THE GALACTIC CENTER

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Recent infrared and radio observations of the Galactic Center are reviewed. For the region between 1 and 100 pc most of the observed phenomena can be explained by a large density of late-type stars, a ring of molecular material, and a number of regions of active star formation. The central parsec (Sgr A) appears to be a unique region of activity in the Galaxy; this result is based on recent high angular resolution data at 30 to 100 μm and high resolution spectral line observations at 12.8 μm. The observations are discussed in terms of the mass, density structure, and luminosity of the region; the ultimate source of the activity is discussed.

I. INTRODUCTION

The subject of the Galactic Center has recently been reviewed in a major work by Oort (1977). More recent reviews have been given by Wollman (1978) and Lacy (1980). In this paper we will concentrate chiefly on the discussion and interpretation of data obtained since Oort's review, and will further restrict our topic to two particular scale sizes. Firstly we will inventory the types of sources found within the central few hundred parsecs of the Galactic Center. Our purpose is to provide a frame of reference for the interpretation of observations of galactic nuclei such as those discussed at this meeting by Rieke; the Galaxy provides our only realistic chance to resolve spatially the various components within this region. Secondly we will discuss the nature of the central parsec of the Galaxy; again the proximity of the source provides an unparalleled opportunity for detailed study. We will see that this central region is unique in the Galaxy.

The numbers given in this review are order-of-magnitude only. At a distance of 10 kpc our two scale sizes correspond roughly to the central 1° and central ½' of the Galaxy respectively.

C. G. Wynn-Williams and D. P. Cruikshank (eds.), Infrared Astronomy, 281–295.

II. THE REGION 1 < R < 200 PARSECS

a) Near Infrared Observations

The near infrared radiation from the Galactic Center comes predominantly from late type stars (Becklin and Neugebauer 1968). Figure 1 shows the 2.2 μm emission of the central 1°.1 presented in the form of a photograph. As in the larger scale 2 μm maps presented at this meeting by Okuda the emission is extended along the Galactic plane. The peak in the 2 μm surface brightness is the dynamical center of the Galaxy (Becklin and Neugebauer 1968; Sanders and Lowinger 1972). The extinction over much of the region corresponds to $A_V \sim 30$ mag (Becklin and Neugebauer 1968; Becklin et al. 1978b). The presence of patches of rather different extinction has been demonstrated (Rieke, Telesco, and Harper 1978; Becklin and Neugebauer 1978; Lebofsky 1979);a good example is the dark patch in Figure 1 directly below the center, which coincides in position with a molecular cloud (Solomon et al. 1972; Hildebrand et al. 1978). For our purposes the distortion to our interpretation caused by variable extinction is slight.

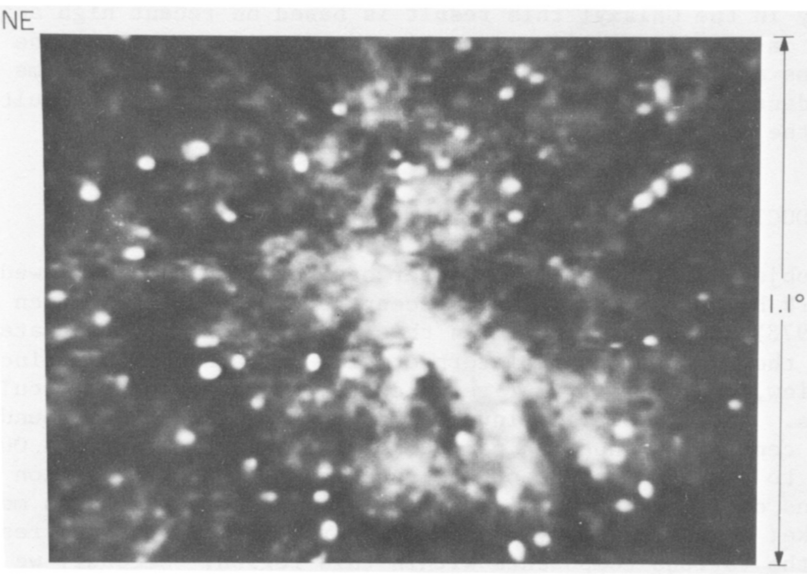

Figure 1. A 2.2 μm map of the central 1° of the Galactic Center in the form of a black and white photograph. The angular resolution is 1'.2 (Becklin, Neugebauer, and Early 1974).

