The Galactic Center Tom Armstrong 7/30/84

The center of our Galaxy is heavily obscured by dust at optical wavelengths; the visual extinction is ~ 30 magnitudes. And at ultraviolet wavelengths, where the photons are energetic enough to ionize hydrogen, the interstellar gas hides the galactic center from view. Consequently, all we know of this region is due to observations at IR or longer wavelengths, where extinction from dust is less of a problem, or to X-ray and γ-ray observations, since the absorption by interstellar gas falls off at these very short wavelengths. Since the technology for working at these wavelengths is relatively new, so is the study of the galactic center.

In a sense, the beginning of the study of the galactic center coincides with the beginning of radio astronomy; the "star hiss" that Karl Jansky discovered in the early 1930's is due to synchrotron radiation from the galactic plane, and the strongest source of this radiation in the plane is the galactic center. Radio astronomy has remained the primary means of studying this region until recently, when IR (in the 1960's), FIR, X-ray, and γ-ray (all in the 1970's) observations became possible. With the development of new instruments in all the available bands, the study of the galactic center has become quite active, especially in the last ten years.

I will concentrate in this talk on the inner 50 to 100 parsecs (corresponding at the galactic center distance of about 9 kpc to the inner 15′ to 30′), although I will mention that the atomic hydrogen distribution in the inner ~1.5 kpc of the Galaxy is dominated by a rotating, perhaps expanding disk of ~100 pc thickness tilted by roughly 20° with respect to the overall plane of the Galaxy, and that the "bulge" that surrounds the galactic center has a core radius of ~140 pc and may be bar-like.

The most obvious thing about the distribution of radio emission from the galactic center is its asymmetry (Fig. 1). There is a definite preponderance of emission from positive galactic longitudes, and this applies to continuum, H I, and molecular spectral line emission. In the continuum, the most prominent feature is the central source, Sgr A (Fig. 2), which consists of a point source, *Sgr A**, embedded in a spiral-like structure (together constituting *Sgr A (West)*) lying on the edge of a shell structure, possibly a supernova remnant, and known as *Sgr A (East)*. The dynamical center of the Galaxy lies near or at the point source in Sgr A (West), at $(\ell, b) = (-3\overset{\prime}{.}34, -2\overset{\prime}{.}75)$.

Maybe the most striking feature is the *continuum arc*, perpendicular to the galactic plane, crossing it at $\ell \sim 15'$, and connected (at least in projection) to Sgr A by a bridge of emission rising out of the plane. Recent observations by Yusef-Zadeh, Morris, and Chance (1984) using the VLA at 20 cm show that the arc and the bridge have a rich filamentary structure (Fig. 3). The filaments are probably due to some sort of magnetic phenomenon. FIR observations (Dent *et al.* 1982) and recombination line observations (Gusten and Downes 1980) show the bridge, but not the arc, so the bridge emission appears to be thermal emission from ionized gas, while the arc is nonthermal. The X-ray emission (Watson *et al.* 1981) is dominated by an extended component, but there are also about a dozen point sources, including one that coincides with Sgr A (West) (Fig 4.). The nature of these point sources is still unclear, but they may be luminous early-type stars.

The neutral molecular gas near the galactic center also follows an asymmetric distribution. Most of the material in this *Sgr A complex* is contained in three massive clouds, one at more negative longitudes than the galactic center and two at more positive longitudes, and all lying slightly below the plane of the Galaxy (Fig. 5). The two at positive longitudes are known collectively as the *50 km/s cloud*. Their velocities are indeed within ~5 km/s of each other, and they appear blended together, so they are probably parts of a single (sub)complex. The one at negative longitude is the *20 km/s cloud* (really closer to 12 km/s). It is spatially distinct from the 50 km/s cloud, but it is similar in other respects. There are other bits and pieces of molecular emission, including a somewhat tenuous link to Sgr B2, a GMC/H II complex at $\ell \sim 40'$.

These Sgr A clouds bear a family resemblance to the giant molecular clouds (GMCs) found elsewhere in the Galaxy that are the sites of massive star formation, but they are unique in several ways. In the first place, they *don't* seem to be active sites of massive star formation; the number of water masers and compact H II regions seen in these clouds is much smaller than we would expect from similar clouds elsewhere in the Galaxy. Second, in spite of the fact that massive stars don't seem to be forming, the clouds are quite warm by GMC standards. Just how warm is a matter of some debate: FIR observations give dust temperatures around 40 K, while molecular observations give gas kinetic temperatures of anywhere from 15 K to 120 K. Third, the linewidths are also quite high, 15 to 30 km/s and often more, as opposed to 5 to 10 km/s in normal GMCs. Fourth, the regions over which the linewidths and temperatures are high are not confined to small areas of the clouds, but extend over the entire complex. Finally, these clouds do not seem to show the degree of clumpiness that exists in other GMCs, although the evidence on this point is still sketchy.

These clouds also seem to have an intimate relationship to the large-scale ionized gas. Not only is the distribution asymmetric in the same sense, but the 50 km/s cloud is nestled in the arm formed by the continuum arc and bridge. One of the unsettled questions about the molecular gas is its actual (as opposed to projected) distance from Sgr A. The fact that the continuum emission and the molecular emission are anticorrelated in many places certainly suggests that the boundary between them is real rather than a projection effect. The presence at the core of the 15 km/s cloud of a small nonthermal arc that looks like it might be a shock wave propagating from Sgr A (East) into the cloud also suggests a physical association between the ionized gas and the molecular material. On the other hand, one might expect tidal effects from the ~3×10^7 M(solar) mass of the inner 5 pc to disrupt the relatively tenuous molecular clouds if they are closer that ~100 pc, and thus conclude that the clouds are in fact more distant than that from Sgr A.

A related and equally difficult question is the relative placement along the line of sight of the molecular clouds and the components of Sgr A. The radial velocities of the clouds tell us that they are receding, but are they in front of Sgr A and falling into it, or behind Sgr A and being expelled? Combining emission and absorption observations should answer this question. For example, NH_3 observations toward Sgr A with a beam size of 1.'5 show molecular emission, hence the presence of molecular gas in that direction (Armstrong and Barrett 1984). If that gas is in front of Sgr A, then observations with the VLA, which has a resolution of ~5" in D array at 24 GHz, should show absorption of the continuum radiation at those positions where the brightness temperature of the continuum is greater than the excitation temperature of the molecules (which is true over most of Sgr A). However, in the case of the galactic center, drawing reliable conclusions has proved quite difficult because of the very complicated geometry of this region.

