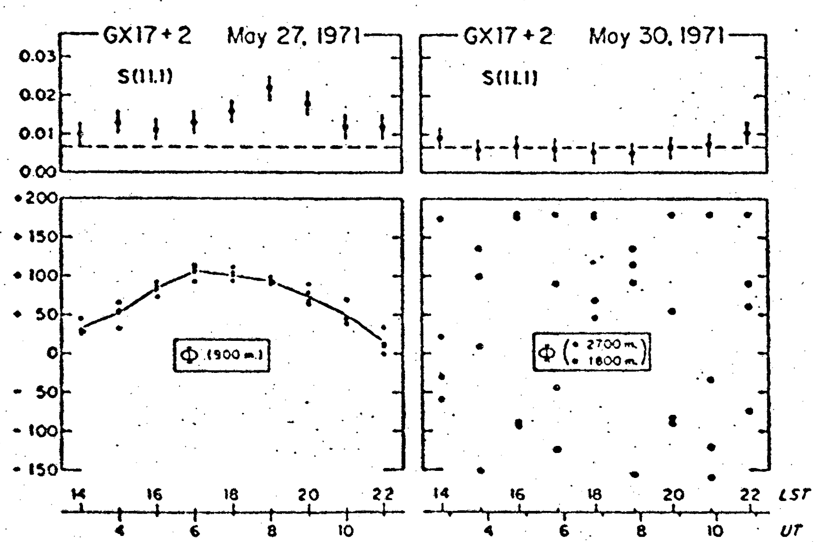


FIG. 1.—Map of the radio source appearing in the GX 17+2 field on 1971 May 27. The circle represents the error limit of the MIT X-ray position (with the 4′ collimator); the polygon represents the error limit of the *Uhuru* X-ray position.



CYG X-1: The identification of a radio counterpart to CYG X-1 was made independently with the Green Bank interferometer and the Westerbork array. The following is the GB 11.1 cm map of the source. The accurate radio position led to an identification with HDE 226868 a spectroscopic binary with a BOIb star.and a nearly invisible companion. Recent work has found a weak helium emission line associated with the "other" object. If this data is confirmed, the mass of the "other" star is 15 solar masses, and would be indeed a "black hole".