b) Radio Continuum Observations

Figure 2 is a composite map of the radio continuum emission from the central 1° of the Galaxy (Downes et al. 1979); the solid contours

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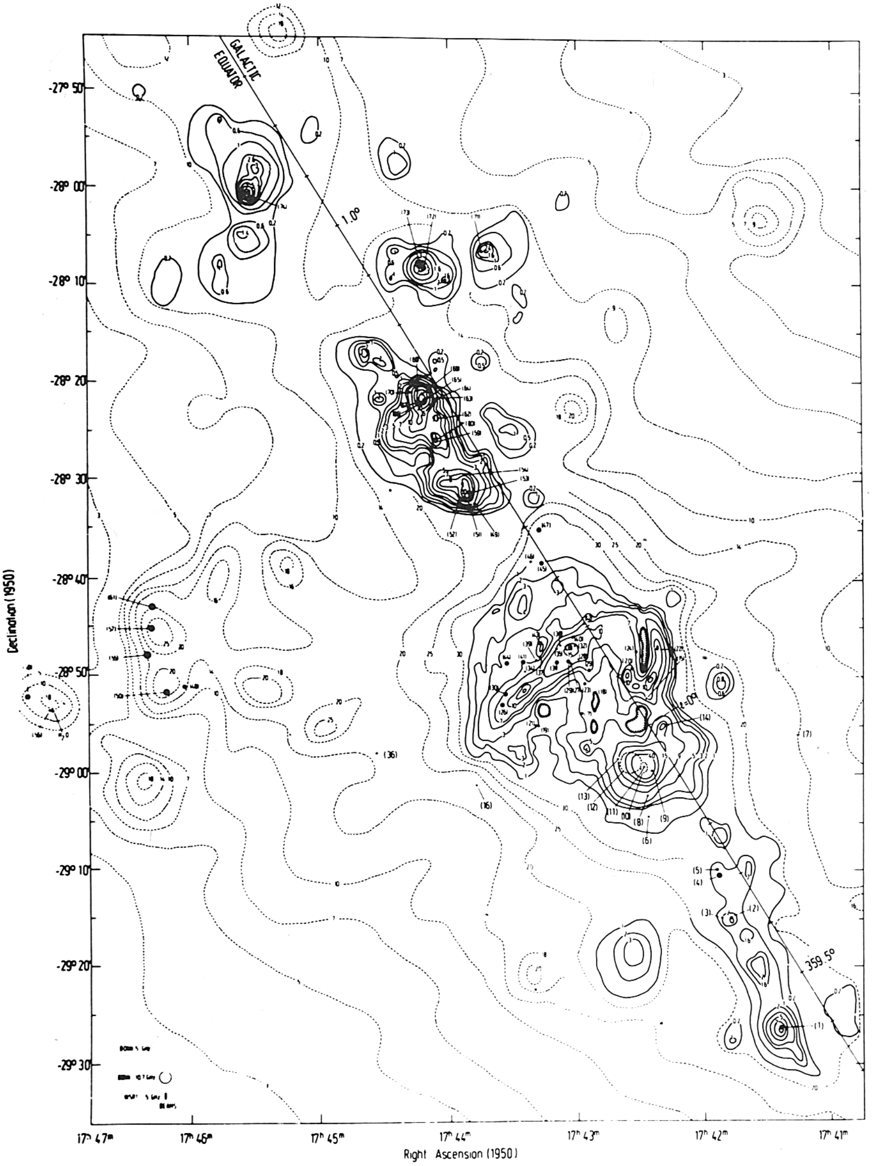

Figure 2. Composite diagram of the radio continuum sources in the Galactic Center region (Downes et al. 1979).

