Galactic Centers -- Ours and Other Galaxies'

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ABSTRACT. Viewed from outside the Local Group, the Galactic Center would be a paragon of ordinariness, both with regard to its stellar population and its nonstellar emission in the radio, infrared, and X-ray. Nonetheless, at a very modest level it shows evidence for many of the processes that we believe dominate the properties of exotic galactic nuclei.

1.The Cosmic Zoom Lens

As we celebrate the wealth of detail observable in the Galactic Center, we should also reflect on the role of similar features in observations of other galaxies. Consider, for example, the famous edge-on Sb galaxy NGC 4565, shown in an image at 2.2μm in Figure 1. Two pixels, a total of 1.2 X 2.4 arcsec, have been whited out near the nucleus of NGC 4565 to illustrate the scale of the smallest resolvable features. The comparable region in the Milky Way is illustrated at 2.2μm in Figure 2, from Glass, Catchpole, and Whitelock (1987). Within the burned-out concentration of stars around the Galactic center in Figure 2, another small area has been blacked out. A map of this region at 2.2μm is presented in Figure 3; we have now zoomed down to the central 1.5 X 1 parsecs , with a resolution of $\leq$ .04 pc (in this review, we take the distance to the Galactic Center to be 8 kpc (Reid 1988), with the corresponding scale of 1 pc = 26").

Much of this conference was devoted to the molecular ring and its contents, all of which extend only slightly beyond the area of Figure 3 and would be far less than a single resolution element in any but the very closest external galaxies. Most of the remainder described observations of subtle large scale features, the detection of which would be far beyond the sensitivity and dynamic range of our instruments trained on any other galaxy. We need a perspective on other galaxies to judge whether these phenomena are likely to be common in the Universe at large, and perhaps to encourage work toward more detailed comparisons that will be possible in the future.

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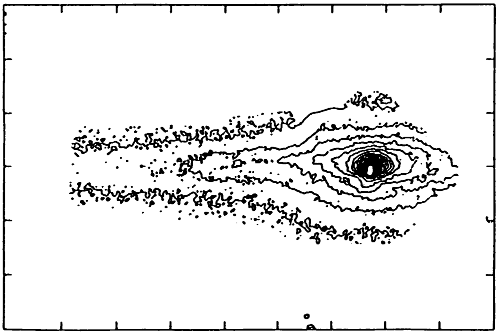

Figure 1. Image of NGC 4565 at 2.2μm. This image is reproduced to resemble the map of the Milky Way by Melnick et al. (1987). Two pixels (1.2 X 2.4 arcsec) have been whited out near the nucleus.

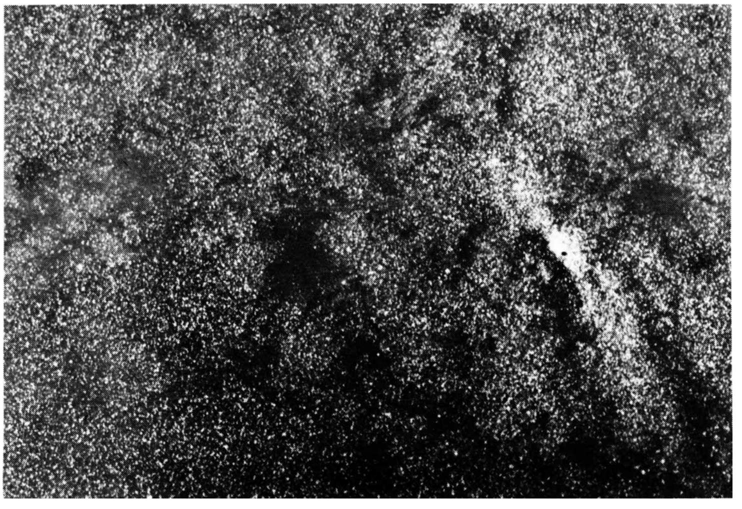

Figure 2. The Bulge and Nucleus of the Milky Way at 2.2μm. The area corresponds to the whited out area in the image of NGC 4565 above. A 40" X 25" region has been blacked out in the burned-out central concentration of stars.
This image is reproduced from Glass, Catchpole, and Whitelock (1987), by permission.

