The Discovery of Sgr A*

Part 2: "We've got a Tiger by the Tail"

Robert L. Brown
National Astronomy and Ionosphere Center

March 25, 2004

Dear Bob

Enclosed are analyses of the data you sent (X band). The following is my feelings for the data.

1). The phases are probably good to ±60°. The trends (if any) are atmospheric -- they could also be seen in the phases of NRAO530, and I was unable to correct for the atmosphere completely. The phases shown are not impressive, and do not set stringent limits on any model.

2). The amplitudes aren't bad. Formally, the r.m.s. per point is ~ 150 mfu, but the "real error is ~200 mfu. There are no strong trends, but the arithmatic average used in computing the average amplitudes could conceivably be a factor (a small one I should think). You might rerun the program on the INTNBA45 output, this time using a standard vector average. Also, you'll note the total powers are running ~ 9 rather than 5 or 6. This means the true amplitudes may need to be increased by ~ 50%.

Ed's writeup places the hills at HA $\lesssim 2^h45^m$ and HA $\gtrsim 4^h$. The X band data is consistent with these limits. At S band, the amplitudes drop off for HA $\gtrsim 3^h$ (elevation angles $\lesssim 15°$).

By the way, the most careful job of hand calibrating the S band data you sent gave essentially the same results as the quick and dirty calibration I did last Feb on Sgr A. Do you think its worth recalibrating the other data? If so, use PARMS PCONV=2, GCONV=2'

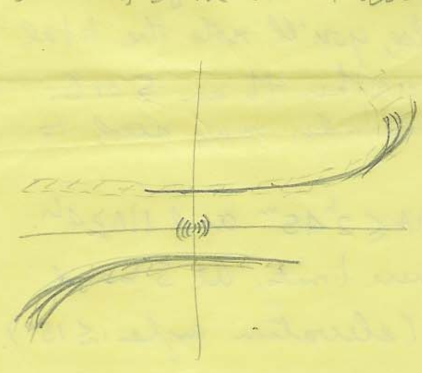
OK, so here's how I now see things.

DATA:	Amp (f.u.)	Phase	
S band	0.5–0.6	180°	no large variations ($\gtrsim$ 20%) in A or ϕ
X band	$\gtrsim$ 1.0	?	" " " A

CONSISTENT MODELS

The one and only simple one that comes to mind is that there is only one source which is "negative" and unresolved at both S and X band. Even if the X band data is totally ignored, I still think this model is the only simple one. I don't believe the source can be double, at least not with separations $\gtrsim$ the lobe separation ~0".6 → 1" (depending on HA), or we'd see the effect. However, I might be wrong...

There are, of course, an infinite # of source distributions consistent with our data. Most all would involve negative sources, I'm sure. All of these models require



the phases to be 180° along our (u,v) tracks. Since we get so close to the u,v origin (~80,000 λ), we might get some help from the 85' tracks, shown in the figure. Of course, the 85's see all kinds of structure we resolve out with the ...

I'm anxious to see how the model calculations come out.

Bruce

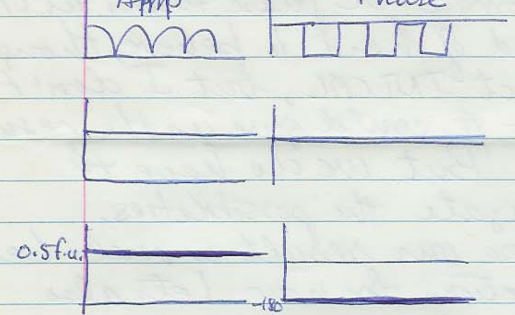
[illegible]

VIA AIR MAIL

Babbie Bob Brown
NRAO Edgemont Rd
Charlottesville, Va.
22901

Dear Keeper of the Royal Data

I got the computer stuff yesterday. Thanks. There was quite a surprise in it. We don't have two positive sources in Sgr A. Instead, we have one, and its negative!