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show the 10.7 GHz flux. The radio emission is also extended chiefly along the Galactic plane. Recombination line measurements (Pauls et al. 1976; Gardner and Whiteoak 1977) show that much of the radio continuum emission is free-free radiation from HII regions; the origin and nature of the extended non-thermal emission will not be discussed here.

The HII region Sgr A (West) (Ekers et al. 1975; Pauls et al. 1976) coincides with the peak of the 2 μm emission, and is located in the Galactic nucleus.

c) Molecular Line Observations

Many authors (Scoville 1972; Kaifu, Kato, and Iguchi 1972; Scoville and Solomon 1973; Bania 1977; Cohen 1977) have interpreted longitude-velocity plots of molecular emission from the central 2° of the Galaxy in terms of an expanding ring of material (see Oort 1977, §5.5). The observations suggest that the ring has a current radius R ∿ 200 pc, an age of several million years, and a total mass of $\sim 10^7$ $M_\odot$ (e.g., Gusten and Downes 1980). If the presence of such an expanding ring is a persistent or recurrent event in the Galactic Center, an average mass loss rate from the inner Galaxy of 1 $M_\odot$ yr^{-1} is required to sustain it.

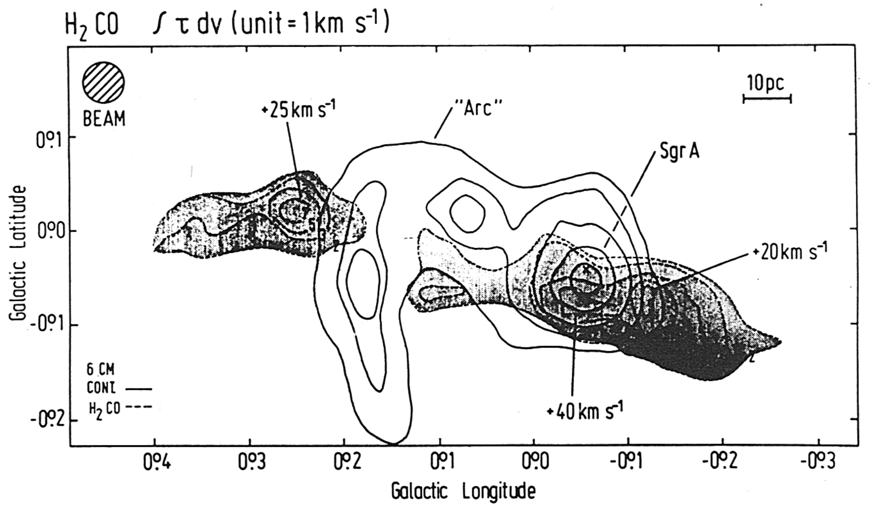

Figure 3. Maps of the integrated H_2CO optical depth of the dense molecular clouds in the vicinity of Sgr A (Gusten and Downes 1980).

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Many discrete molecular clouds are also seen in the Galactic plane; Sgr B2 is a famous example (e.g., Oort 1977). The line of sight location of these clouds is a problem; in particular, molecular clouds are seen near the position of Sgr A. Figure 3 (Gusten and Downes 1980) shows the integrated H_2CO optical depth map superposed on the radio continuum contours (cf. Figure 2). In the past such data have sometimes been interpreted as showing that Sgr A is located in a molecular cloud (e.g., Figure 1, Wollman 1978). This is unlikely to be true. Recent data suggest a model in which no molecular clouds lie within 50 pc of the Galactic center (Gusten and Downes 1980, Figure 4). Dynamical arguments based on tidal disruption considerations give a similar limit if the clouds are to have significant lifetimes.

