THE LUMINOSITY OF THE CENTRAL PARSEC OF THE GALAXY

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ABSTRACT. The luminosity of the central 5 pc of the Galaxy - encompassing the inner regions of the rotating ring of dust and gas which surrounds the galactic center - emerges primarily at infrared wavelengths in the form of thermal emission from heated dust. The nature and location of the sources which heat the dust can be inferred from the spatial and temperature distribution of the thermal infrared emission (λ>20um), from studies of the ionized gas in this region, and from direct imaging in the near infrared. These observations show that the principal heating sources within this 5-pc region are concentrated within the central parsec of the Galaxy and indicate that the luminosity of these sources is within a factor of two of 10^7 $L_\odot$. The near-infrared observations of the compact sources at the galactic center do not reveal a single dominant source but suggest instead that the several components of the IRS-16 complex, taken together, may contribute the bulk of the luminosity; however, the data also permit a single object to dominate the energetics of this region. We draw attention to the striking morphological similarities between the galactic center and the innermost regions of the 30 Doradus nebula in the Large Magellanic Cloud and speculate that the luminosity sources in the galactic center may resemble the early-type supergiants in 30 Doradus.

1. INTRODUCTION

The phenomena seen within the central few parsecs of the Galaxy challenge our understanding of astrophysical processes and are important as well as links to more distant active galactic nuclei. Knowledge of the luminosity of this region can provide constraints on the nature of these phenomena. The bulk of the luminosity of this central region is observed at Earth in the form of thermal emission from heated dust. Our direct view of the source(s) which heat the dust is obscured by the approximately 30 magnitudes of visual extinction along the line of sight to Sgr A. As a result, we must rely on a variety of indirect arguments to answer the following central questions:

1.1. What is the luminosity of the central parsec of the Galaxy?

1.2. Which objects produce it?

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1.3. What sorts of objects are they?

In this paper, we review the infrared and radio data which bear on these questions. We confine ourselves to estimating the luminosity of the optical and ultraviolet sources which apparently dominate the energetics of this region. We thus neglect luminosity in other forms - gamma-rays, x-rays, mass loss and stellar winds - which are less important quantitatively but which may also provide important clues to understanding the phenomena occurring at the galactic center.

For numerical estimates, we adopt the newly-accepted value of 8.5 kpc to the galactic center and revise older numbers where appropriate; in most instances, distances are reduced by a factor 0.85 and luminosities by 0.72. Using this distance, 1 parsec at the galactic center subtends an angle of 24 arcsec. We adopt as the unit of luminosity the solar luminosity, L_o, equal to $4x10^{33}$ erg/s.

2. THE NEED FOR A CENTRAL LUMINOSITY SOURCE

Although the luminosity of the late-type stars at the galactic center is appreciable - $4.3x10^6$ L_o within the central 1.7 pc radius (Becklin and Neugebauer, 1968) - it is clear that additional luminosity sources are present within the central few pc of the Galaxy. First, the ionized gas in the Sgr A HII region requires at least $1.3x10^5$ ultraviolet photons/sec (Mezger and Wink, 1986), or a minimum luminosity of $7x10^5$ L_o, more ionizing radiation than expected from the late-type stars. Second, the analysis presented by Gatley et al (1977) shows that the far-infrared radiation is much more sharply peaked at the galactic center than is the distribution of late-type stars. In fact, their analysis indicates that a central optical/ultraviolet luminosity source of $2.2x10^6$ L_o which could account for the ionization, would also dominate the heating of the dust in the galactic center out to distances of 2.5 pc. We now believe that the luminosity of the central cluster is closer to $10^7 L_o$; thus it will in fact dominate the heating out to still greater distances, as is assumed in the discussion below and discussed in greater detail by Becklin, Gatley, and Werner (1982).