Two pt sources (equal)

One pt source (positive)

What we've got

I'm sort of worried that we have a calibration error of 180°, but somehow I can't bring myself to believe that's behind our results. Its not a random calibration error – after all we have 6 independent baselines on 2 days, and all the phases are ~180° (except in the hills) and the amplitudes hang in there at 0.5 f.u. (with a possible slight decline to 0.45 f.u. when the projected baseline gets longest).

What if the data is OK? We've got a tiger by the tail. We're seeing absorption of ~ 10^5 °K (maybe 10^7 if the VLB observation holds up). But what ~~are~~ is the absorption against? Clearly some source of $\gtrsim 10^5$ °K (10^7 °K). OK, but we don't see evidence of the emission source on our baseline (though the 8085 GHz map of Balick/Sanders shows an emission source of size ~ few seconds and peak brightness $\gtrsim 10^3$ °K (its unresolved at 8085 MHz).

The modelling can be done with either INTMAP or INTQMAP, whichever is fastest. It would also be nice to compare the model visibilities to the data — INTQMAP is best for this because NATWT and UVDISP options of INTMAP don't go well together. The problem, of course, is to find the minimum S_{em} and θ_{em}. (I suspect θ_{em} will come out $\sim 1-10''$). Then we'll see if S_{em} is consistent with the Balick / Sanders 2695 MHz map.

Have fun. I'll be calling you about all this. Its interesting to conjecture we're seeing a black hole — to keep its mass below $\sim 10^8 M_\odot$ (Sanders 21cm paper) its size must be $< 10^{-3}$ arc sec. It could also be an opaque syncrotron source sitting in a bright background but in order to keep the magnetic field reasonable the size has to be awfully small.

Still no word from Goss / Downes.

Me

P.S. The two positive sources we saw are the two nearest sidelobes of the main beam response (check for yourself). The reason a two point source model fit the map so well is that we sampled only once in each u v direction without extensive coverage — i.e. coverage such as ⊕ would have not given us a map which two pt. sources would have fit well, but ∓ does. Anyway you might compare the visibility of the double against

CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA 91109

OWENS VALLEY
RADIO OBSERVATORY

June 2, 1972

Dr. D. E. Hogg
NRAO
P. O. Box 2
Greenbank, W. Virginia 24944

Dear Dave,

I hope this request is self-explanatory and if there are any questions please write Dennis and me.

I will call in several weeks to discuss this proposal and also to talk about the baseline problems at 21 cm. We leave California on July 5 for Germany. Again thanks for your hospitality in March; next time I'm at NRAO I plan to watch out for those football games organized by Bruiser Fomalont!

Cheers,

Miller

W. Miller Goss

MEMORANDUM TO: D. Heeschen
D. Hogg
W. E. Howard

FROM: D. Downes Max Planck Institut, Bonn
W. M. Goss

We wish to propose observations of Sgr A and Sgr B2 with the radio link interferometer system at NRAO. We would like to use the receivers at both 2.7 and 8.7 GHz, and baselines of both 11 and 35 km.

I. SOURCES

1. Sgr A
In view of the increasing interest in highly collapsed nuclear objects as probable sources of the energy in QSO's and radio galaxies, it is of paramount importance to pursue investigations of compact structure in Sgr A. Although the center of our Galaxy is relatively quiescent, it is so close that we can observe details on a much finer linear scale than is possible in external galaxies, even with VLB techniques.

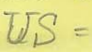
2. Sgr B2
The discovery of compact continuum sources in Sgr B2 (Ekers and Lynden-Bell 1971, Hobbs et al. 1971, Martin and Downes 1972, Welch 1972) indicates that it would be profitable to investigate this source with longer baselines.

II. SIGNAL-to-NOISE

With a 100 K system temperature and 35 MHz bandwidth, the r.m.s. noise is $\sim 2 \times 10^{-2}$ K for a 1-sec integration. On the basis of observations of these sources to baselines of 25 000 λ (Downes and Martin 1971, Ekers and Lynden-Bell 1971, Martin and Downes 1972) we might reasonably expect to observe fringe visibilities of ~ 1 f.u. in both these sources over baselines of $10^5 \lambda$. With 42 and 85-ft aerials, this fringe visibility would correspond to a $T_A \sim 5 \times 10^{-2}$ K.