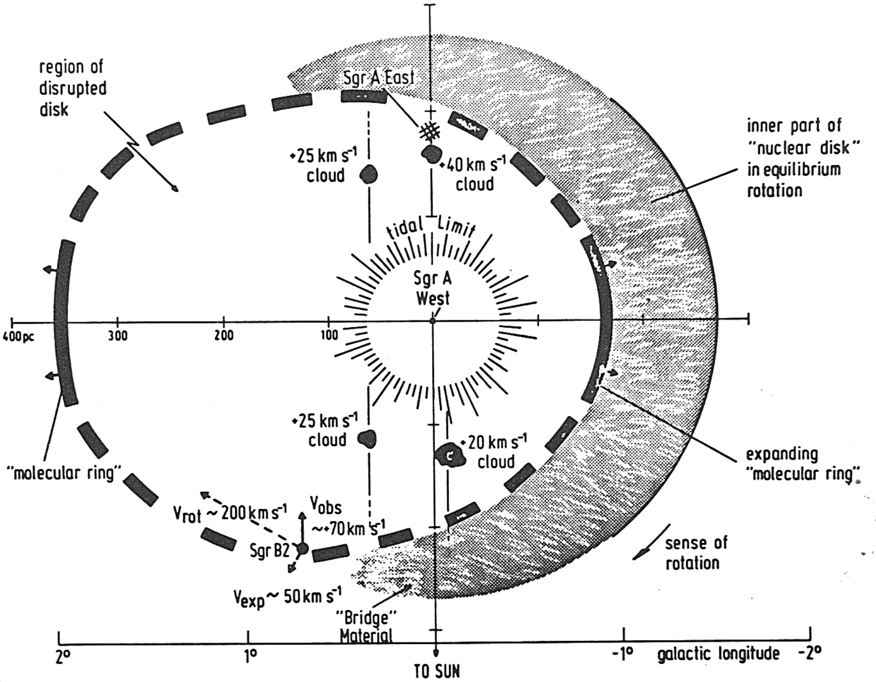

Figure 4. Possible locations of molecular clouds in the Galactic Center region, as viewed from above the galactic plane (Gusten and Downes 1980).

d) Far Infrared Observations

In reviews at this meeting by Okuda and Drapatz we saw that far infrared emission at wavelengths around 100 μm is common throughout the Galactic plane. This radiation is thermal emission from dust heated by starlight. As we saw, much effort has been invested in defining the

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dominant luminosity source in heating the dust. Provided that the absorption optical depth is not less than unity, little power will escape conversion into the far infrared regardless of its source. It is most important to appreciate that the dust density necessary to satisfy this condition is low, and does not imply, for example, densities typical of molecular clouds.