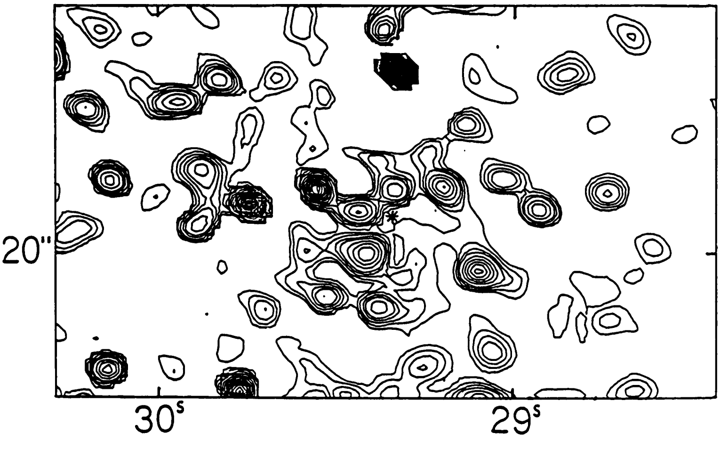

Figure 3. Central 1.5 X 1 parsecs of the Milky Way at 2.2μm. This area corresponds to the blacked out region in Figure 2. The position of Sgr A* is indicated by a *.

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2. The Galactic Center as a galactic center

2.1. The Host Galaxy

The image in Figure 1 has been reproduced to be as similar as possible to the 2.4μm map of the Milky Way obtained by Melnick et al. (1987); a comparison with that work shows the strong similarity except for the later type of the Milky Way as indicated by its less prominent bulge. Thus, if the stellar population of the Milky Way is imaged at a wavelength where the interstellar absorption does not distort our view, it does in fact appear to be a relatively normal Sbc or very early Sc galaxy. This classification is consistent with a variety of determinations tabulated by Hodge (1983).

2.2. The Stellar Population

Other galactic centers are studied most extensively in terms of their starlight as revealed by optical and limited infrared observations. Because of the strong interstellar extinction, the starlight from the Galactic Center was only discovered 20 years ago by observing in the near infrared (Becklin and Neugebauer 1968). Detailed comparisons with the stellar populations in other galaxies are only possible at these wavelengths, ironically where the spectra of most normal galactic nuclei have an extremely high degree of similarity.

The initial studies of the stellar distribution around the Galactic Center found it to agree closely with that in M31 (Becklin and Neugebauer 1968). Outside the central few parsecs, the observations are consistent with a fall-off in surface brightness as r^{-2} or slightly slower. To first order, this distribution is consistent with the Hubble law,

$$\text{Surface Bright.} = a \,/\, (1 + r/b)^2,$$

which is a good fit to the inner shapes of elliptical galaxies and the bulges of many spirals. However, it has become increasingly evident during the past 10 years that, even at 2μm, nonuniformities in the interstellar extinction strongly distort our view of the Galactic Center (Rieke, Telesco, and Harper 1978; Lebofsky 1979; Glass, Catchpole, and Whitelock 1987; Gatley, DePoy, and Fowler 1988), for example being responsible for most of the departure from spherical symmetry within the central few parsecs. Refining our knowledge of the distribution of surface brightness will require careful correction for extinction, which can now be measured through large-scale maps with infrared arrays.

