INFRARED OBSERVATIONS OF THE NUCLEAR REGION

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ABSTRACT

Infrared observations have provided considerable information about the structure and energetics of the galactic center. The stellar bulge dominates the mass and luminosity of the nuclear region. The luminosity of the bulge is strongly peaked toward the center, even within the central parsec. Dust in the nuclear disk absorbs the power output of the central portion of the bulge and reemits it in the far infrared. Near the center, molecular clouds move in a plane apparently tilted toward the Sun. Within the central few parsecs, or core, the inclination may be as large as 45^o. The total power output of the core is about twice that of the bulge population alone. The source of excess luminosity is uncertain, but evidence points to ongoing star formation associated with the Sgr A molecular complex.

1. INTRODUCTION

Becklin and Neugebauer (1968) published the first infrared studies of the center of our Galaxy. Since then, virtually every new development in infrared astronomical instrumentation has been applied in the search for hints about galactic nuclear structure and energetics. The results teach us a great deal about both the galactic center and the capabilities of infrared astronomy.

In describing the galactic center, the nomenclature of Oort (1977) is adopted. The large-scale structures of the nuclear region are the stellar bulge and the gaseous nuclear disk. The disk is about 1500 pc in diameter. Strong infrared emission from dust in the nuclear disk is limited to the region inside $r \simeq 200$ pc. Within this radius, the gas is primarily either molecular or ionized. Molecular clouds lie close to the galactic plane ($\Delta z \simeq 30$ pc), whereas the layer of ionized gas is

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much thicker ($\Delta z \simeq 100$ pc at the center). Since molecular clouds occupy a small fraction of the volume of the region, this inner ionized/molecular portion of the nuclear disk will be referred to as the H II disk.

The central few parsecs is called the core. Its most distinguishing infrared feature is 10μ continuum emission from warm dust associated with the dense ionized gas of the Sgr A West thermal H II region. In any volume about the center significantly larger than the core, the stellar bulge accounts for nearly all the luminosity. Within the core, the total power output is about twice that of the bulge population alone. The source of excess luminosity is uncertain, but various evidence points to star formation.

Almost all the infrared radiation from the nuclear region is optically thin thermal emission from dust. This dust enshrouds the central portion of the bulge and soaks up all the energy radiated at wavelengths shorter than about 1μ. This energy is reradiated in the mid- and far-infrared, a wavelength region in which the properties of the emitting dust are not well known. The small amount of undegraded near-infrared radiation that does penetrate the nuclear dust encounters a comparable or larger quantity of dust in the outer disk. By the time it reaches us, a near-infrared spectrum, which might inform us about some hot source at the center, is so heavily reddened that its shape reflects the shape of the extinction more than that of the emission. Fortunately, improvements in sensitivity and resolution during the past five years have allowed the identification of some luminosity sources on the basis of unambiguous spectral features. Examples are CO-band absorption (→ red giant) and ion fine-structure line emission (→ H II region). These identifications in turn provide checks on the assumptions about extinction. The result is a picture with enough internal consistency to be moderately convincing. Some fundamentals and many details are missing, but the past decade of investigations has provided a solid framework within which the next generation of questions can be formulated.

It is impossible to acknowledge here all the contributions that have been made to the present understanding of the infrared emission from the galactic center. However, several recent papers of broad scope deserve special mention. These can direct the reader to earlier literature. A series by Becklin, Neugebauer, and collaborators (Becklin et al. 1978a,b; Willner 1978; Neugebauer et al. 1978) discusses the core in detail. Rieke et al. (1978) review both the near- and mid-infrared structure of the core and the far-infrared emission from the immediate surroundings. Their paper also provides a rather complete guide to the literature. Gatley et al. (1977) investigate the far-infrared emission from the central few tens of parsecs with attention to determining the far-infrared properties of dust in the region. Krügel and Tutukov (1978) have constructed a model for infrared radiation from the galactic center which incorporates the known essential features and serves as a guide to the general distribution of sources and luminosity throughout the region. Finally, a complete review of both radio and infrared observations of the galactic center is given by Oort (1977).

2. THE BULGE

The bulge accounts for nearly all the mass and luminosity in the nuclear region. Because of the contribution of red giants, the bulge is bright at 2μ, where the intervening extinction is only a few magnitudes. The 2μ brightness distribution has been mapped extensively (Becklin and Neugebauer 1968, 1975, 1978; Ito et al. 1977; Maihara et al. 1978; Oda et al. 1978). It is elongated approximately along the plane and is strongly peaked toward the center. Even within the central parsec, the bulge appears to be an identifiable, centrally condensed structure.