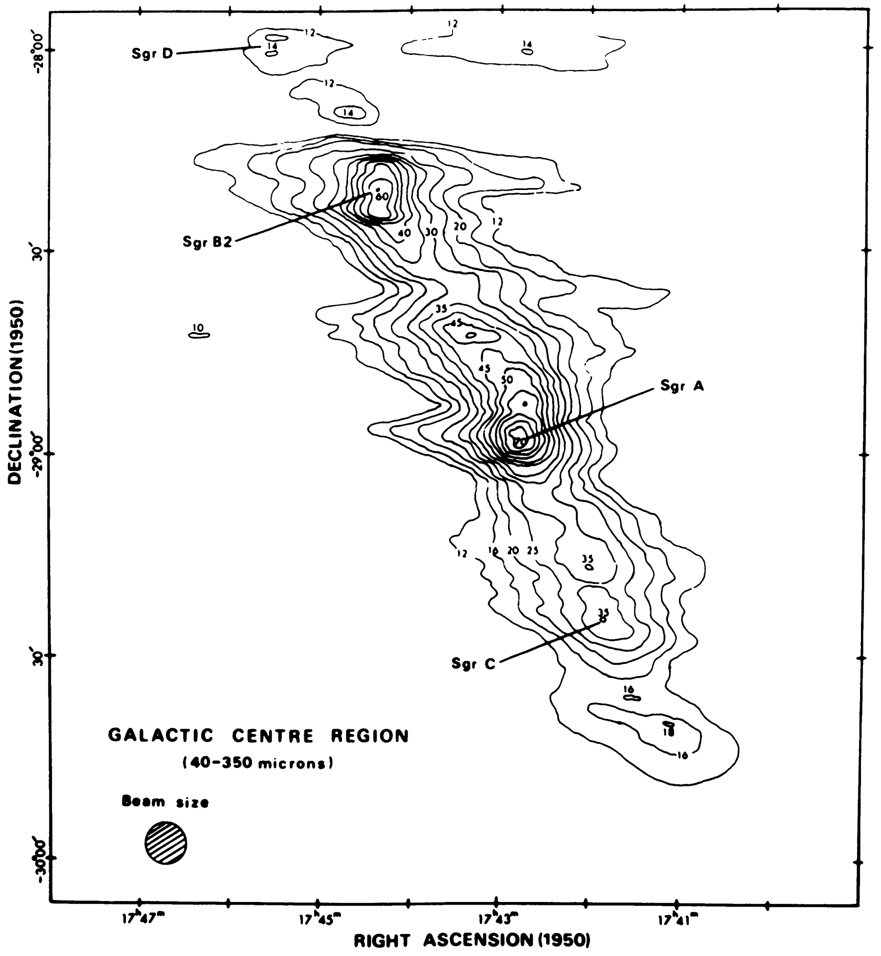

Figure 5. Far-infrared map of the Galactic Center region. Contour unit: 0.95×10^{-10} W m^{-2} (Alvarez et al. 1974).

Figure 5 (Alvarez et al. 1975) shows the far infrared emission from the central 1° of the Galaxy. Again the emission is elongated along the Galactic plane. There is a correlation between far infrared and radio continuum surface brightness (cf. Figure 2). Clearly this is because the luminosity available to heat the dust is locally increased at the HII regions. If the dust density also rises locally, no more luminosity will be available to heat it.

e) Star Formation and Molecular Clouds

There is a correlation between the occurrence of molecular clouds and HII regions in the region 10 < R < 200 pc. For example, Sgr B2 is one of the densest molecular clouds in the Galaxy (Scoville, Solomon, and Penzias 1975) and contains seven HII regions each comparable to the Orion Nebula (Martin and Downes 1972). There is very strong evidence that star formation is occurring at a high rate (Mezger and Smith 1977) in the molecular clouds near the Galactic Center (Gatley et al. 1978; Gusten and Downes 1980).

III. THE CENTRAL PARSEC

The position of the Galactic Center is the peak of the 2 μm distribution (Figure 1) and thus the peak of the density of the late type stars. It coincides with the HII region Sgr A (Figure 2) and a cluster of compact 10 μm sources (Rieke and Low 1973). The supernova remnant Sgr A (East) (Pauls et al. 1976) is not within the central parsec, and will not be discussed. There is an ultracompact non-thermal source (Balick and Brown 1974; Lo et al. 1977) which probably is within the central parsec.

The late type stars within the central parsec provide $L \gtrsim 10^6 L_\odot$ and their mass is deduced to be $\gtrsim 3 \times 10^6 M_\odot$ (Becklin and Neugebauer 1968). The HII region requires $L > 10^6 L_\odot$ in the ultraviolet to maintain the ionization.

The concentration of observable phenomena toward the Galactic Center makes confusion a problem; only angular resolutions of 30" or better can lead directly to understanding of the central parsec. Recent improvements in technology have now allowed study at this level of detail. These observations clearly show that conditions within the central parsec are unique.

a) The NeII Line Observations

The properties of the ionized plasma in Sgr A can be deduced from observations of the NeII line at 12.8 μm (Aitken et al. 1974; Willner 1978; Lacy et al. 1979; Lacy et al. 1980). These observations are of critical importance because they have both high angular resolution and high spectral resolution, which gives velocity information.

Figure 6 shows the central NeII line velocity (Lacy et al. 1980) at the positions of the 10 μm continuum features (Becklin et al. 1978a). The distribution of integrated NeII line intensity is similar in appearance to the 10 μm continuum map of the hot dust.