3. "THE STANDARD PICTURE"

It is often possible in analyzing infrared radiation from galactic sources to take the total infrared luminosity as an estimate of the luminosity of the heating sources, making the implicit assumption that the optical/ultraviolet heating radiation is absorbed close to its origin. That this approach could not be applied to the galactic center became clear from the observations by Becklin et al (1982; hereafter BGW). These observations provided maps of the central 10 pc of the Galaxy made with 30 arcsec resolution simultaneously at 30, 50, and 100um, using a common focal plane aperture to provide automatic registration of the maps at the three wavelengths. The results of the multi-wavelength mapping are shown in Figure 1 and discussed in detail by BGW. The principal observational result is that the 30um peak lies between the lobes seen in the far infrared. Ground-based observations

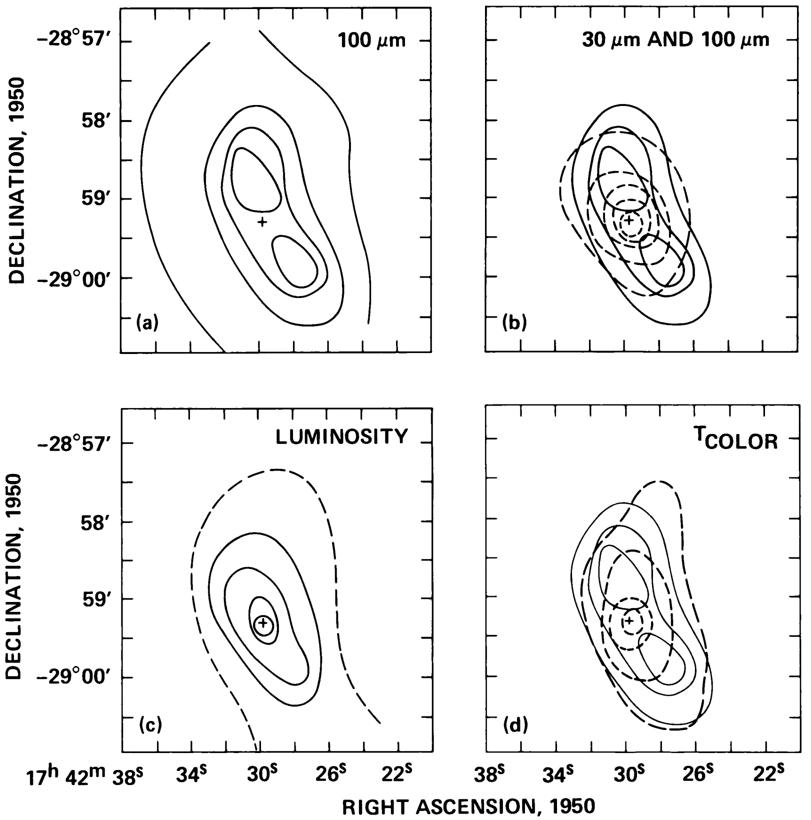

Figure 1. High angular resolution far-infrared observations of the galactic center (Becklin et al, 1982). (a) Map of the galactic center region made with 30" resolution at 100um; (b) The 100um map is superposed on a 30um map made simultaneously with 30" resolution, using a common focal plane aperture; (c) The 25-130um luminosity of the galactic center, derived from the 30, 50 (not shown), and 100um maps; (d) The 50-100 um color temperature, assuming gray particle emission, superposed on the 100um flux map. Contour levels - 100um: 0.25, 0.5, 0.75 and 1.0 x 3000 Jy/beam; 30 um: 0.125, 0.25, 0.5, 0.75, and 1.0 x 4300 Jy/beam; Luminosity map: 0.125, 0.25, 0.50, 0.75, 1.0 x 7×10^5 $L_\odot$/beam; Color temperature map: 60, 70, 80, 100 K. The cross in each figure denotes the position of the centroid of the galactic center emission at 34μm as derived from ground-based measurements.

show that the 30um peak coincides to within a few arcseconds with the position of the galactic center as determined from near-infrared and radio observations. Thus the galactic center lies between the lobes seen at 100um; both the 25-130um luminosity/beam and the 50/100um color temperature (Figure 1) decrease uniformly with position away from the galactic center. Taken together, these results require that the luminosity sources are concentrated toward the galactic center and that the dust density decrease inwards over the central 2-3 pc of the Galaxy.