From the distribution of 2μ surface brightness, one might hope to extract the mass distribution. However, the brightness distribution is modified to an uncertain extent by dust in the nuclear region. The 2μ optical depth from the center to the edge of the nuclear disk is probably in the range $0.3 \lesssim \tau_{2.2\mu} \lesssim 1.5$. There is also some uncertainty in the absolute and relative calibration of various 2μ brightness measurements. The radial dependence of the true luminosity density in the central kiloparsec is probably between $r^{-1.5}$ and $r^{-2.0}$, assuming the stellar population is independent of radius.

3. THE H II DISK

The central region of the bulge is bathed in the diffuse thermal plasma of the H II disk (Pauls et al. 1976). Within the central few tens of parsecs, the average electron density is ~ 100 cm^{-3}. Young, hot stars which have recently formed in the central region may account for ionization of the H II disk. The evidence for star formation is mostly indirect, however, and ionization may have a different cause. The matter of star formation will be discussed further in connection with the core.

Dust in the H II disk absorbs the power output of the central portion of the bulge and reemits it in the far infrared. Since reradiation of bulge luminosity accounts for nearly all the far-infrared emission, one can conclude that there is no unidentified, heavily obscured, and dominantly powerful source of energy associated with the core.

Molecular clouds near the center lie close to the galactic plane. They occupy a relatively small fraction of the volume of the region, and probably play a minor role in the thermalization and transport of energy from the bulge. The Sgr A complex is of particular interest, since it is close to the center. Column density estimates and far-infrared observations indicate that this cloud should be opaque at 2μ. If the entire cloud were in front of the center, the 2μ continuum from the bulge would be weak in the direction of any part of the cloud. Since this effect is not seen, most of the Sgr A complex must lie behind the center, as indicated by radio observations (Oort 1977).

4. THE CORE

The central few parsecs, or core, is the site of a variety of phenomena. Background emission from what is apparently the bulge component dominates the 2μ continuum. The compact 2μ source IRS 16 (Becklin and Neugebauer 1975) may be the high-density central condensation of the bulge population. Thus the stellar bulge may be an identifiable structure on a scale as small as 0.1 pc, and IRS 16 may be the dynamical center of the Galaxy. Within the uncertainty of 2", IRS 16 coincides with the radio point source discovered by Balick and Brown (1974).

In addition to the bulge emission there are various compact or point sources bright at 2μ. The detection of CO absorption in several of these identifies them as red giants. One has the luminosity of a supergiant and is probably much younger than the bulge population. Stars have apparently formed recently.

A possible site of star formation is the dense, ionized ridge of the Sgr A West thermal H II region. The southern declination prevents complete high-resolution radio mapping of this cloud. However, warm dust associated with the ionized gas makes the ridge bright at 10μ, and infrared line emission mapping confirms that the ridge is the region of highest emission measure. Hence, the 10μ continuum map (Rieke et al. 1978) is probably a reasonable guide to the distribution of ionized gas in the core.

The Ne II 12.8μ line has been used to map the velocity structure of gas in and near the ridge (Wollman et al. 1977). As in molecular clouds near the center, the velocity dispersion is large and radial motion is indicated. There is also the appearance of rotation with a velocity of about 200 km s^{-1}. The location of the axis of rotation is uncertain by several arcsec but may pass through IRS 16. This is the most direct evidence that IRS 16 is (or is very near) the dynamical center. From these motions, the total mass in the central parsec is estimated to be several times 10^6 $M_\odot$. This roughly agrees with the mass estimated on the basis of the luminosity (Becklin and Neugebauer 1968; Sanders and Lowinger 1972) and is very small compared with the mass of gas which seems to flow in and out of the central region during the lifetime of the Galaxy.

Several bright, compact 10μ sources lie along the H II ridge. They may be the locations of newly formed O stars responsible for local excess heating of the dust. The luminosities of the sources are appropriate for O stars and can account for the ionization of the ridge and immediate surroundings. The total mid-infrared luminosity of the ridge, including the compact sources, is comparable to that of the bulge population within the core.

Since the infrared emission from the compact sources differs in several aspects from that of typical compact H II regions, the identification with O stars is uncertain. The ridge sources are unusually bright relative to the emission measure of the associated gas, and their spectra are abnormally hot. The spectrum of the brightest 10μ source may indicate two components at different temperatures. The ionization excitation of the ridge is rather low considering the luminosities of the stars apparently responsible. Furthermore, ionization could be due to some process unique to the core, eliminating the need for O stars.