As with external galaxies, there is considerable uncertainty in measuring the core radius, b, of the stellar distribution. If one simply counts bright sources at 2.2μm, the density increases rapidly with decreasing radius to a core of ~0.1 pc (Bailey 1980; Allen, Hyland, and Jones 1983). However, within a radius of 1 pc, there is a population of objects that seem to be unrepresented or extremely rare outside this region -- the components of IRS 16 and the cores of the 10μm sources IRS 1, 3, 5, 6, 8, 9, 10W, and 13 (Becklin and Neugebauer 1975; Rieke,

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Telesco, and Harper 1978; Bailey, Hough, and Axon 1984; Allen and Sanders 1986; Rieke, Rieke, and Paul 1988). If these objects are excluded, the core may be substantially larger; Rieke and Lebofsky (1987) argue from measurements of the surface brightness between bright, individual sources that the core radius may be ~ 0.8 pc. For all other galaxies except members of the Local Group, the distinction between these two core radii would be impossible to make because of the small angular scale involved. For M31, where the lack of a 10μm excess precludes the presence of a cluster of 10μm sources similar to those in the Galactic Center, the surface brightness distribution found by Light et al. (1974) is remarkably similar to that of the Galactic Center from the approach of Rieke and Lebofsky (1987).

The stellar luminosity can be estimated by measuring the surface brightness at positions where the extinction is well-behaved and relatively small, and assuming that the true surface brightness is symmetrically distributed around the nucleus. To keep the exercise simple, I have assumed circular symmetry, a Hubble law surface brightness distribution, and an extinction of $A_V = 30$. Because most of the available infrared measurements of external galaxies use aperture photometers, I have corrected the measurements of the Milky Way to a distance of 3 Mpc and an imaginary aperture of 9 arcsec diameter. Measurements of a number of other nearby galaxies have also been corrected to these assumptions, and the resulting comparison is illustrated in Table 1. Although the Milky Way appears to have the most luminous nuclear stellar population among spirals in the Local Group, it is neither particularly bright nor faint compared with a larger sample of galaxies of similar morphological type.

Table 1. Nuclear Stellar Magnitudes for Nearby Sb and Sc Galaxies#

Galaxy		m_K	Galaxy		m_K	Galaxy		m_K
M31	Sb	9.6	M81	Sb	8.3	NGC 4258	Sb	9.2
NGC 4736*	Sb	7.4	NGC 4826	Sb	8.3	NGC 5055	Sb	8.8
Milky Way	Sbc	9.1	**M33**	Sc	11.9	NGC 253*	Sc	8.5
NGC 2403	Sc	10.3	M51	Sc	8.2	NGC 5236*	SBc	8.5
M101	Sc	10.4						

Members of the Local Group are in boldface

Available measurements have been used to estimate the K (2.2μm) magnitude that would be observed through a 9 arcsec diameter aperture if the galaxy were at a distance of 3 Mpc. Under these conditions and assuming normal galaxy colors, $m_K = 9.0$ implies $M_K = -21.1$ and $M_B = -17.2$.

* These galaxies show evidence for recent starbursts that contribute to their stellar luminosity at K.

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One of the interests in the Galactic Center is that individual stars can be studied to determine the stellar population without appeal to spectral synthesis based on composite spectra containing contributions from many stars. Traditional classification techniques, based primarily on optical spectroscopy, can be applied to within ~ 400 pc of the Center in Baade's Window. Many studies of these stars have been published, the most comprehensive by Frogel and Whitford (1987). They find (see also Terndrup 1988; Rich 1988) a population of old stars, but with a very large range of metallicity. The luminosity distribution of this population extends up to late M giants with M_{bol} ~ -5. Frogel and Whitford argue that these stars are of roughly solar mass but are at the extreme tip of the asymptotic giant branch, which has been extended to such high luminosity by the effects of very high metallicity. These extreme stars must stem from a period late enough in the formation of the bulge that many metals have been produced and injected into the interstellar medium; nonetheless, there is no evidence for stars younger than 5 GYr in this region. Frogel and Whitford suggest that this population be taken to define the population of cool stars in other galaxies without recent star formation. Although eventually one would wish to test this definition, it is a helpful hypothesis at the present level of understanding of stellar populations in other galaxies.