As I mentioned above, Sgr A consists of three components. Emission from the shell structure, Sgr A (East), is absorbed by the 50 km/s cloud. Sgr A (West) and Sgr A* also show absorption by H I at 40 to 60 km/s, but there is reason to believe that this gas is not part of the 50 km/s cloud (Liszt and Burton 1984). Sgr A (West), but *not* Sgr A*, shows absorption by H_2CO, also at 40 to 50 km/s. Brown and Liszt (1984) list three possibilities: Sgr A* is in front of Sgr A (West) and the molecular gas; or the molecular gas is very near Sgr A* and is being dissociated by it; or the molecular gas is clumpy and fails to cover Sgr A* only by accident. It may be that this region is so complicated that absorption studies can't reveal the arrangement of the different features after all.

The next smaller size scale to consider is that of the thermal spiral-like structure of Sgr A (West) (Fig. 6) and its immediate environment. Much of the research in the last five years has concentrated on determining the temperature, ionization state, and velocity field of this gas. Sgr A (West) appears to be surrounded by a ring of gas and heated dust with an inner radius of 1 to 2 pc (Fig. 7). The inner edge of this ring is a source of vibrational lines from shocked H_2, and observations of [O I] lines by Genzel *et al.* (1984) show that it is rotating at ~ 70 km/s at 40" to 80" from Sgr A*. This implies a mass interior to 1 pc of $(2 - 5) \times 10^6$ M(solar). The spiral structure of Sgr A (West) lies within this ring, with its arms ending at the ring; it may be that the spiral arms are in fact the inner edge of the ring. This idea is supported by H76α recombination line observations of van Gorkom *et al.* (1983), in which the velocities of the ionized gas match those of the ring at the appropriate places (Fig. 8).

At still smaller scale, the remaining part of Sgr A (West) is the bar structure that crosses the ring. This gas does not fit the model that includes the spiral with the rotating ring; the velocities are wrong. Observations of the [Ne II] line by Lacy *et al.* (1980) (Fig. 9) show that the bar may be rotating about an axis that lies nearly in the plane of the Galaxy; but if it is rotating, it cannot be solid-body rotation, and it is not centered on either Sgr A* or IRS 16 (see below), one of which should be the dynamical center of the Galaxy. The bar is distinct from the ring in other ways as well: it is hotter (12000 K vs. 5000 K in the ring), and the linewidths are greater (200 to 400 km/s vs. 100 km/s). Both probably reflect the influence of the central engine on the gas of the bar. Conflicting models for the origin of the bar have been offered. It may be infalling material from the ring, or it may be material being ejected from some central source in the bar. Both models have difficulties. The infall model fails to account for the velocity discontinuity between the bar and the ring and requires too high a mass for the central object, while the ejection model must explain why both of the obvious candidates for the source of the ejected material, Sgr A* and IRS 16, are on the northern edge of the bar, rather than in the middle.

One more step down in scale brings us to the sources at the center of the bar, IRS 16 and Sgr A*. IRS 16 is a prominent feature in the 2.2 μm map, and was proposed as the galactic center because it is extended, unlike the other 2.2 μm sources, and because of its positional coincidence with the point-like nonthermal source Sgr A*. In the last few years, however, it has become clear that these two sources differ in position by ~1".5 (Fig. 10). The angular sizes of each source have been measured; IRS 16 breaks up into three components, while VLB observations of Sgr A* at high enough frequency to avoid broadening by interstellar scintillation show it to be ~0".015 ± 0".004 ([15 ± 5] $\pm 10^{14}$ cm) in size. Sgr A* is also variable on time scales of a day to months. In addition, it does not appear that the $\sim 10^7$ L(solar) necessary to heat the 2 pc ring can come from IRS 16. It may be that Sgr A* is a moderately low mass nonstellar object, say 10^2 to 10^4 M(solar), gravitationally bound to the star cluster IRS 16, whose mass is $\sim 10^5$ to 10^6 M(solar).

Further evidence on the nature of the central source, whichever it might be, is given in the 511 keV γ-ray observations of Riegler *et al.* (1981). The 511 keV line is due to $e^+ - e^-$ annihilation. Although the γ-ray instrument had a beamsize of 4°, it is likely that the radiation is coming from the galactic center because of the uniqueness of the source and because of its variability. Figure 11 shows spectra from the fall of 1979 and the spring of 1980. There was a significant decline in the 511 keV flux during that time. The requirements for producing 511 keV emission with the linewidth seen imply that the positrons are stopped and annihilated in dense (> 10^5 cm^{-3}), warm (< 5×10^4 K) ionized gas, and that they are produced by a very luminous (> 10^5 L(solar)) compact (<2×10^8 cm) source whose mass could be between 10^2 and 10^6 M(solar).

The galactic center is certainly the site of some unusual activity. Whether Sgr A*, IRS 16, or some other object is the required high-luminosity source is not yet clear; thus we still cannot pin down the nature of the central source, nor can we place the Galaxy either in the class of galaxies with active nuclei or in the class of starburst galaxies.

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Figures

Fig. 1: 10.7 GHz emission as mapped by Pauls *et al.* (1976). Resolution is 1'.3.

Fig. 2: 5 GHz emission mapped at Westerbork and Owens Valley by Ekers *et al.* (1975).

Fig. 3: 1.4 GHz VLA observations by Yusef-Zadeh, Morris, and Chance (1984).

Fig. 4: 0.9-4.0 keV X-ray image from Watson *et al.* (1981).

Fig. 5: NH_3 (1,1) emission (dashed contours) and 2.8 cm continuum emission, from Gusten (1982).

Fig. 6: A copy of Fig. 14 from Brown and Liszt (1984) showing 10.6 μm (Rieke *et al.* 1978) and 15 GHz emission.

Fig. 7: IR maps at 30, 50, and 100 μm and a map of deduced luminosity from Becklin *et al.* (1982).

Fig. 8: A copy of Fig. 15 from Brown and Liszt (1984) showing (a) 100 μm and 5 GHz emission, (b) 15 GHz emission and the position of the ring, (c) a model for the ring, also including the bar feature of Sgr A (West), and (d) a map of H76α from van Gorkom *et al.* (1983).

Fig. 9: [Ne II] emission from the bar region of Sgr A (West) as mapped by Lacy *et al.* (1980).

Fig. 10: Still another figure from Brown and Liszt, this one showing 2.2 μm (Becklin *et al.*) and 1.0μm (Henry *et al.* 1984) emission.

Fig. 11: 511 keV spectra from Riegler *et al.* (1981).