Dear Bob,

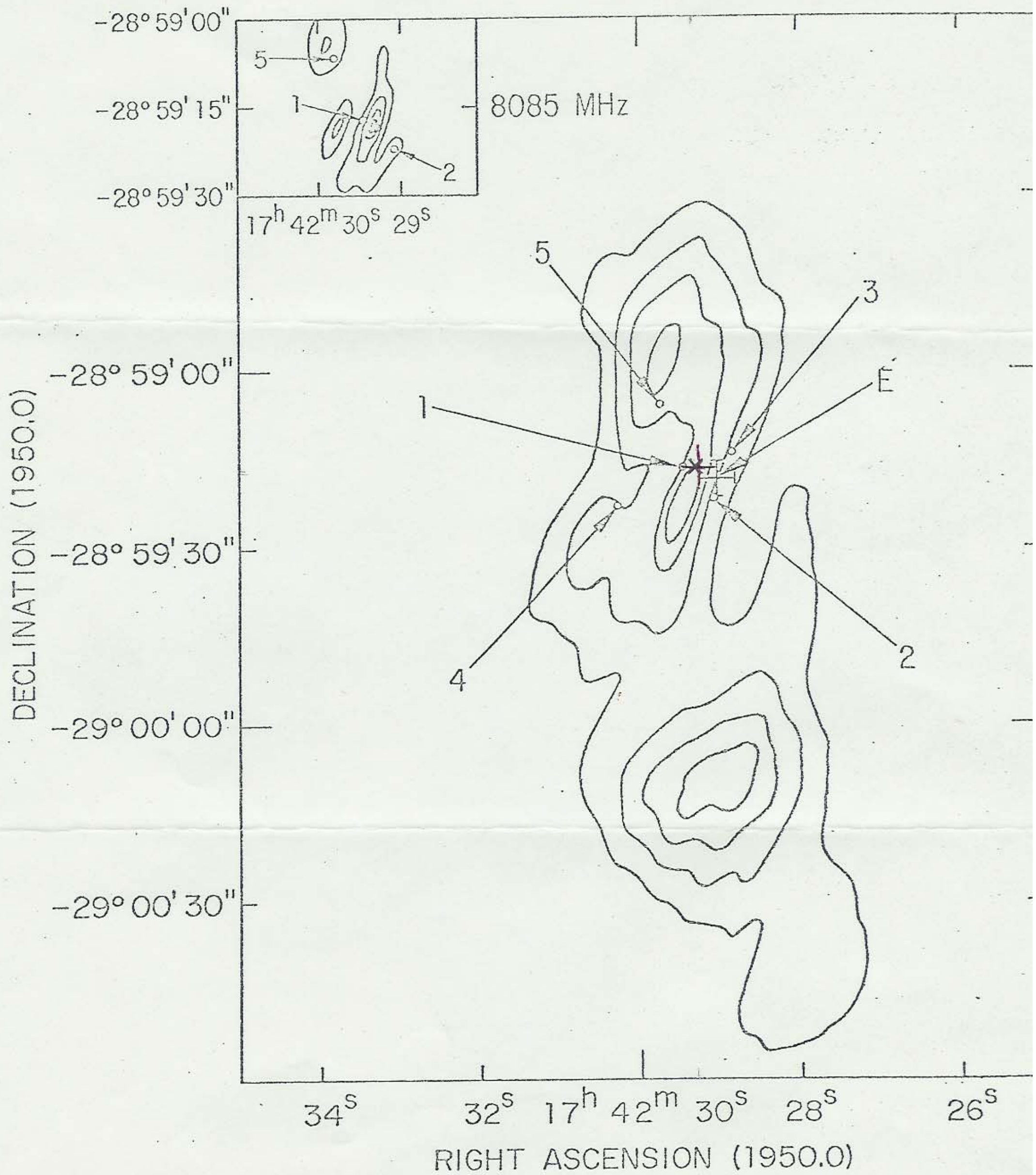
You raised some interesting points in your letter. Let me answer them one at a time.