Allowing for the interstellar extinction, this bulge stellar population should begin to appear at $m_K > 9.5$ in the Galactic Center. This prediction seems confirmed by the discovery that Galactic Center stars above this limit frequently show variability that is consistent with their being Mira variables (Haller and Rieke 1988) similar to those that are common in the bulge population (Feast and Whitelock 1987).

Stars brighter than $M_{bol} = -5$ are likely to be more massive than the ones studied in Baade's Window and hence to be younger (e.g., Jones 1987). The proportion of such stars increases significantly from Baade's Window (at ~400 pc) toward the central 10 parsecs radius in the Galactic Center (Catchpole, Glass, and Whitelock 1988). This behavior seems to continue a trend found for both the Milky Way and M31 outside 400 pc (see, e.g., Mould 1986). Many OH/IR stars with characteristics that suggest ages of a few hundred million years are found concentrated in the central ~ 100 pc (Winnberg et al. 1985; Lindqvist et al. 1988). From integrated infrared colors, Soifer et al. (1986) suggest that there is a similar concentration of these stars in M31. The stellar K brightness distribution in the central 15 pc of the Galaxy shows these high luminosity stars as a prominent high luminosity tail in the stellar brightness distribution that has no counterpart in the Baade's Window population (Rieke 1988).

All of these observations suggest the presence of a distinct central stellar population component in both galaxies. Unless there is an extreme metallicity gradient within the central few hundred parsecs of the Galaxy, for which there is no other evidence, the most probable explanation is an intermediate age population of stars within the central ~ 100 pc, with a main sequence turnoff at a few $M_{\odot}$. We know that such populations are a relatively common feature in the centers of spiral galaxies (e.g., Pritchet 1977; Frogel 1985).

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2.3. Other Emission Mechanisms

2.3.1. Radio. The survey by Hummel et al. (1985) of radio emission at 1.5 GHz from Sbc galaxies provides a sample for comparison with the Galactic Center. Measurements of the Galactic Center on a physical scale similar to that achieved on the external galaxies can be found in some of the pioneering radio literature, e.g. Westerhout (1958). The survey of Hummel et al. would have adequate sensitivity to detect a source of the luminosity of the Galactic Center for only eight of the included galaxies; of these eight, four (NGC 2903, 5005, 5055, and 5248) are more luminous than the Galactic Center, two (NGC 4088 and 4258) are similar, and two (NGC 3887 and 3949) have upper limits near the luminosity of the Galactic Center. The galaxies detected at low luminosity have source sizes less than 0.8 and 0.5 kpc respectively, consistent with the size of ~ 0.3 kpc for the Galactic Center.

The structure in the Galactic Center on smaller scales, such as the Sgr A complex, would be very difficult to detect from outside the Local Group at the sensitivity and angular resolution currently available, probably falling completely below achievable limits beyond 10 Mpc. Within the Local Group, both M31 and M33 have been mapped with beams that would include this complex, and the radio emission at 1.4 GHz from each galaxy is more than an order of magnitude less than that from Sgr A (Hjellming and Smarr 1982; Walterbos and Grave 1985; Viallefond et al. 1986). From the comparison with larger scale fluxes in the preceding paragraph, this result shows M31 and M33 to be substantially underluminous rather than the Milky Way to be overluminous.

Given that no analog exists in M31 and M33, detection of the "radio spiral" and other features in Sgr AW would not be feasible in other spiral galaxies. On the other hand, more luminous versions may exist. A particularly interesting case is the flat spectrum VLBI source Sgr A*, which Lo (1987) has compared with sources in M104 and M81.