The infrared energy distribution of the central 30 arcsec (Figure 2) shows a higher color temperature but a lower surface brightness than that of spiral arm HII region-molecular cloud complexes such as K3-50 and G333.6. This implies that the column density of dust producing the far-infrared emission from the galactic center is much less than in the comparison regions, which is consistent with the picture presented here.

The infrared luminosity of the central 1.3 pc of the Galaxy is found from Figure 2 to be 1.4×10^6 L_o, divided approximately equally between the 3-25 and the 25-130um bands. This is less than three times greater than the luminosity available in this region in the form of trapped Ly-alpha photons. By contrast, dust-embedded HII regions elsewhere in the galactic center have far infrared luminosities 7 to 16 times the trapped Ly-alpha luminosity (Gatley et al 1978). Thus much of the ultraviolet and visible radiation of the ionizing sources streams freely through the central parsec of the Galaxy and heats the surrounding dust (BGW). The elongation of the far-infared emission along the galactic plane indicates a toroidal or disk-like distribution for the dust, and the lobes seen at 100um were interpreted as the limb-brightened inner edges of the torus. The central cavity in the distribution of interstellar material predicted from these observations is dramatically confirmed in the high resolution HCN map of Gusten et al (1987), and the properties of the surrounding torus of dust and gas have been discussed by Gusten (1987) and by Genzel (1988). Note that the existence of the central cavity permits a single centrally-located object to dominate the energetics of the inner 5 pc of the Galaxy.

High angular resolution imaging in the 1-10um region of the central parsec of the Galaxy has identified numerous compact sources which lie within the central cavity, and photometry and spectrophotometry indicates that many of these are not late-type giants (Neugebauer et al, 1976; Rieke, Rieke and Paul, 1988; hereafter RRP). While other sources may also contribute, it seems most productive to assess the possible contribution of these early-type objects, loosely referred to as "the central cluster", to the ionization and heating of the galactic center.

The total far-infrared luminosity of the 2.5 x 5 pc region within the lowest solid contour of the luminosity map (Figure 1c) is 3.5×10^6 L_o. The arguments given above suggest that the heating due to the central cluster dominates that due to the late-type stars over this region. On this basis, BGW derived a lower limit of 7×10^6 L_o for L_c, the optical/ultraviolet luminosity of the central cluster, from the assumption that the dust torus subtends an angle no greater than 2π sr

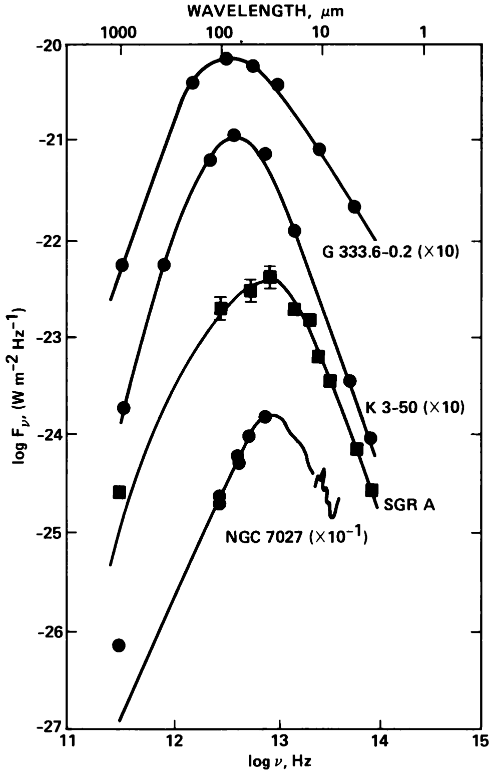

Figure 2. The 3-to-1000um energy distribution of the central 30 arcsec of the Galaxy (Sgr A) is compared with those of the HII regions G333.6-0.2 and K3-50 and the planetary nebula NGC 7027 (Becklin et al, 1982).