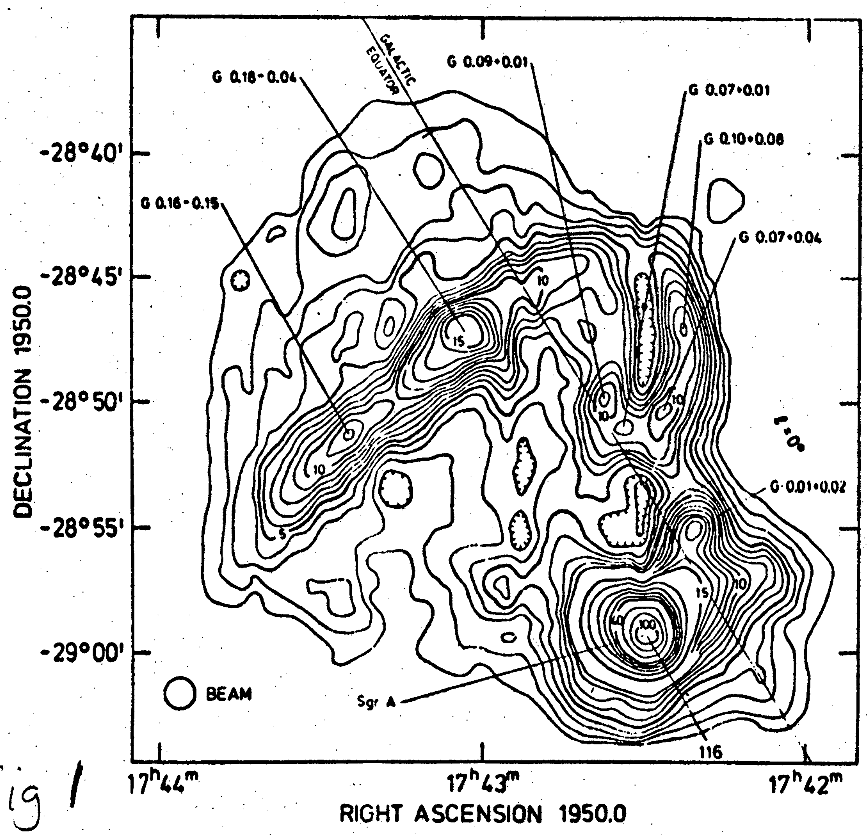


Fig 1

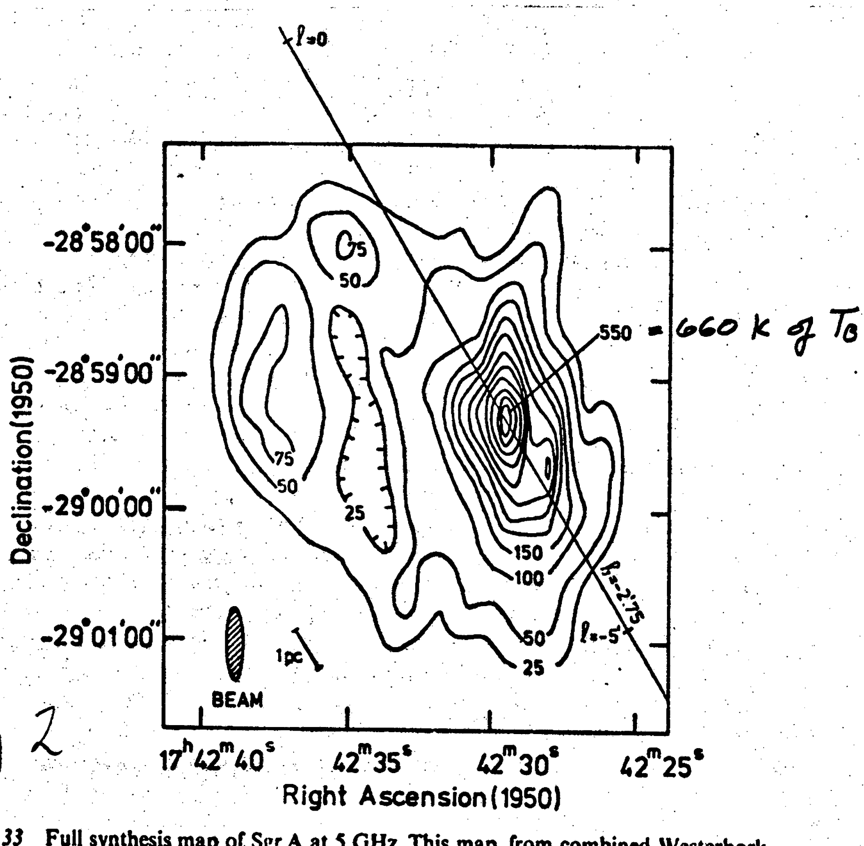
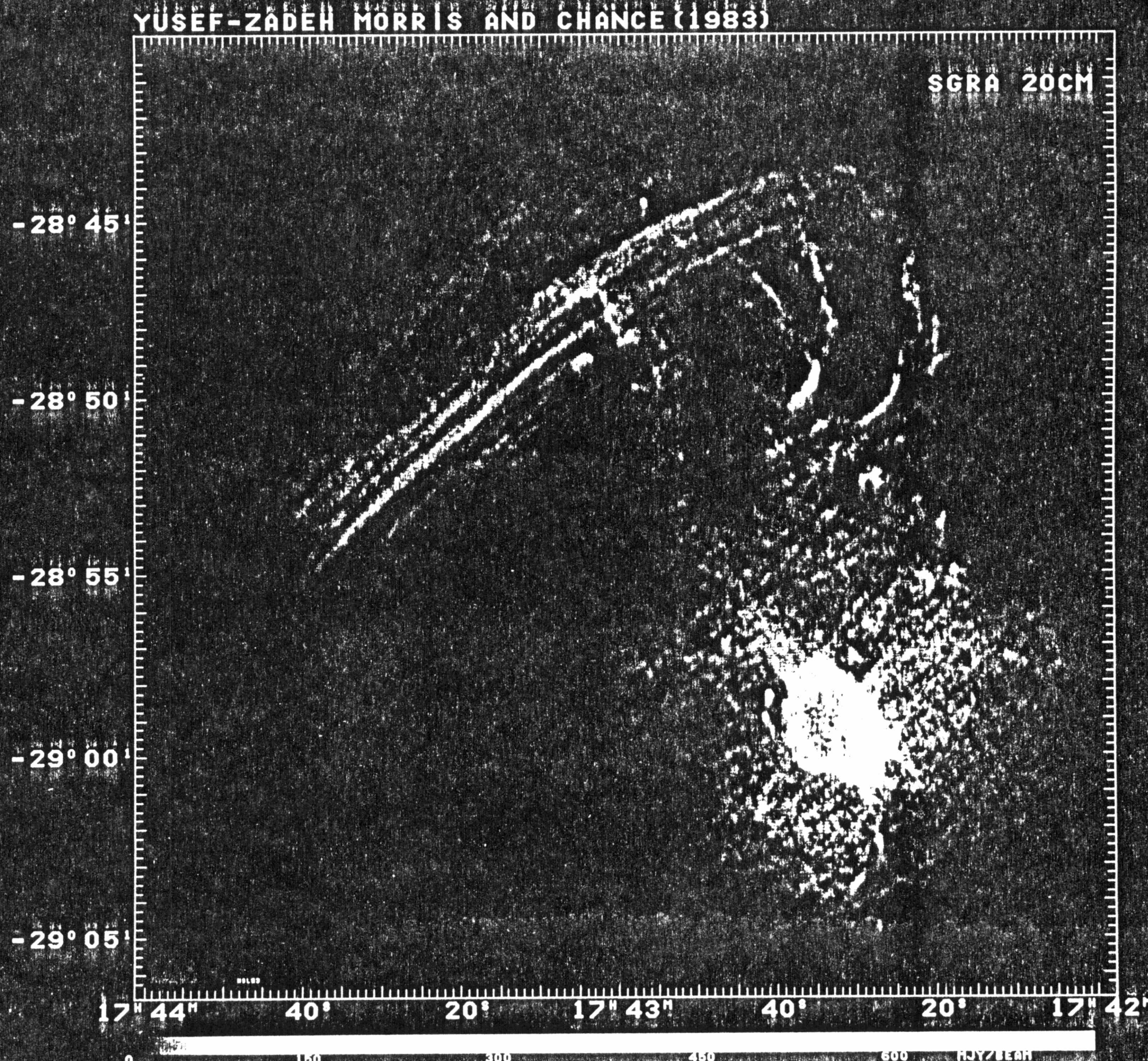