2.3.2. Molecular Gas. The most generally observed molecular line in other galactic nuclei is the J = 1-0 transition of CO at 115 GHz. In what will soon become a familiar refrain, it is difficult to make comparisons with the Galactic Center on comparable physical scales. For such purposes, the survey of the Galactic Plane at ~ 0.5° resolution by Dame et al. (1987) is particularly useful. Collapsed onto zero Galactic latitude, it shows strong emission > 800 K km sec^{-1} deg^{-1} over the central 350 pc with a peak brightness of 1900 K km sec^{-1} deg^{-1} at Sgr B and a subsidiary peak nearly as bright on Sgr A. Comparison with the survey of optically bright Virgo galaxies by Kenney and Young (1988) shows the central 4 kpc of the Galaxy to lie in the lowest third of their sample in CO luminosity, at or below their detection limit. The possibilities for comparison of smaller scale structures by looking at nearer galaxies are not entirely satisfactory. M31 is virtually devoid of nuclear CO emission (Stark 1979). Outside the Local Group, the central peak in CO in the Galactic Center would be an unresolved point with most existing single dish measurements. The case of M51 strikes a cautionary note in interpreting such data; single dish observations (Scoville and Young 1983) show a strong central CO concentration, whereas interferometer data at higher angular resolution (Lo et al. 1987) demonstrate that the inner 600 pc is largely free of CO and the apparent central concentration actually results from a circumnuclear ring or spiral arms.

2.3.3. Far and Mid Infrared. Although IRAS has provided us with far infrared measurements of tens of thousands of galaxies, comparisons with the Galactic Center are severely limited by the angular resolution of this survey. For example, the beam width at 60μm projects to ~ 1.3 kpc at a distance of 3 Mpc. The integrated far infrared luminosity of the Milky Way is ~ 1×10^{10} $L_{\odot}$ (Cox and Mezger 1988; Nishimura, Low and Kurtz 1980), a typical to slightly high level of activity for galaxies of similar type (Rieke and Lebofsky 1986). About 10% of this energy comes from the central 2 kpc (Nishimura, Low, and Kurtz 1980).

The far infrared emission in the Galactic Center is very similar in structure to the nonthermal radio output (e.g., Odenwald and Fazio 1984). This behavior is as predicted by the tight correlation between integrated far infrared and radio flux densities for external galaxies (Helou, Soifer, and Rowan-Robinson 1985). Some correlation might be expected since the radio flux is generated by cosmic rays which in turn probably originate from supernova explosions that are a measure of the number of recently formed stars, and the far infrared arises from heating of dust by recently formed stars. However, a full explanation of the observed very tight proportionality has not been put forward.

The Milky Way as a whole as well as the central 350 pc also fall within the proportionality between CO and far infrared luminosity observed for other galaxies (Young 1988). This correlation arises because the CO is a measure of the amount of molecular gas suitable for star formation, and the far infrared measures the rate of formation. In general, the Galactic measures fall toward the inactive, low dust temperature side of this correlation. Thus, the efficiency in formation of stars from molecular gas in the Galactic Center (i.e., central 400 pc) is similar to that in the larger regions observed in far infrared and CO in other relatively quiescent galaxies, and the heating of the dust responsible for the far infrared emission is probably to a significant extent from relatively hot and young stars. Given the low luminosity of the region the cool stellar population may make an important additional contribution to the heating, but not enough to disturb the CO/IR correlation.

The far IR survey of Nishimura, Low, and Kurtz (1980) and the CO one of Dame et al. (1987) are presented as collapsed onto the Galactic Plane and at similar resolution of 0.5°, making them easy to compare. Both measures are strongly peaked on the Galactic Center with a FWHM of ~ 400 pc. Within a factor of two, the longitudinal distribution of CO and far infrared emission track each other over a diameter of 10 kpc or more, suggesting a detailed correspondence between amount of molecular matter and the rate of star formation. As expected, areas near individual luminous HII regions are shifted toward the more active, high temperature side of the CO/Far IR relation. An additional comparison in two dimensions and with IRAS data is given by Dame et al. (1987).

Groundbased measurements in the mid-infrared, particularly at 10

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and 20µm, can give insight to the structure of nearby galactic nuclei on a scale of ~ 100 pc, potentially including hints of infrared clusters similar to that in Sgr AW. A comparison with nearby galaxies (Rieke and Lebofsky 1982) shows the Galactic Center to rank relatively high in small-scale 10µm luminosity, but still an order of magnitude below the brightest nearby galaxies, M82 and NGC 253.