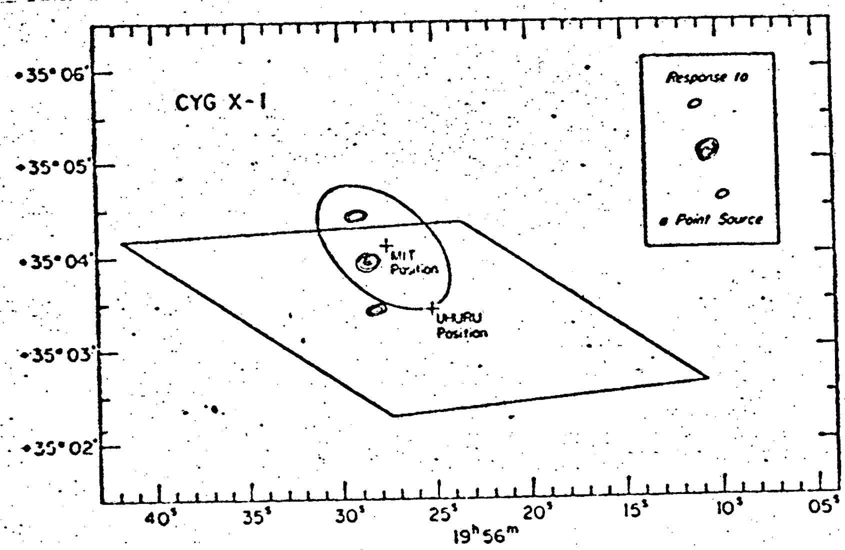


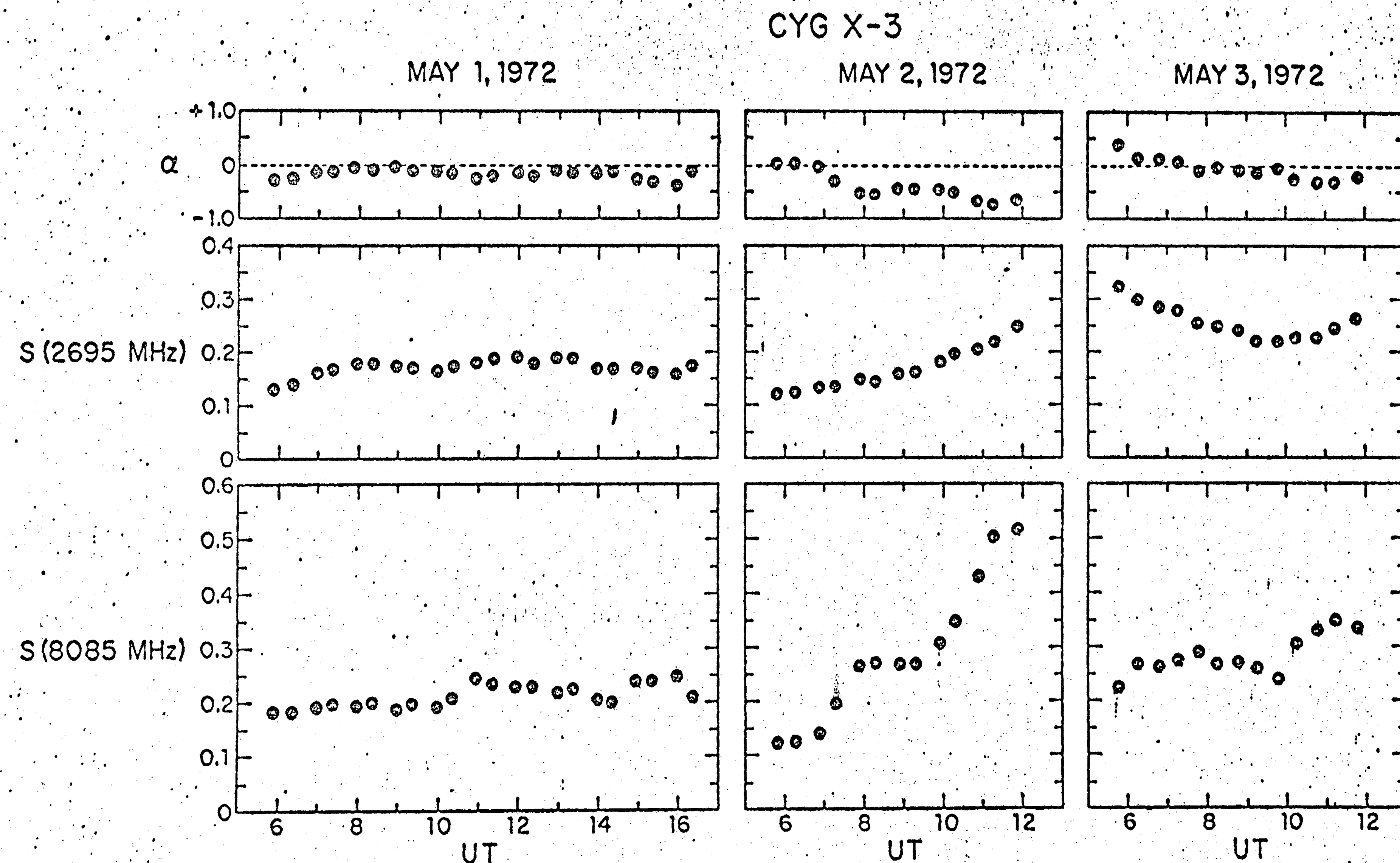
FIG. 3.—Map of the radio source (with the response to a point source in the upper right corner) in the Cyg X-1 field, 1971 May 13–June 1. Ellipse shows the error limits for the MIT position; the polygon, the error limits for the *Uhuru* position.