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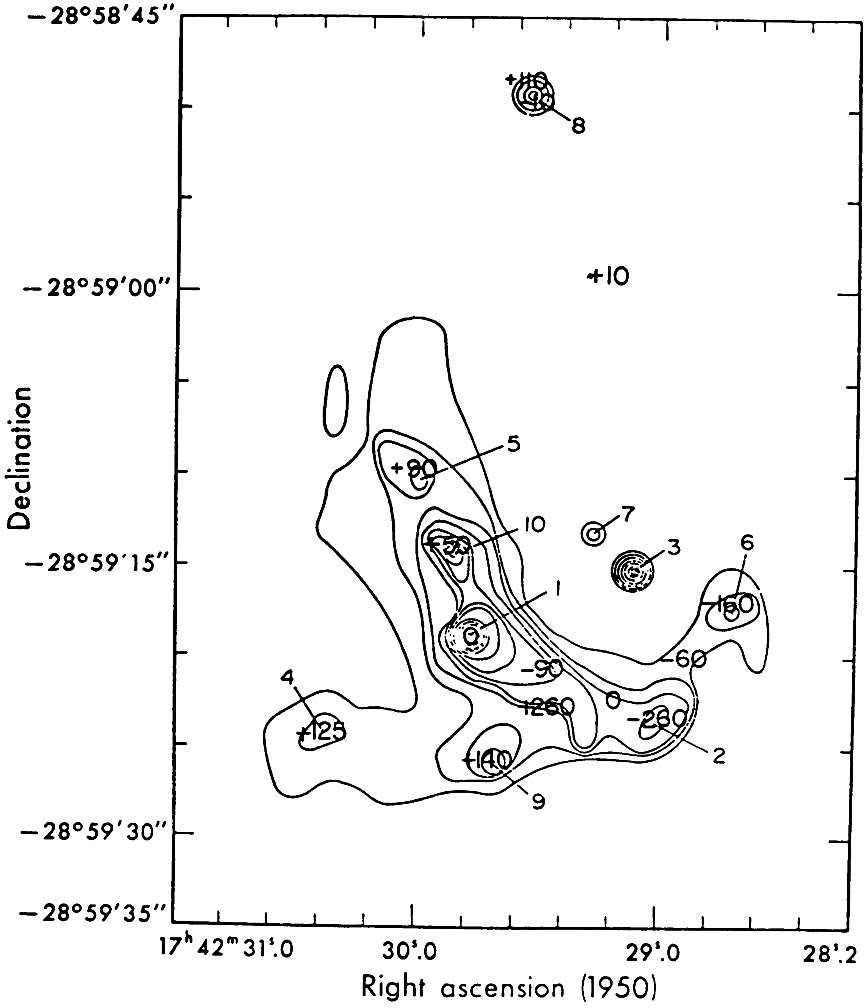

Figure 6. Velocities of the ionized gas clouds superimposed on the 10 μm continuum map (Lacy et al. 1980).

The major results of the NeII line observations can be summarized as follows:

1) The plasma is very clumpy.

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2) The velocities of these plasma clumps are high (200 km/sec, Figure 6).

3) The velocity dispersion in the individual plasma clumps is high (50 km/sec).

4) The plasma excitation is low, implying an effective temperature for the exciting source (if radiative) of $T_{ex} < 35{,}000$ K. (This result follows from observations of fine structure lines other than NeII).

5) A typical plasma clump has

Mass: $M \sim 1\ M_\odot$
Luminosity: $L \sim 10^5\ L_\odot$
Internal velocity dispersion: $\Delta v \sim 50$ km/sec
Size: $D \sim 0.1 - 0.5$ pc
Lifetime: $T \sim 10^4$ years

6) The individual plasma clouds

(a) Show no intrinsic silicate absorption (Becklin et al. 1978a);
(b) Show no unidentified spectral features common in the 3-8 μm spectra of galactic HII regions (Willner et al. 1979; Gatley et al., unpublished);
(c) Are collectively responsible for the bulk of the free-free emission from Sgr A (West);
(d) Fill only a few percent of the total volume of Sgr A (West).