2.3.4. X-Ray. Watson et al. (1981) report soft X-ray imaging of a 1^o X 1^o field centered on the Galactic Center. They find a diffuse component roughly 35 X 70 parsecs in size, lying along the Galactic plane, and emitting ~ 400 L_o between 0.9 and 4.5 kev (correcting their luminosity estimate to a distance of 8 kpc). Within the diffuse source are 9 compact objects (beam size ~ 1') emitting ~ 70 L_o, of which Sgr AW accounts for 40%. Among spiral galaxies, only M31 (van Speybroeck et al. 1979) and M33 (Markert and Rallis 1983) have been imaged at an adequate physical scale to isolate structures of the size of the Galactic Center diffuse emission. The nuclear X-ray luminosity in the former case is ~ 2 X 10^4 L_o, and in the latter ~ 3 X 10^5 L_o, in both instances lying within the projected diameter of the Einstein HRI beam of ~ 15 pc. Given the absence of any other indications of activity, it is remarkable that the nuclei of M31 and M33 outshine that of the Milky Way by 2 to 3 orders of magnitude in the X-ray.

Fabbiano and Trinchieri (1985) find a correlation between the stellar near infrared and X-ray luminosities of spiral galaxies. The ratio of X-ray to H-band luminosity in the Galactic Center is an order of magnitude less than the average for other galaxies. This result suggests that the corrections to the low energy X-ray flux due to spectrum and interstellar absorption may have been underestimated; within the errors estimated by Watson et al. (1981), it is possible to bring the ratio just into agreement with those for other spirals. Thus, most of the already weak X-ray emission probably originates from the stars; the Galactic Center seems to be completely free of "active" X-ray sources, except possibly for a few tens of L_o associated with Sgr AW.

Fabbiano (1986) compares the X-ray population of the bulge of the Milky Way with that in the bulges of other nearby spiral galaxies. She concludes that there is a high degree of similarity, with the bulk of the emission originating in binary X-ray stars. A few exceptional galaxies, not including the Milky Way, show an additional bulge or inner disk component that may be associated with recent starbursts.

2.4.Summary

For the Galactic Center as a galactic center, as with the Sun as a star, the most distinguishing characteristic is that we are bound in orbit around it and can study it in the detail which this proximity allows. Neither the galaxy it lies within nor any of its forms of emission lie far from the norm. In accounting for the apparently exotic phenomena we see in the region, we should not violate this perspective.

3. Processes in Galactic Nuclei

Despite the modest level of activity in the Galactic Center, the detail with which it can be observed should provide clues to processes that we can see in distant galaxies because they occur there on a much more dramatic scale. In a way, the very ordinariness of the Milky Way enhances the significance of these clues, since they must then arise through common processes that are likely to operate throughout the local Universe.

3.1. Starbursts

There is now substantial evidence for the presence of very massive and luminous stars within the central 2 pc of the Galaxy. It is generally agreed that IRS 7 is of spectral type M1 or M2 Ia (Lebofsky, Rieke, and Tokunaga 1982; Sellgren et al. 1987). Geballe (1988) has detected CO absorption in the spectrum of this star that requires it to lie in or behind the Galactic Center. Yusef-Zadeh, Ekers, and Morris (1988) and Rieke and Rieke (1988a) find that the star is embedded in ionized gas that can be understood as the mass-loss wind being ionized by the ambient UV field, if the star is within ~ 0.5 pc of the Galactic Center. Because of the short lifetime of such a luminous star, IRS 7 must have formed more or less where we see it. IRS 3 has properties that suggest that it may also be a highly evolved supergiant within the same region (Rieke and Rieke 1988a). If the normal ratio of red to blue stars holds (Humphreys 1978), then there should be roughly 11 blue stars of similar luminosity accompanying IRS 7, and possibly more with IRS 3. These blue stars could contribute a significant portion of the total luminosity and ionizing flux in the region.