1. Poss. of an emission double separated by 2."3 or so. Enclosed is a full blown treatment of what you'd expect to observe from this model. To summarize, if you situate a coordinate system midway between the points, then the important scale size $S = 2.''3/2 = 1.''15$, and very major changes in the visibility can be expected over distances in the u,v plane $US =$  $= \frac{\pi}{2}$

$$\Rightarrow U \sim \left[\frac{1.''15}{2\times10^5 \ ''/\text{rad}}\right]^{-1} \cdot \frac{\pi}{2} \sim 27,000\,\lambda.$$

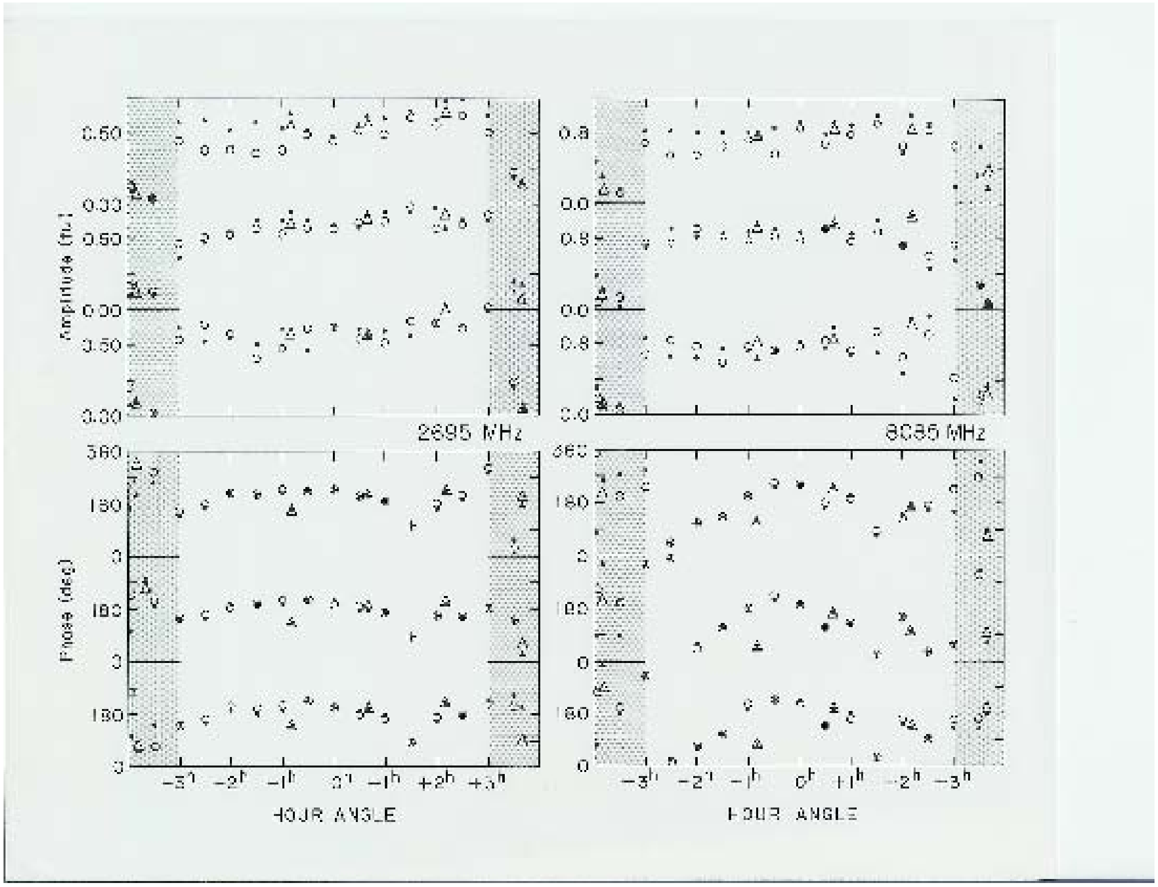
Since we covered $\sim 200,000\,\lambda$ in the u direction and $\sim 120,000\,\lambda$ in the v direction, we should have seen $\gtrsim 5$ bumps in the amplitude and phase. We didn't.