Fig 2

Figure 33 Full synthesis map of Sgr A at 5 GHz. This map, from combined Westerbork-Owens Valley Radio Synthesis Telescopes, is sometimes referred to as the "WORST" map. Half-power widths of synthesized beam 6.^{s}3 × 34" ($\alpha \times \delta$); contour unit 1.2 K in brightness temperature. The zero contour corresponds approximately to the 60-K contour in a 6-cm survey with the Parkes 64-m telescope by Whiteoak & Gardner (1973). The straight line is the latitude circle at $b = -2'.75$, which is probably the real galactic equator; the zero point of galactic longitude is marked; and the center of the concentrated source, which is presumably the actual center of the Galaxy, lies at $l = -3'.34$ (Ekers et al. 1975).

Fig. 3


YUSEF-ZADEH MORRIS AND CHANCE (1983)
SGRA 20CM
-28° 45'
-28° 50'
-28° 55'
-29° 00'
-29° 05'
17H 44M
40S
20S
17H 43M
40S
20S
17H 42M
0
150
300
450
600
MJY/BEAM

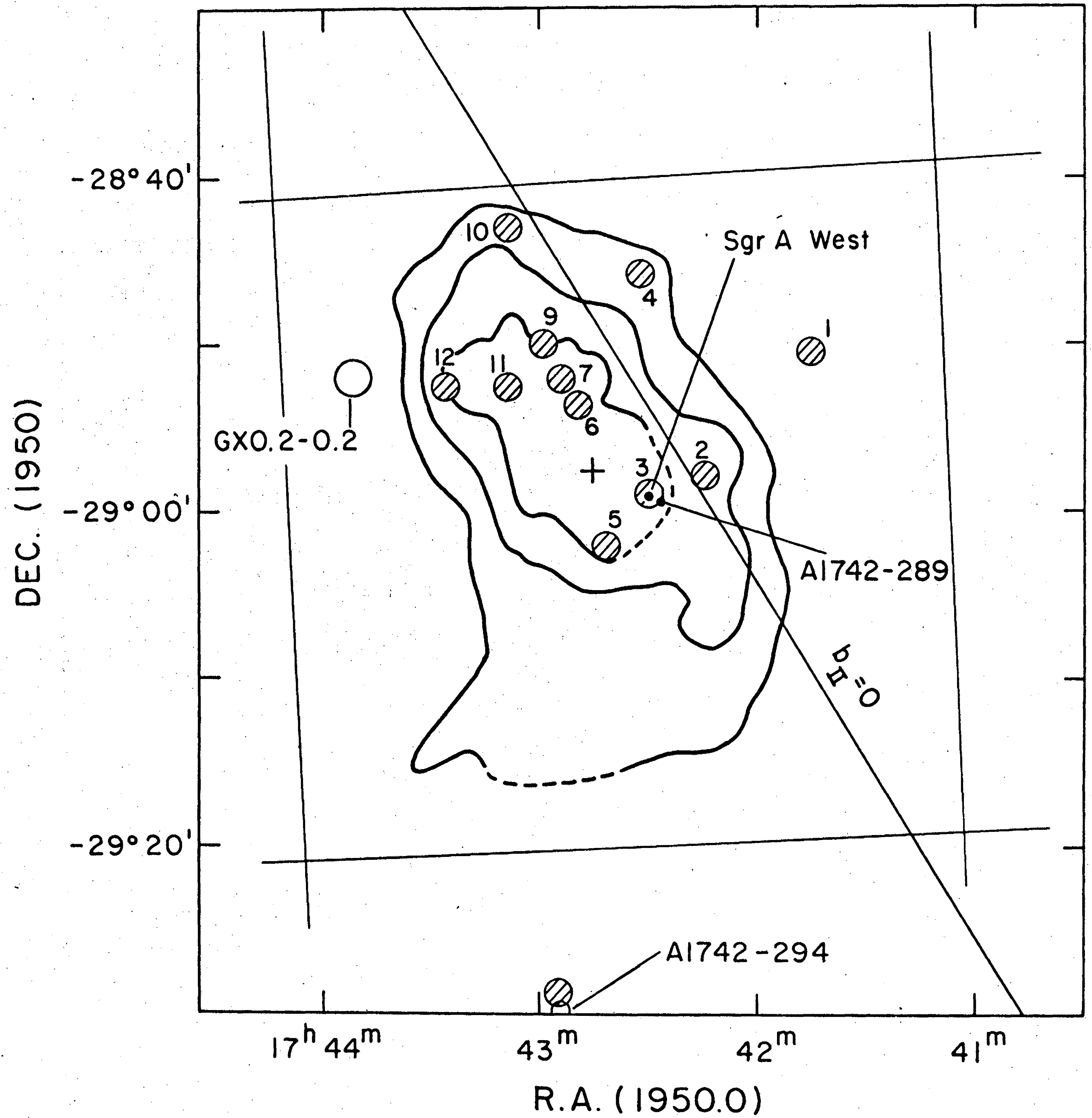
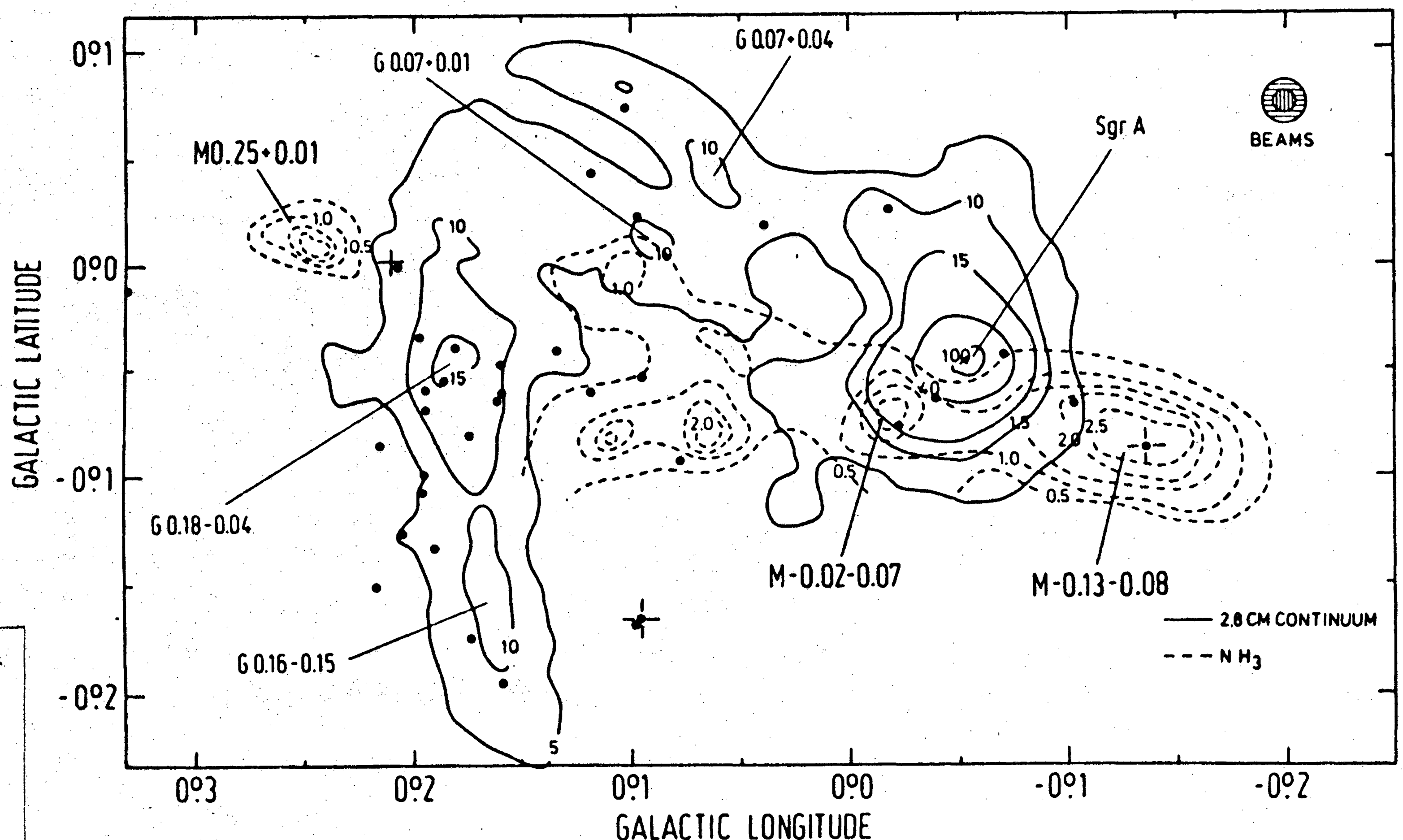