There is additional evidence for massive, recently formed stars. Allen, Hyland, and Hillier (1988) report a blue (after dereddening) star with broad He I and weak hydrogen that lies ~ 0.5 pc to the SW of IRS 16. They argue that this object has the characteristics of a Wolf-Rayet star of type WN8 or 9. Some members of the IRS 16 cluster may also be related to late WN stars; this would account for the broad helium line and weak hydrogen (Hall, Kleinmann, and Scoville 1982). However, additional work is required to clarify the stellar evolutionary implications of so many WN stars in this region; moreover, some of the IRS 16 components are exceptionally bright, and they do not show the 4-3 triplet lines of HeI (Wollman, Smith, and Larson 1982) that are expected from such stars (Williams 1982).

In addition, the stellar velocities measured by McGinn et al. (1988) and Rieke and Rieke (1988b) suggest a high rate of rotation within the central 2 pc radius, with the same sense and roughly in the same direction on the sky as the molecular ring. The hypothesis that the stars have formed recently would be strengthened considerably if it can be shown that the molecular ring and the brightest stars within it form a dynamical entity.

The present conditions within the molecular ring should not be conducive to star formation, both because of the absence of dense condensations of gas and because of the strong flux of ionizing photons.

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Struck-Marcell and Scalo (1987) (and others listed by them) have shown that, under fairly general conditions, a system of gas in the central regions of a galaxy will undergo repetitive bursts of star formation concentrated within the nucleus. These bursts are self-quenching and the models suggest that star formation will be suppressed most of the time. Such theoretical modeling may help explain the current state of the Galactic Center within an evolutionary perspective.

3.2. Mergers

It is now generally accepted that mergers have a profound effect on the radio, infrared, and optical properties of galaxies, inducing large bursts of star formation and possibly activating exotic nuclear sources. There is no evidence for large-scale merger activity in the Galactic Center. However, there are two clouds with very high CO luminosities and velocity widths within the central 1.5 kpc (e.g., Dame et al. 1987). It is difficult to account for the energies represented by the velocity widths of these clouds by any mechanisms internal to the clouds or driven by the Galactic Center (Thaddeus, private communication). There is a possibility that these velocities are driven by the kinetic energy of modest sized objects falling into the region.

3.3. Active Nucleus

The presence in Sgr A* of an extremely compact flat spectrum radio source with characteristics that suggest the presence of a black hole (Lo 1987) has raised hopes for a miniature active nucleus in the Galactic Center. The spectra of such sources from radio to X-ray can be crudely characterized by stating that there is equal energy per logarithmic frequency interval (see, e.g., Cruz-Gonzales and Huchra 1984; Landau et al. 1986). The radio and X-ray properties of the Galactic Center are consistent with this possibility.

The X-ray to infrared (Malkan 1984) and radio to infrared/optical (Condon, Buckman, and Machalski 1979) luminosity ratios are tightly constrained and well determined for active sources. The infrared source corresponding to Sgr A* would be at K magnitude ~ 15, well beyond the current detection limits in the heavily confused region around Sgr A* (Allen 1987; Rieke, Rieke, and Paul 1988). Any source of this K magnitude would contribute negligibly to the energetics of the region (see, e.g., Rieke and Lebofsky 1982; Lacy 1982). Of course, this argument does not rule out the possibility of some other type of non-stellar engine powering the Galactic Center.

3.4. Broad Line Region

In view of concerns about the stability of the broad line gas clouds close to the nucleus of a Seyfert 1 galaxy, some have proposed that these clouds are replenished by gas from the outer atmospheres or mass loss winds of late type stars, ionized by the X-ray or UV flux of the nucleus (e.g., Mathews 1983; Scoville and Norman 1988). Even without an active nucleus, this mechanism can operate so long as the ambient UV field is strong enough. Recent observations (Yusef-Zadeh, Ekers, and Morris 1988; Rieke and Rieke 1988a) suggest that such ionization is indeed occurring in IRS 7; future studies of additional Galactic Center stars could provide a more detailed understanding of this proposal for broad line clouds.