2. Poss. of calibration error. You just proved that's unlikely, although we haven't tested the on line program. It would be most capricious of the on-line program to change the phases of Sgr-A by 180° while leaving the phases of all the other calibrators at 0°. On the other hand, Sgr-A was further south than the other calibrators, and maybe there's some critical declination for which the on-line computer screws up the phase by 180°.

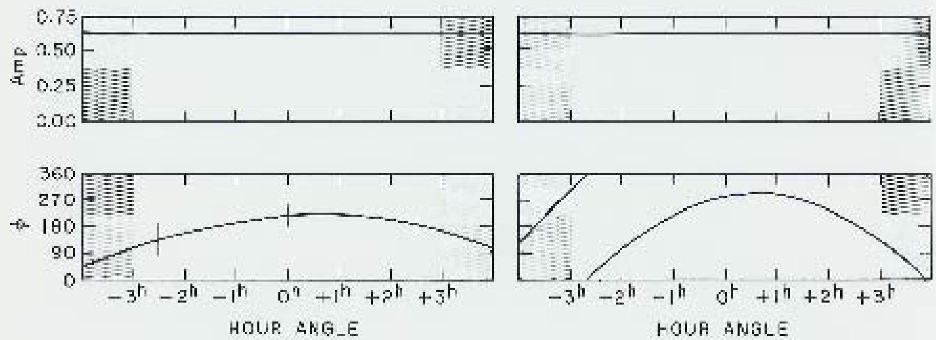


+ = position of 35km radio source

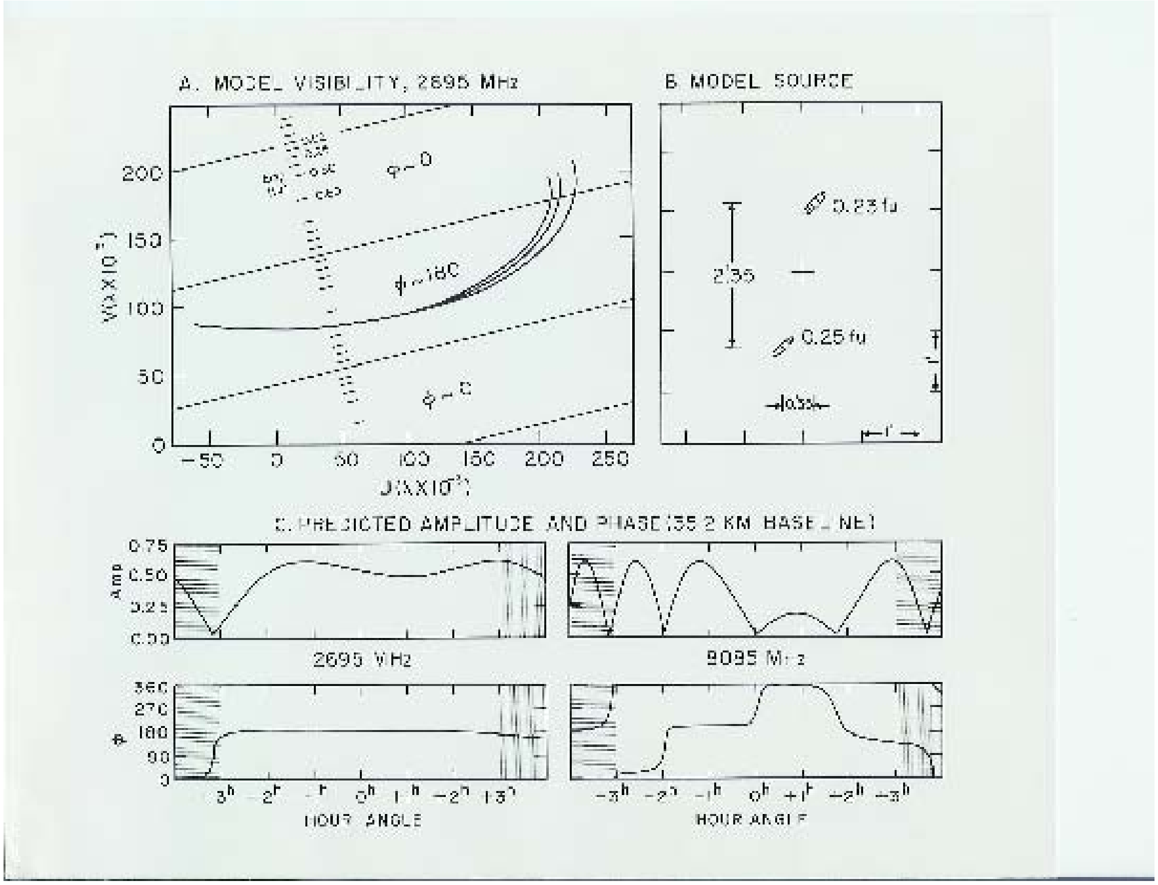
X = position of 10.5μ "centroid" (Riecke & Low, 1973)