-28°40'
-29°00'
-29°20'
DEC. (1950)
17h 44m
43m
42m
41m
R.A. (1950.0)
Sgr A West
A1742-289
A1742-294
GX0.2-0.2
b_II=0
1
2
3
4
5
6
7
9
10
11
12

Fig 4



G 0.07+0.04
G 0.07+0.01
M0.25+0.01
Sgr A
BEAMS
G 0.18-0.04
G 0.16-0.15
M-0.02-0.07
M-0.13-0.08
2.8 CM CONTINUUM
NH_3
GALACTIC LATITUDE
GALACTIC LONGITUDE
0°1
0°0
-0°1
-0°2
0°3
0°2
0°1
0°0
-0°1
-0°2

Fig 5

Fig. 5

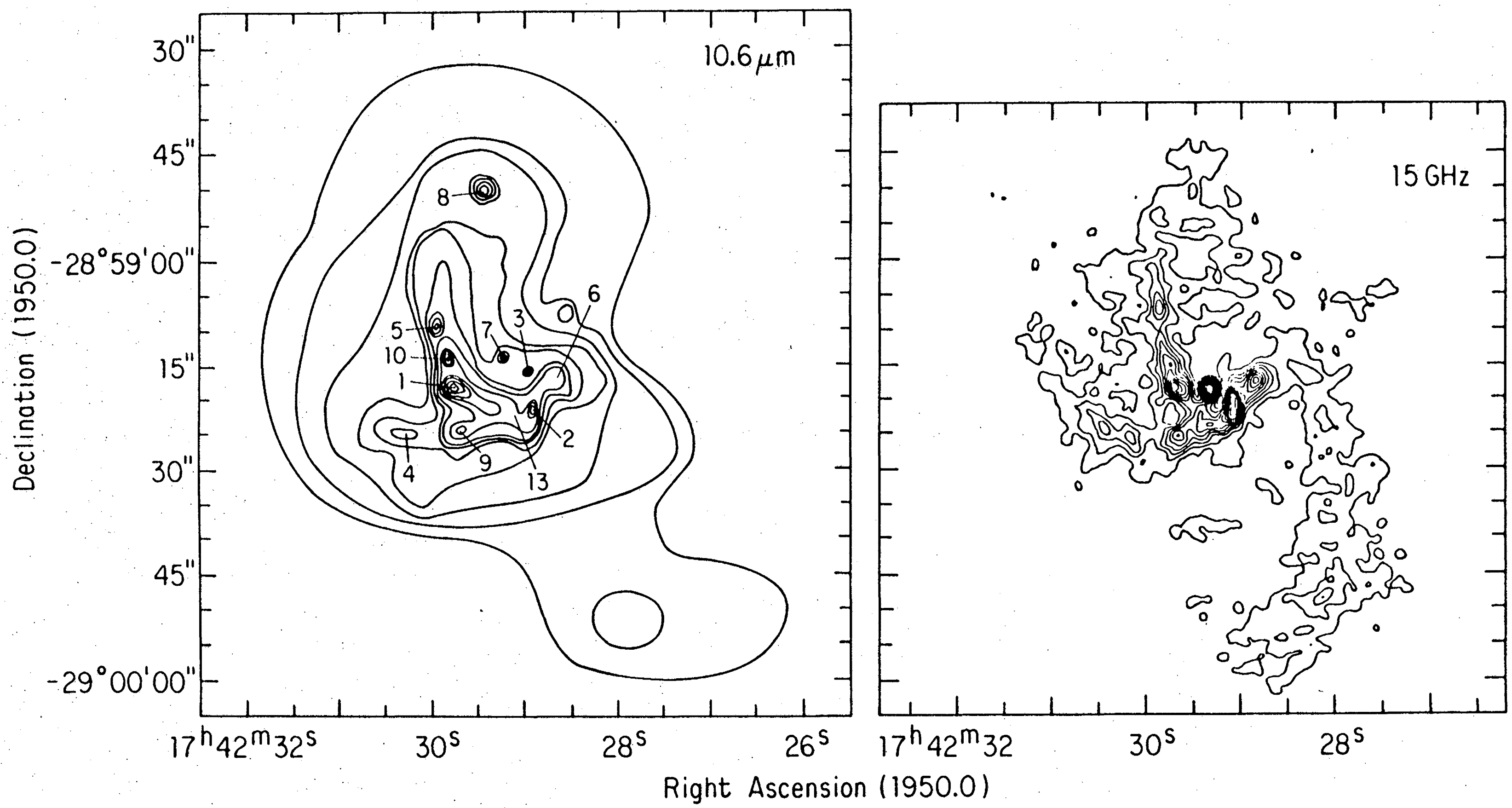
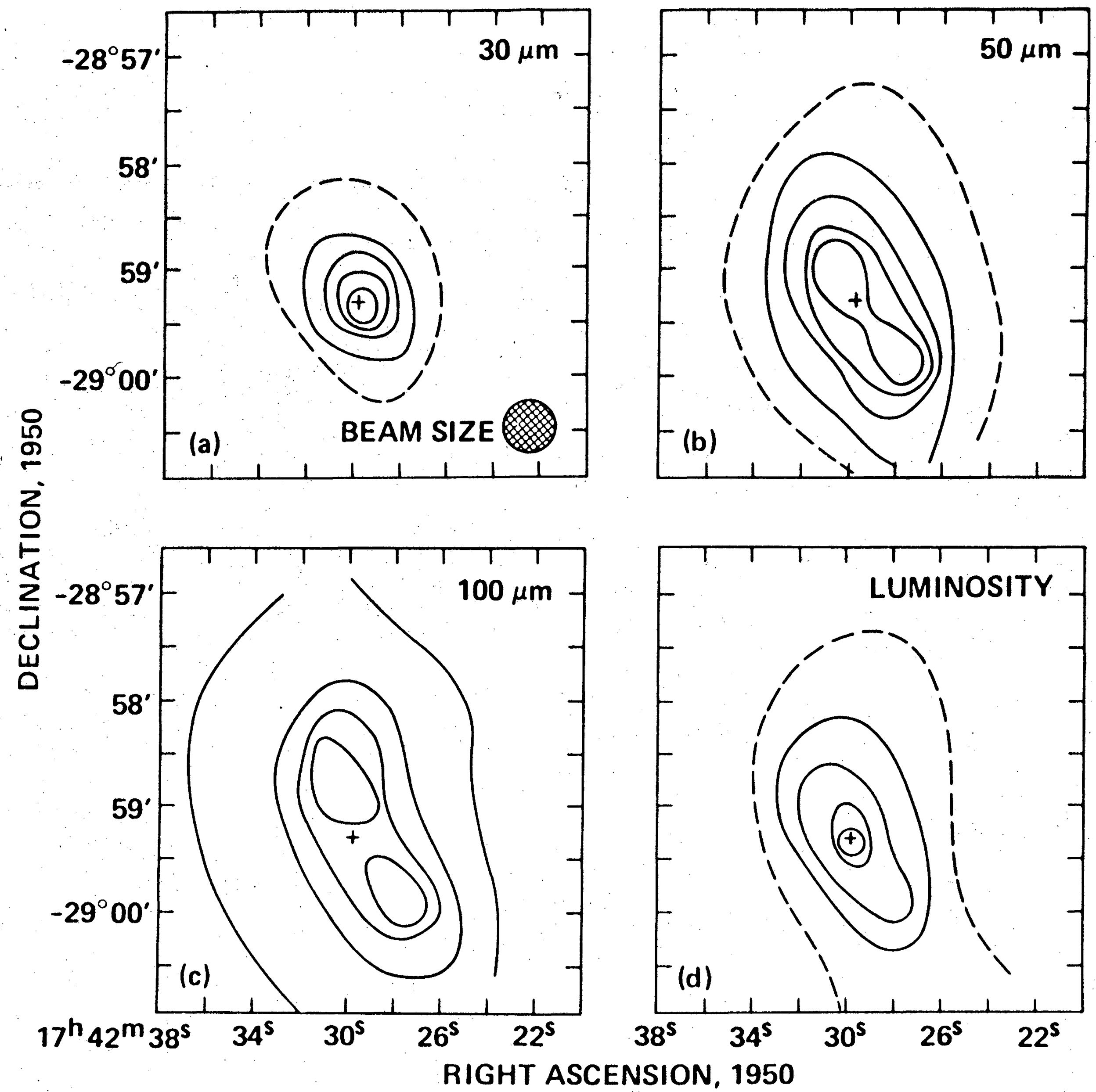

10.6 μm
15 GHz
30"
45"
-28°59'00"
15"
30"
45"
-29°00'00"
Declination (1950.0)
17h42m32s
30s
28s
26s
17h42m32
30s
28s
Right Ascension (1950.0)
8
5
10
1
7
3
6
4
9
13
2