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as seen from the luminosity sources. They also derived a weak upper limit of $2x10^7$ L_o by comparing the dust temperature in the torus to that seen in other regions where the luminosity of the heating sources is known from direct optical and/or ultraviolet study.

4. MODIFICATIONS TO THE STANDARD PICTURE

4.1. Considerations of the Ionized Gas

To summarize, the data presented above suggest that a source - or a cluster of sources - with $L_c \approx 10^7$ L_o is located within the central cavity and heats the dust in the surrounding torus. It is most natural to identify these sources with the objects which ionize the plasma within the cavity. Serabyn and Lacy (1985) analyze the near-infrared fine structure emission from the plasma and conclude that a single source with $T_{eff} \approx 35,000$K and L(bol)$\approx 7x10^6$ L_o is consistent with the quantity and state of ionization of the plasma and also with the bolometric luminosity observed in the far infrared. The predicted near-infrared brightness of such an object - 9th magnitude at 2.2um - is comparable with what is observed from the compact components of the near infrared source IRS-16 (RRP), removing an inconsistency noted earlier by Lacy, Townes, and Hollenbach (1982). Of course, Serabyn and Lacy's arguments do not exclude the possibility that the ionizing sources are accompanied by slightly cooler objects which could contribute a substantial amount of near-ultraviolet and visible luminosity without providing additional ionization.

Although most of its luminosity goes into heating the dust and ionizing the gas, the central cluster may also be responsible for heating the warm, neutral gas seen in the adjacent torus in infrared emission lines of OI (63um), CII (157um) and SiII (35um) and also in emission from highly excited CO molecules (Genzel et al,1985; Lugten et al,1986; Graf et al, 1988). It is likely that this gas is concentrated in photo-dissociation regions at the surfaces of cooler clumps of molecular gas (Genzel, 1988) and is heated in part by photoelectrons ejected from the dust as modelled by Tielens and Hollenbach (1985). The total luminosity emitted from the inner regions of the torus in these lines is 1.4-to-$3.5x10^4$ L_o. The dust in the same regions radiates $3.5x10^6$ L_o, so that the heating efficiency is 0.004-0.01, in the range predicted by the Tielens and Hollenbach models.

4.2. Geometry of the Torus

The detailed studies of the gas in the torus by Gusten et al (1987) and others have improved our understanding of its geometry and show that it is a relatively thin disk inclined to our line of sight rather than a thick, edge-on disk. Thus the solid angle subtended at the luminosity sources by the torus could be as small as 0.25π rather than the 2π assumed by BGW. Moreover, the clumpiness of the gas inferred from the line observations (Genzel, 1988) could allow some of the heating photons emitted in the plane of the disk to penetrate beyond the central region included in the luminosity estimate given above. Taken together, these effects might indicate a luminosity for the

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central cluster exceeding $5x10^7$ L_o, perhaps reviving the discrepancies with the near-infrared observations cited above. On the other hand, Mezger and Wink (1986) argue that the overall dust density in the galactic center region is sufficiently high that the radiation from the central cluster does not penetrate to large distances in any direction; thus "what you see is what you get", and $L_c = 3.5x10^6$ L_o. However, the radiograph of the Sgr A complex presented by Morris and Yusef-Zadeh (1987) shows streamers of emission, apparently originating within the central cavity, which extend to great distances to the northwest. These may indicate a strong wind emanating from the central cluster, suggesting that photons ought to be able to escape fairly freely as well, at least in this direction.