2695 MHz
8085 MHz
Amplitude (fu)
Phase (deg)
HOUR ANGLE
HOUR ANGLE



0.75
0.50
0.25
0.00
Amp
360
270
180
90
0
φ
−3h −2h −1h 0h +1h +2h +3h
HOUR ANGLE
HOUR ANGLE


A. MODEL VISIBILITY, 2695 MHz
B. MODEL SOURCE
$\phi \sim 0$
$\phi \sim 180$
$\phi \sim 0$
V(λX10^3)
U(λX10^3)
0.23 fu
0.25 fu
2'.35
C. PREDICTED AMPLITUDE AND PHASE (35.2 KM BASELINE)
Amp
2695 MHz
8085 MHz
HOUR ANGLE
HOUR ANGLE

Bob - read critically and give me a call. How about running

INTEDIT [POSITION SGR-A; (17 42 29.264) (-28 59 16.38)]
INTAVG - INCLUDE SBAND, END REWIND, INCLUDE XBAND
INTSCRIB
INTQMAP - INCLUDE XBAND
INTQMAP - INCLUDE XBAND IR2R
INTQ MAP - INCLUDE SBAND IR2R

Rough draft 4/25/74

I sent a copy of the draft to Fred Lo and gave one to Cyril Hazard (who happens to be here right now)

INTENSE SUB ARC SECOND STRUCTURE IN THE GALACTIC CENTER

BRUCE BALICK

Lick Observatory, Board of Studies in Astronomy and Astrophysics

University of California, Santa Cruz

and

ROBERT L. BROWN

National Radio Astronomy Observatory*

Charlottesville, Vriginia 22901

*Operated by Associated Universities, Inc. under contract to the National Science Foundation.

Dear Bob

Enclosed are two drafts of the paper. The first of these (hereafter reffered to as paper I, or the "blue" paper) involves a major reorganization of the text as suggested by Cyril Hazard. The second of these (hereafter referred to as paper II, or the "white paper on Sgr A'" - eat your heart out NBC) is much the same as the draft I sent you with some minor corrections.

Please read them both from the point of view of the organization (as well as content), then give me a call. The figures should be ready late next week.

Bruce

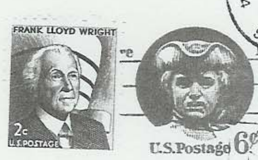
THE ASTROPHYSICAL JOURNAL

Kitt Peak National Observatory
Box 26732, Tucson, Arizona 85726

This will acknowledge receipt of a manuscript entitled "Intense Sub-Arcsecond Structure in the Galactic Center,"
by Bruce Balick and Robert L. Brown
together with 4 figures. The paper will receive prompt attention, and I shall notify you if there are any questions regarding publication. **Mean-time may I draw your attention to the fact that there is a page charge for papers published in the *Astrophysical Journal*. Unless I hear from you to the contrary, I shall assume that your Department, University, Observatory is willing to pay the charges.**

HELMUT A. ABT, *Editor*

DATE 1974 June 3



Dr. Robert L. Brown
National Radio Astronomy Observatory
Edgemont Road
Charlottesville, Virginia 22901