7) The most likely source of the gas in the plasma clumps is mass loss from the late type stars. There must also be a gas sink, in order to maintain the very low gas density throughout most of the volume of the central parsec.

In summary, then, the NeII observations clearly show that Sgr A is not a normal galactic HII region.

b) The Far Infrared Observations

In normal galactic HII regions the far infrared measurements will give the total luminosity, as we saw earlier in §1(d). Indeed low resolution ($\gtrsim$ 1') observations of Sgr A (e.g., Gatley et al. 1977) have been interpreted in just this way.

High resolution ($\lesssim$ 30") far infrared observations (Harvey, Campbell, and Hoffman 1976; Rieke, Telesco, and Harper 1978) show a double lobed structure. Figure 7 (Gatley, Becklin, and Werner 1981) shows new 30 and 100 μm maps of Sgr A. The maps reveal the striking result that the 100 μm surface brightness <u>does not peak at the position</u>

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of the center of the Galaxy[1]; the 30 μm surface brightness does peak at the center. Independent of any model, these observations require that the dust absorption optical depth at uv and visual wavelengths be much less than unity within the central parsec of the Galaxy.

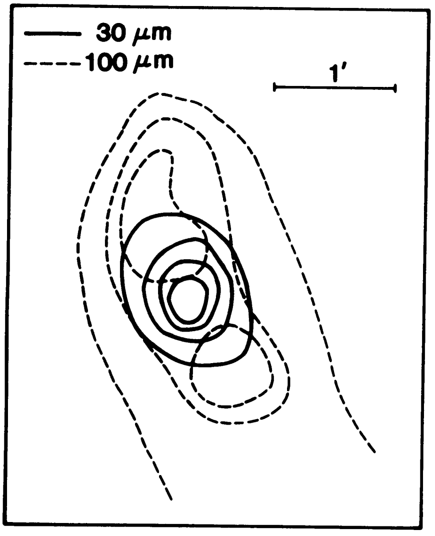

Figure 7. 30 μm and 100 μm maps of the Galactic Center obtained with coincident 30" beams (Gatley, Becklin, and Werner 1981).

The observed double-lobed structure can be generated by a central source of luminosity $L \sim 1 - 3 \times 10^7 L_\odot$. Such a central source is consistent with the observed fact that the far infrared color temperature is highest at the position of Sgr A. This luminosity source can ionize the plasma clumps, suggesting that the individual clumps may not contain luminosity sources. The double-lobed appearance of the far infrared surface brightness occurs naturally if the dust density is very low in the central parsec, and rises beyond 1 pc with the dust somewhat confined in the plane of the Galaxy.

c) The Excitation of the Plasma Clumps

Observations of infrared fine structure lines (Lacy et al. 1980) appear to rule out shock excitation rather conclusively.

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[1] The original paper by Harvey, Campbell, and Hoffmann (1976) contains a positional error in declination; all the contours in their Figure 1 should be moved 15 arcsec to the north. This erratum was kindly communicated to us by Dr. Harvey.

Three sources of radiative ionization seem worthy of consideration, namely:

1) Star Formation

The absence of molecular clouds within 50 pc of Sgr A suggests that conditions appropriate for star formation do not currently exist at the Galactic Center. This is not an insuperable objection, as is shown by comparison with the source 30 Doradus in the Large Magellanic Cloud (Werner et al. 1978).

2) Planetary Nebulae

The plasma clumps have been compared to planetary nebula. (Becklin and Neugebauer 1975; Alloin, Cruz-Gonzáles, and Peimbert 1976; Rieke, Telesco, and Harper 1978). There are problems with the production rate, mass, excitation, and luminosity if the sources are planetary nebulae, but the problems of understanding stellar evolution in the environment of the Galactic Center remain to be addressed (e.g., Edwards 1980).