On the other hand, many of the observed peculiarities may result from the unique location of the cloud. Because of the large mass of the core, gas dynamics will differ from that normally associated with star formation. Also, the high luminosity density in the core likely results in an unusually high dust temperature. Aitken et al. (1976) have suggested that the low ionization excitation is the consequence of somewhat high metal abundances. Finally, whereas the mid-infrared spectra of compact H II regions are normally affected by dust associated with cool circumnebular gas, the line of sight to the ridge sources seems to avoid most of the associated molecular cloud. Thus, the interpretation of the compact sources as the locations of O stars, while not firm, seems reasonable.

All the 2μ sources identified as cool giants, including the background contribution of the bulge, are reddened by about 30 visual magnitudes (Becklin et al. 1978b). This apparently represents a rather uniform minimum extinction and must be due to dust well outside the core. Patchy additional extinction is seen to correlate in position with the distribution of formaldehyde near the core (Rieke et al. 1978). This finding is significant in light of the conclusion mentioned earlier that most of the Sgr A complex is behind the center.

These observations and the velocity structure of the H II ridge suggest that part of the Sgr A cloud has spiralled around the core and lies in front of and below the center (Fig. 1). Star formation and subsequent ionization is occurring on the inner edge of this toroidal segment. In order to account for the appearance of the ridge, the location of the foreground molecular cloud, and the relatively low and uniform extinction to the 2μ sources, the plane of motion of the cloud near the center must be tilted toward the Sun. The shape of the H II ridge indicates a tilt perhaps as large as 45° within the central few parsecs. According to the observed distribution of formaldehyde, the molecular portion of the cloud depicted in Figure 1 must extend downward at least far enough to cover the radio continuum source Sgr A East ($\sim$6 pc).

5. CONCLUSIONS

The essential conclusions to be drawn from the infrared studies of the galactic center can be summarized as follows: The stellar bulge accounts for virtually all the mass and luminosity of the nuclear region. The luminosity density of the bulge is strongly peaked toward the center. Even within the central parsec, the bulge appears to be a centrally condensed feature. Dust in the nuclear disk absorbs the power output

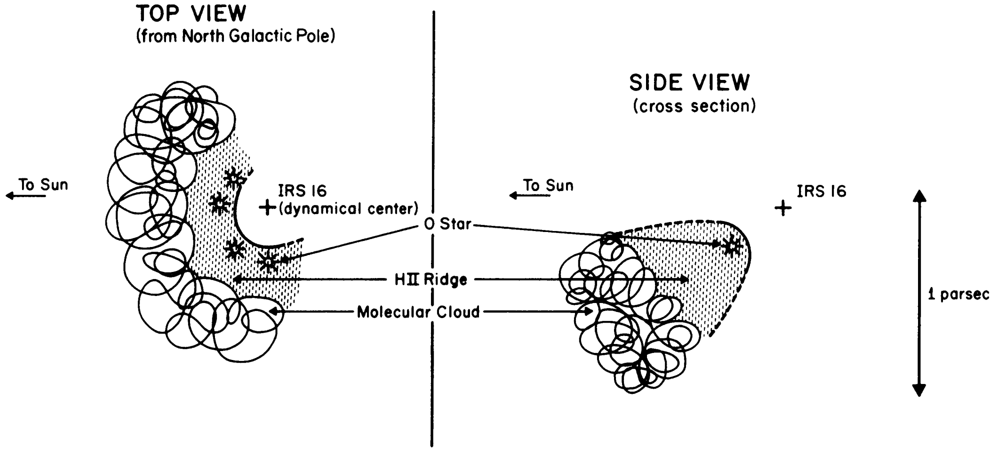

FIG. 1. Suggested location of dense gas in the core.

of the central portion of the bulge and reemits it in the far infrared. The central few parsecs, or core, is not currently a site of violent activity. Nor is it entirely quiescent. The power output of the core is about twice that of the bulge population alone. This excess luminosity may be due to recent or ongoing star formation. Based on the motion of ionized gas in the core, the total mass in the central parsec is estimated to be a few times 10^6 $M_\odot$, in agreement with the mass estimated on the basis of the luminosity. This is much smaller than the total mass of gas that seems to flow in and out of the center during the lifetime of the Galaxy. Various observations suggest that part of the Sgr A molecular cloud is curled around the core and moves in a plane inclined toward the Sun. Within the central parsec, the inclination may be as large as 45°. Star formation on the inner boundary of this cloud can account for the mid-infrared structure of the core.