3.5. Unseen Mass

The mass in the Galactic Center has now been measured in considerable detail from the velocities of the gas, including the molecular ring (e.g., Genzel and Townes 1987) and the coherent structures seen inside the ring (Serabyn and Lacy 1985; Serabyn 1988). New measurements allow an independent determination from stellar velocities (Winnberg et al. 1985; Sellgren et al. 1987; Lindqvist et al. 1988; Rieke and Rieke 1988b; McGinn et al. 1988). Outside the inner edge of the molecular ring (radius ~ 1.5 pc), all these determinations are reasonably consistent and can be modeled satisfactorily assuming a constant ratio of M/L ~ 2 for the stars (Sanders 1988), in good agreement with expectations from other galaxies. Inside the molecular ring, there are some minor discrepancies which will undoubtedly be resolved as additional measurements improve the accuracy of the various methods.

However, perhaps the most significant points are already clear. First, the measurements exclude an unseen nuclear mass as large as ~ 5 X 10^6 $M_\odot$ for virtually any plausible assumptions in their interpretation. Second, if it is assumed that the stellar mass in the central parsec is associated with the low luminosity stars, and therefore that a core radius of ~ 0.8 pc holds for this mass, then the available velocity measurements taken together strongly suggest the presence of additional mass of a few million $M_\odot$, although its form and distribution within the central parsec remain unclear. These conclusions can be contrasted with the unseen masses of ~ 10^7 $M_\odot$ recently deduced for the nuclei of M31 and M32 (Tonry 1987; Dressler and Richstone 1988; Kormendy 1988), and evidence that larger unseen masses are relatively common in Sc galaxies (Rubin and Graham 1987). Taken together, these results suggest that unseen nuclear mass is a common feature in significant galaxies. However, the Galactic Center may have less unseen nuclear mass than other members of the Local Group. If so, unseen mass is unlikely to be directly responsible for the radio and infrared emission, where the Galactic Center is relatively bright, but may be connected with the bright X-ray source in M31. Since it is not required to produce large amounts of energy, unseen mass in the Galactic Center could take a variety of forms and need not be concentrated into a single, massive black hole.

3.6. Molecular Ring

The variability timescales of the near infrared fluxes from a number of Seyfert 1 galaxies suggest the presence of a circumnuclear cloud about two parsecs in diameter, where dust absorbs a portion of the nuclear ultraviolet output and reradiates it in the infrared (Penston et

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al. 1974; Lebofsky and Rieke 1980). It is likely that angular momentum has flattened this cloud into a disk and the nuclear activity has blown out the center to produce a ring; for example, such a geometry accounts for the small extinction toward the nuclei themselves. Many Seyfert 2 galaxies are evidently similar, but with the circumnuclear ring of gas oriented to block our direct view of the active nucleus (Antonucci and Miller 1985). The scale deduced for these rings is remarkably similar to that of the molecular ring in the Galactic Center; Krolik and Begelman (1988) discuss this analogy in more detail.

Given that such a prosaic galaxy as the Milky Way has a molecular ring with some similarity to those in Seyfert galaxies, it is possible that circumnuclear disks and rings are created and maintained in virtually all galaxies. These features would represent one of the final stages in the feeding of gas into the nuclei of galaxies and hence their presence and characteristics are a key clue to the natures of both nonthermal nuclear activity powered by massive black holes and also compact nuclear starbursts.

4. Conclusion

For astronomers in the Virgo cluster with instruments and intellects similar to ours, the Galactic Center is probably no more prominent than another entry on various lists of "complete samples". Nonetheless, it encompasses much that we have reason to imagine takes place in the centers of other galaxies, and an intimate understanding of these processes is an ample reward for the effort invested in its study.

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