3) Exotic Phenomena

Many of the phenomena observed throughout the central few hundred parsecs can be explained via a single hypothesis, namely a central object currently radiating $\sim 10^7 L_\odot$ largely in the soft ultraviolet, and capable of periodic outbursts. This exotic object can be responsible for:

(a) The excitation of the plasma clumps;

(b) The far infrared luminosity;

(c) Removing gas to maintain the low densities either through accretion or expulsion;

(d) The expansion of the molecular ring at $R \sim 200$ pc through an outburst some 10^7 years ago;

(e) The high rate of star formation, which can be triggered by the passage of the expanding molecular ring;

(f) The occurrence of the ultracompact non-thermal source;

(g) A link between the Galactic nucleus and active nuclei observed in other galaxies.

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DISCUSSION FOLLOWING PAPER DELIVERED BY I. GATLEY

BLITZ: A recent article by Burton and Liszt uses elliptical streamlines to successfully model the tilted distribution of molecular gas seen toward the Galactic Center. It therefore appears unnecessary to require an explanation for the radial motions of this molecular gas (i.e. expansion) in the Galactic Center. That is, such motions may not exist for the overwhelming majority of molecular gas.

GATLEY: That is certainly a possibility, and the interpretations of the dynamical data are by no means unequivocal. In particular, Oort (1977) in his review lists various phenomena at larger radii which indicate that an explosion has taken place.

BLITZ: Oort pointed out a discrepancy of a factor of 10 (greater, in fact, according to more recent observations) between the extinction derived toward the Galactic Center from the infrared observations, and those implied by CO observations. Do you have any new thoughts on this problem?

GATLEY: While the extinction through a typical molecular cloud is certainly much larger than 27 magnitudes, the data indicate that these clouds are displaced from the peak of Sgr A, and that there is no such cloud in the line of sight to the center.

HYLAND: What kind of exotic object do you postulate as the power source for the Galactic Center?

GATLEY: The neon velocities can be interpreted to give a limit on the mass of a central object. Two possible distributions of matter have been suggested by the Berkeley Group. One is a uniform distribution of stars following the contours of the 2 μm profile, giving some 10^7 $M_\odot$ of stars. A second model comprises, in addition to the stars, a compact 3×10^6 $M_\odot$ object at the center. According to those authors, a black hole accreting 10^{-5} $M_\odot$ yr^{-1} will emit very close to the luminosity and the exciting spectrum we require to explain both the far infrared luminosity and the ionization we see in the plasma clouds.

HOLLENBACH: A fundamental problem with having a single ionization source in the Galactic Center is that it should be brighter at 2 μm than any observed source. This is true for an accretion disk around a massive black hole as well as a single blackbody source with $T < 35\,000$ K.

GATLEY: If you tilt your accretion disk so that its axis is along the axis of the Galaxy, does this reduce its 2 μm flux density to the level of IRS 16, the source which coincides with the VLBI radio source?

HOLLENBACH: We need more than a factor of 10, and we have doubts about the validity of tilting the disk in the direction you suggest, because the neon data are indicative of rotation in quite a different direction to the rotation axis of the Galaxy.

GATLEY: I would answer that by saying that firstly the neon data are based on only about 14 points. Secondly, the plasma clouds are young objects so that the velocities of the gas reflect the motions of the objects producing the gas, not the overall infall motions towards the center.

T. L. WILSON: Determining the lifetimes of the clouds by dividing their diameters by their expansion velocities is open to question. Such an argument applied to Orion gives a dynamical age much less than the age of the stars.

SCOVILLE: Also, if each H II region has a lifetime of about 10^4 years and 1 $M_\odot$ of gas, I do not see how you would produce enough material out of them to give the 1 $M_\odot$ yr^{-1} needed for the expanding molecular ring.

GATLEY: I agree with you. Either there has to be some sweeping-up of mass, or else we have to let things accumulate for a length of time. It is interesting that if we take the expected mass loss rate for late-type stars you accumulate more gas and dust than you see over very large-scale sizes out to 100 pc, in only about 10^8 years.

SCOVILLE: Why is this material not ionized?

GATLEY: Perhaps the source of excitation is located in the very nucleus. Also in the plane itself, where the material will accumulate, one will achieve optical depth unity.

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