Among the unanswered questions, that of the mass distribution of the central portion of the bulge may be the most significant. As mentioned earlier, the motion of ionized gas in the core is characterized in part by rotation with a velocity of about 200 km s^{-1}. Approximately the same velocity characterizes rotation throughout the disk, indicating that the radial dependence of the mass density is approximately $\rho(r) \propto r^{-2}$. On the other hand the core may contain unidentified excess mass, and the large-scale density distribution in the nuclear region may be flatter than r^{-2}. Multicolor, near-infrared mapping of the central region of the bulge will help answer this question.

The phenomena that distinguish the core may result from interactions between the disk and the bulge which are not yet understood. More must be learned about the details of star formation and of the compact sources in the core. Because of its unique status as the apparent dynamical center of the Galaxy, IRS 16 warrants special attention. Radio observations can provide a broader multidimentional picture of the nuclear disk. The dynamics of the H II disk is largely undetermined. The motion of molecular clouds in the nuclear region is not yet understood. Both infrared and radio observations indicate that the axis of rotation of gas in the disk may be a function of radius.

Considering the certainty of radial gas flow in the nuclear region, the relatively small mass currently found in the core indicates a roughly balanced circulation of gas in and out of the central region. The ring-like structures observed at radio wavelengths are most likely expanding. The infrared observations suggest that amorphous clouds such as Sgr A and Sgr B are making their way into the center. This situation may be a phase in some as yet unidentified cycle of galactic nuclear activity. It is also interesting to consider the possibility that the center of the Galaxy is in an approximately steady state.

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DISCUSSION

Peimbert: Are there emission line observations in the infrared, in addition to those of the neon 12.8μ line, which can be used to determine the degree of ionization?

Wollman: Yes. The S IV 10.5μ line is not seen to a limit that allows only a small fraction of the gas to be highly ionized. The same conclusion follows from observations of the O III 88μ line, which is quite weak. Comparison between the Ne II 12.8μ line strength and the intensities of hydrogen IR recombination lines also indicates that low ionization states account for most of the ionized gas in the core.

Verschuur: The 2.4μ map of Okuda et al. seems to indicate a tilt at the center in a direction opposite to the tilt which Burton and Liszt talked about.

Wollman: That is a possibility. It is also possible that a band of extinction tilted in the same general direction as the CO could produce the observed effect.

Greyber: Would you explain the nature of the intense 2μ source close to IRS 16?

Wollman: Based on its luminosity and atmospheric CO band absorption, this source (IRS.7) is judged to be an M supergiant.

Bok: We have heard from several sides that there may well be a black hole at the center. There has been no mention this morning of this possibility. If there were a black hole, would one then not expect some spectacular effects of this black hole upon the radio and infrared distribution very near the center?

Wollman: The total mass within the central parsec is approximately $5x10^6$ $M_\odot$. The observed radial flow of gas in the nuclear region is quite large--perhaps 1 $M_\odot$ y^{-1}. It seems that under these circumstances, a black hole at the center would grow to be much larger than the observed mass in the core. I consider this evidence against the existence of a black hole at the center.

Oort: It may be confusing to talk about a "dynamical" center of the Galaxy which is quite different from the position of Sagittarius A West. I believe that there is direct evidence for the existence of a center of mass at the position of the ultra-compact radio core. This evidence comes from the motions of the Ne II condensations that are observed in the region of $\sim$ 1 pc radius around the compact core. These motions indicate that there is a mass of about $5x10^6$ $M_\odot$ within 0.5 pc.

Burton: Although it seems difficult to argue against the identification of the infrared centroid with the center of the galactic mass distribution, it is puzzling that the central longitude of the large-scale CO patterns is some 10' distant. The plane b = 0° and the direction l = b =10° have earlier been derived from the location of the HI density and velocity centroids. The λ21 cm line provides insufficient resolution to provide the detailed location of the center, but the 1'-resolution CO data are useful for this purpose. Because the CO gas motions are presumably ordered by gravitational forces, and because they show such a clear, symmetric kinematic pattern, it does not seem unreasonable to think that the center of this pattern would coincide with the center of the inner-Galaxy mass distribution.

Wollman: Perhaps the observations are telling us that the distribution of mass does not have a simple azimuthal symmetry. In any event, it is clear that the dynamics of the disk is not yet understood.

Burton: Regarding the location of the dynamical center near Sgr A West: Are you worried that the molecular complexes near there have a large net positive velocity. The molecular complexes are parts of consistent patterns which extend over at least 2°, consequently they cannot be highly localized.

Oort: Couldn't the cloud you refer to have been expelled from the center, and only a small part of it be seen in absorption against Sagittarius A East?

Kerr: I think we should not apply the phrase "dynamical center of the Galaxy" to a particular point until we understand more about the physics of the region.