THE ASTROPHYSICAL JOURNAL, 194:265–270, 1974 December 1

INTENSE SUB-ARCSECOND STRUCTURE IN THE GALACTIC CENTER

BRUCE BALICK
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz
AND
ROBERT L. BROWN
National Radio Astronomy Observatory*
Received 1974 June 3

ABSTRACT

The detection of strong radio emission in the direction of the inner 1-pc core of the galactic nucleus is reported. The structure is bright (brightness temperature $\gtrsim 10^7$ ° K), unresolved ($\theta \lesssim 0\farcs1$), and distributed within a few seconds of the brightest infrared and radio emission seen previously.

Subject headings: galactic nuclei — radio sources

I. INTRODUCTION

The nucleus of the Galaxy is a region of great interest both because of its possible dynamical effects on our own Galaxy (Sanders and Prendergast 1974) and because it might provide insight into the processes governing other more energetic galactic nuclei (Saslaw 1973). The interesting inner portions are now being observed in some detail at several wavelengths. Rieke and Low (1973) have shown there exist at least five small-diameter sources and an extended background of infrared (IR) emission located within a 20″ region. Radio synthesis observations with resolutions of 10″ or less have been made of this same vicinity (called Sgr A West by radio astronomers) at 2.7, 5.0, and 8.1 GHz (Downes and Martin 1971; Balick and Sanders 1974; Ekers 1974); these show that there exists structure over a wide range of scale sizes in the region of the IR emission (we refer to this inner 2- or 3-pc core as the IR/radio complex). Although the interpretation of the observations is far from unambiguous, it seems clear that the IR fine structure is generically related to that at radio wavelengths.

Balick and Sanders (1974) have suggested that the structure they observed on size scales between 2″ and 20″ in Sgr A West is predominantly ionized gas typical of fine structure in other H II regions. Therefore we included the IR/radio complex as part of a program searching for "super-bright radio knots" in H II regions (Miley *et al.* 1970) using the new 35-km baseline interferometer of the National Radio Astronomy Observatory (NRAO). For Sgr A West, the fringes were so strong as to be detectable above the noise level in only a few seconds.

II. OBSERVATIONS AND DATA REDUCTION

The NRAO interferometer consists of three 85-foot (26-m) telescopes separable by up to 2.7 km and a new 45-foot (14-m) telescope located about 35 km southwest of the other dishes on top of a mountain. The instrument operates simultaneously at 2695 MHz (11 cm) and 8085 MHz (3.7 cm), and the lobe separations vary between 2″ and 0″.2, depending on frequency and projected baseline length. Because the 45-foot and associated systems have not been described previously, we present a short description here.

The 45-foot telescope is a portable, fully steerable telescope with an aperture efficiency of ~70 percent at both 2.7 and 8.1 GHz. The local oscillator signal is transmitted to (and from) the remote 45-foot from Green Bank over a phase-stable 1.3475-GHz radio link. A second wide-band 18-GHz link carries instructions uplink and the IF signals and digital data downlink. Except under conditions of inclement weather the radio links are quite stable, and the 45-foot system is operated remotely from the Green Bank site. Aside from the lower sensitivity and relatively narrow field of view (see below), the 45-foot system can be considered identical to the 85-foot systems.

The present observations were conducted on 1974 February 13 and 15 under conditions of excellent weather and minimal instrumental difficulties. Phase and gain calibrations were made by reference to NRAO 530 which was observed every half hour, and which is essentially unresolved on the present baseline. Its flux (4.3 fu at 2.7 GHz, 5.4 fu at 8.1 GHz) and position ($\alpha_{1950} = 17^h30^m13\fs542 \pm 0\fs003$, $\delta_{1950} = -13°02'45\farcs83 \pm 0\farcs07$) were determined by comparison with 3C 84, 3C 120, 3C 138, 3C 345, and BL Lac whose fluxes and positions had been accurately measured earlier.