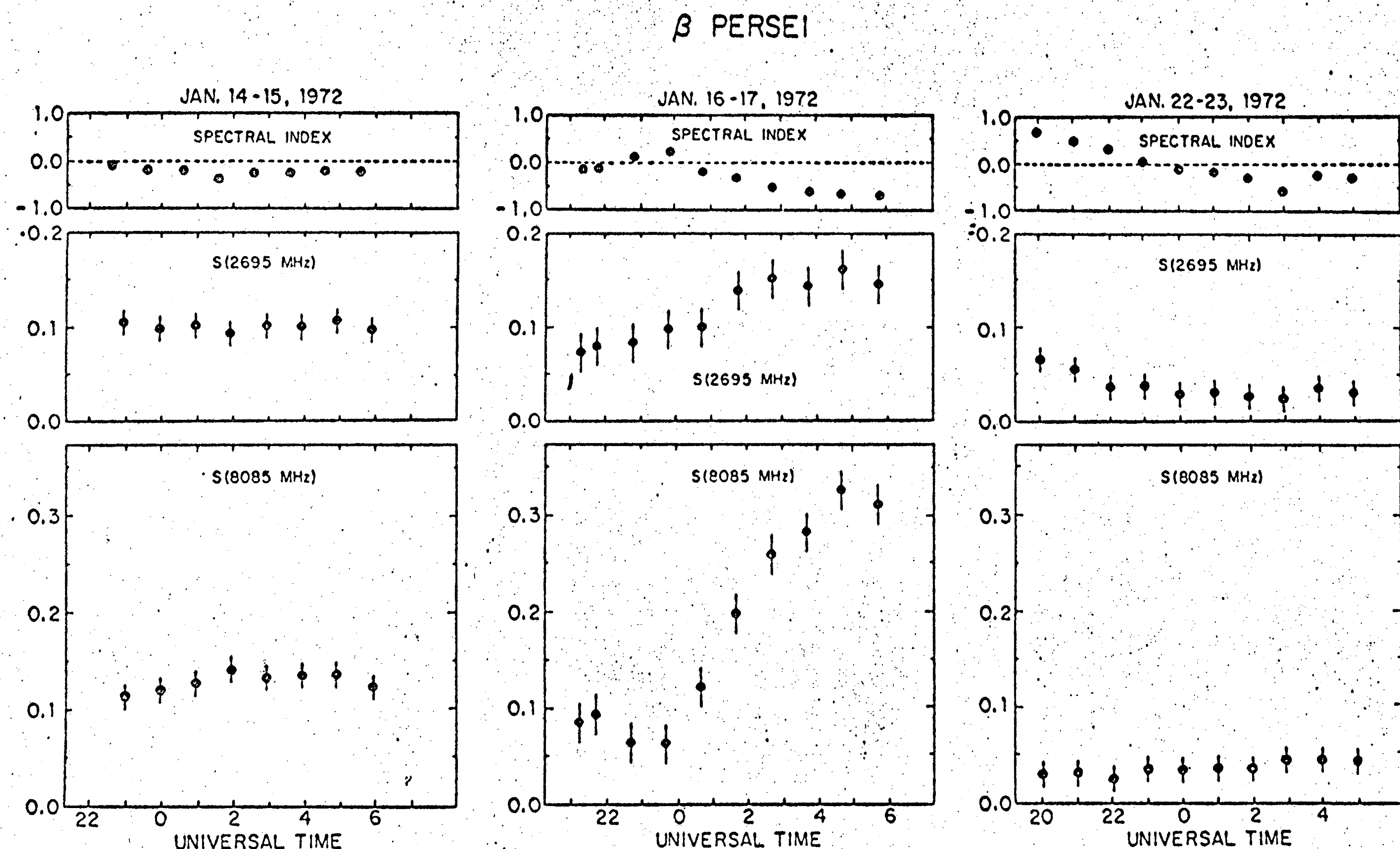
GX9+1: In Nov. 1971, a weak radio source appeared in the error box of this X-ray source.

CYG X-3: This radio counterpart was first detected with the Westerbork array. It is unusual because

1) It is the strongest of the radio stars
2) Its spectrum is mostly thermal
3) Most of the time it looks just like β Persei (Algol). The following two figures show this.

Most recently we have found CYG X-3 to undergo rapid flaring at mm wavelengths on time scales of minutes.


CYG X-3
MAY 1, 1972
MAY 2, 1972
MAY 3, 1972
α
+1.0
0
-1.0
S (2695 MHz)
0.4
0.3
0.2
0.1
0
S (8085 MHz)
0.6
0.5
0.4
0.3
0.2
0.1
0
6
8
10
12
14
16
UT


β PERSEI
JAN. 14-15, 1972
JAN. 16-17, 1972
JAN. 22-23, 1972
SPECTRAL INDEX
S(2695 MHz)
S(8085 MHz)
1.0
0.0
-1.0
0.2
0.1
0.3
22
0
2
4
6
20
UNIVERSAL TIME