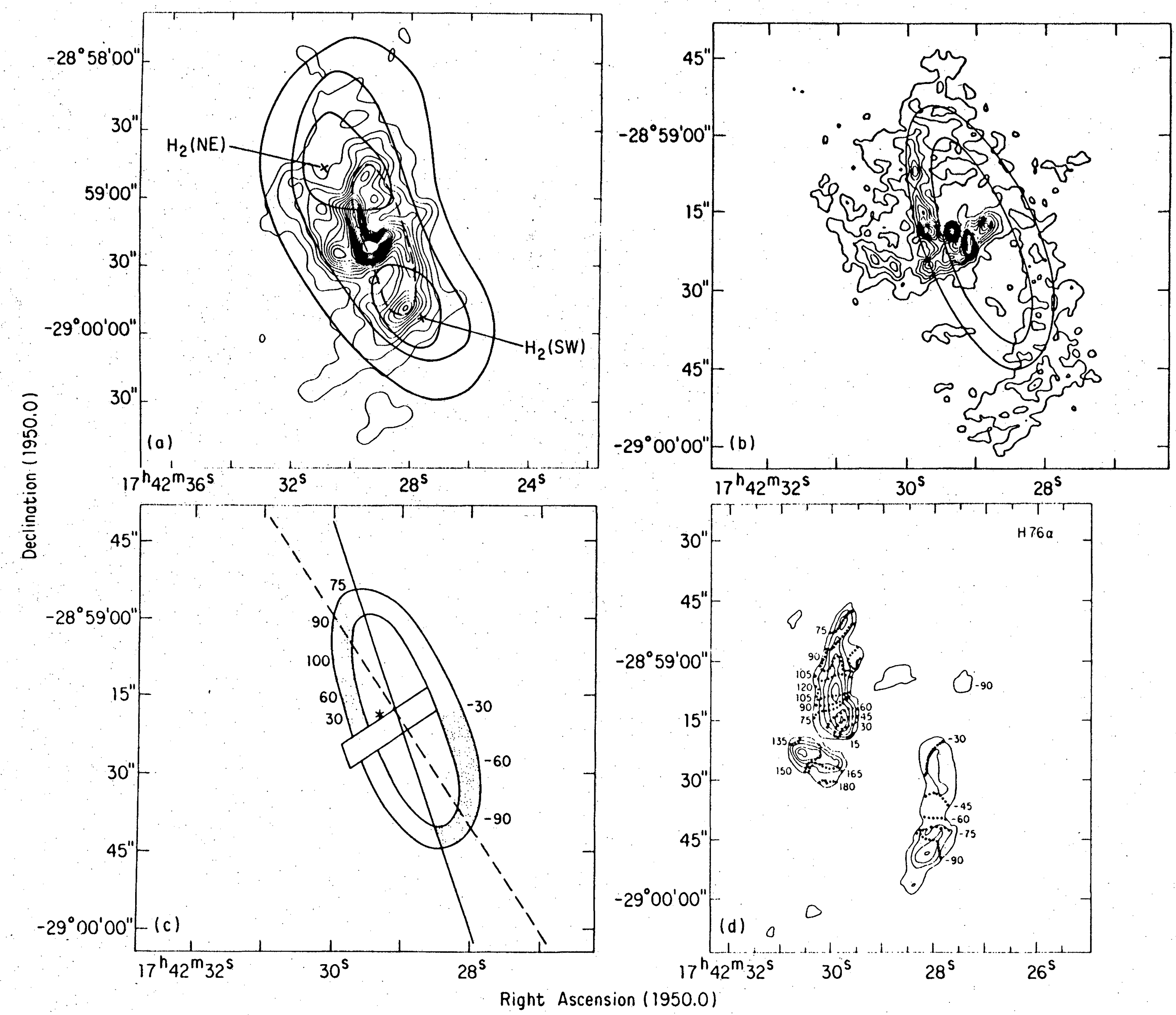
Fig 6



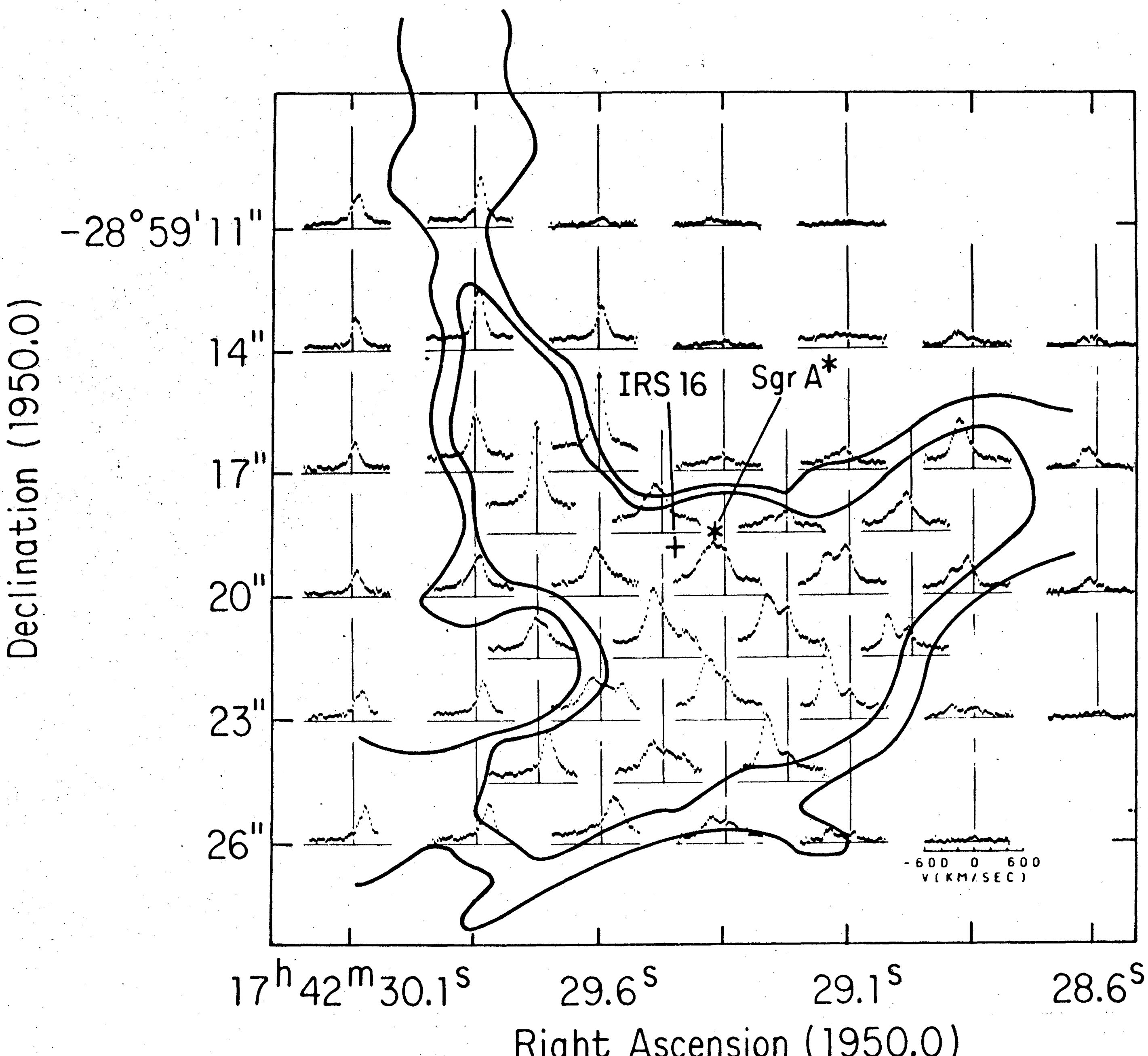
30 μm
50 μm
100 μm
LUMINOSITY
BEAM SIZE
(a)
(b)
(c)
(d)
-28°57′
58′
59′
-29°00′
DECLINATION, 1950
17h42m38s
34s
30s
26s
22s
38s
RIGHT ASCENSION, 1950