Data reduction of 45-foot data consists essentially of the same process used for reducing data from the 85-foot telescopes, and will not be described here. Since the 45-foot signals are correlated with signals from each of the 85-foot antennae, three closely spaced baselines (of length 35.2, 33.8, and 33.2 km) at each of two orthogonal polarizations (left-hand, or L, and right-hand, or R, circular) are obtained, so that consistency and repeatability tests can be made on each of six independent correlators. Because of the wide 30-MHz bandwidth and long baseline length, the

* Operated by Associated Universities, Inc. under contract to the National Science Foundation.

What we knew in June 1974:

1. There was radio structure at the galactic center that was of an angular size <0.1 arc seconds that appeared to be a single compact source offset from the IR position.

2. The source spectrum was "inverted"—the source was stronger at higher frequencies.

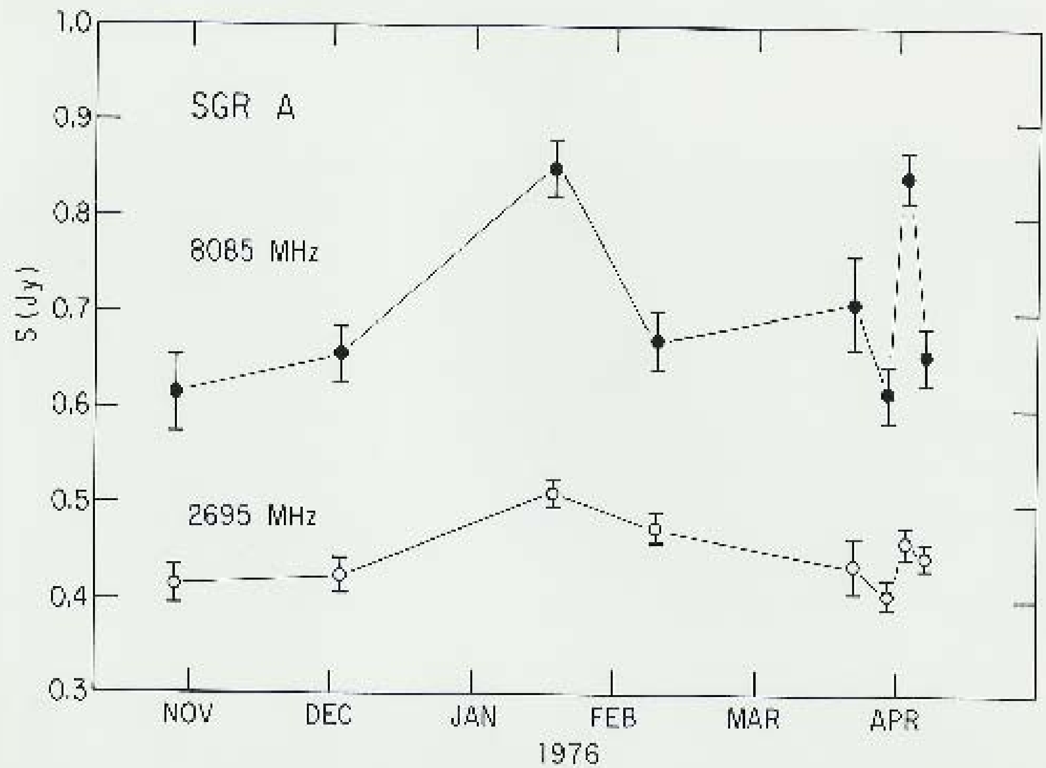
3. The source was unresolved (no spatial structure on scales of ~0."1.

4. The source brightness temperature was greater than 10^7 K: the source is non-thermal.

5. Position, but not the name, of Sgr A*.

A Year Later….

5. The source was variable on a timescale of hours; the variability occurred at the same times at both frequencies but was fractionally greater at the higher frequency.



SGR A
8085 MHz
2695 MHz
S (Jy)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
NOV
DEC
JAN
FEB
MAR
APR
1976

With thanks and sincere appreciation to….

Jim Coe
Jim (“Turkey” Oliver)
Ron Weimer
Dwayne Schiebel
Barry Clark
George Conant
Billy Meredith

David Hogg
Campbell Wade
Ed Fomalont
John Broderick

Len Howell
Bill Howard
David Heeschen