Fig 7

Fig. 8

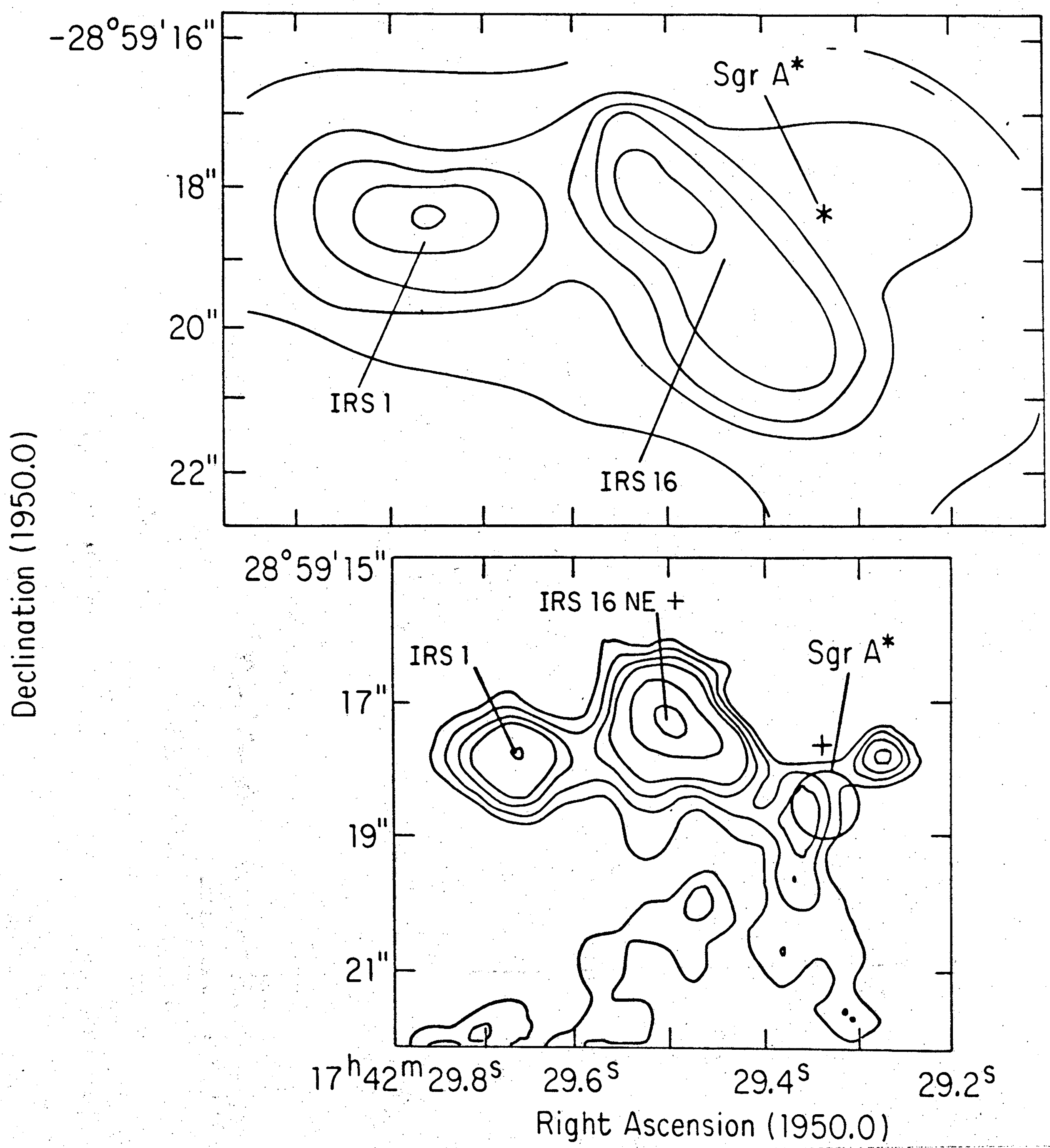


-28°58'00"
30"
59'00"
30"
-29°00'00"
30"
H2(NE)
H2(SW)
(a)
17h42m36s
32s
28s
24s
45"
-28°59'00"
15"
30"
45"
-29°00'00"
(b)
17h42m32s
30s
28s
(c)
75
90
100
60
30
-30
-60
-90
H76α
(d)
75
90
105
120
105
90
75
60
45
30
15
135
150
165
180
-90
-30
-45
-60
-75
-90
26s
Declination (1950.0)
Right Ascension (1950.0)



-28°59'11"
14"
17"
20"
23"
26"
Declination (1950.0)
IRS 16
Sgr A*
-600 0 600
V(KM/SEC)
17h42m30.1s
29.6s
29.1s
28.6s
Right Ascension (1950.0)

Fig 9



-28°59'16"
18"
20"
22"
Sgr A*
IRS 1
IRS 16
28°59'15"
17"
19"
21"
IRS 16 NE +
IRS 1
Sgr A*
17h42m29.8s
29.6s
29.4s
29.2s
Right Ascension (1950.0)
Declination (1950.0)

Fig 10

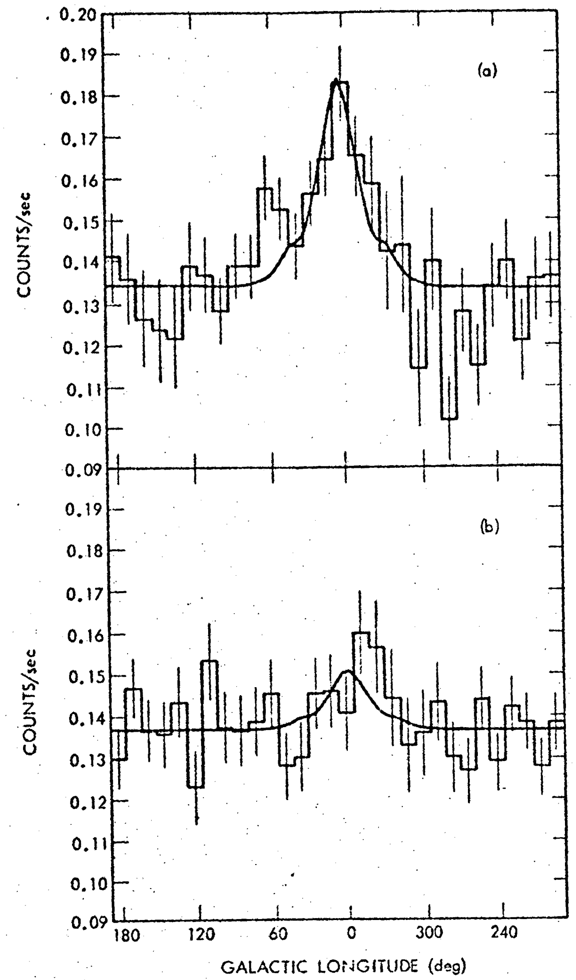


Fig. 1.—Net instrumental and astronomical 511 keV line flux as a function of galactic longitude for the (*a*) 1979 fall galactic plane scan and (*b*) all 1980 spring scans. An on-line bandpass of 8.54 keV was used for the 1979 fall data, and 13.42 keV for the 1980 spring data. The solid lines show the best-fitting background level, source intensity, and source galactic longitude for a point source.

Fig 11