4.3. The Bottom Line

On balance, it seems that 10^7 L_o still remains a good working estimate for the luminosity of the central cluster, with the reduction of the previous estimate due to the reduced distance to the galactic center being balanced by an increase reflecting our improved understanding of the geometry of the inner torus. This estimate is uncertain by at least a factor of two in both directions. It seems unlikely that the luminosity is less than $5x10^6$ L_o, and it could be greater than $2x10^7$ L_o only if the regions above and below the torus are surprisingly dust free. Improved estimates of L_c may come from modelling of the new far-infrared photometry described below, and additional comparisons of the far-infrared continuum data with the line emission from the plasma and from the warm atomic gas in the torus could also provide important constraints.

5. COMPARISON WITH THE INFRARED POINT SOURCES: IS THERE A SMOKING GUN?

Allen (1987) points out that providing both the bolometric luminosity and the ionizing radiation from main sequence stars with $T \approx 35,000K$ requires >100 late O or early B stars; this seems inherently improbable and encourages us to attribute the ionizing and heating to one or several peculiar objects. It is noteworthy that the most peculiar object known at the galactic center, the radio source Sgr A*, which is a black-hole candidate, does not have a compact infrared counterpart either at 2.2um, where RRP have set an upper limit of 11th magnitude, or at 10um (Gezari et al,1985). Sgr A* thus shows no indication of providing a substantial contribution to the luminosity.

Our understanding of the other infrared point sources within the central cluster has been improved immeasurably by the high spatial resolution achieved by lunar occultation studies (Adams et al,1988; Simons, Becklin, and Hodapp, 1988) and, especially, by the images obtained with arrays in the near infrared. The images presented by RRP show that the several components of IRS16 are by far the bluest objects in the central cluster, with de-reddened energy distributions showing a Rayleigh-Jeans slope from 1.2 to 2.2um. In addition, the new spectroscopic studies presented by Lacy, Achtermann, and Bruce (1988) suggest a slight peak in the degree of ionization in the vicinity of IRS16, the 20/30um dust temperature has a peak at this position (Gatley 1982), and the IRS16 complex coincides with the region of high velocity gas flow described by Geballe (1987). Thus while the cores of the brighter objects seen at 10um may also be self-luminous (RRP) it is difficult to avoid the conclusion that the luminosity of the central cluster arises primarily from the IRS16 complex.

A central question underlying the above discussion is whether a single object dominates the energetics of the inner few pc of the Galaxy. The evidence for such an object is far from compelling. The absence of any infrared point source at the position of Sgr A* and the rather remarkable similarity of the near infrared brightnesses of the components of IRS16 (IRS 16NE, NW, and SW differ in 2.2um brightness by less than 10%) provide no evidence for a single dominant source. Perhaps the leading current candidate for a singular object is IRS16NE, which is about 40% brighter than its companions at 1.2um. However, the extinction to the galactic center at 1.2um is about 8.5 magnitudes, so 40% brightness variations at this wavelength cannot be considered significant. We must therefore conclude that if a single object dominates the energetics of the galactic center, it appears to be extraordinarily well-camouflaged in the near infrared. Thus the smoking gun has not been found; unfortunately, it appears from the discussion below that the near infrared is not the best place to look for it.

6. NEW FAR-INFRARED OBSERVATIONS

Recently Davidson et al (1988) have used the University of Texas 8-channel bolometer system on the Kuiper Airborne Observatory to obtain improved far-infrared images of the central 8 pc of the Galaxy. The beamsize for these measurements was 22" x 18" (EW x NS) at 50um and 36" x 24" at 100um; for the images presented below, the resolution has been improved by about a factor of two in the EW direction through the application of maximum entropy techniques. The observations at each wavelength were repeated twice using different sets of guide stars and different scan directions and reduced with careful attention to the absolute position of the maps. Based on the agreement between the two sets of data, we estimate that the positions are accurate to 4 arcsec. The general picture emerging from the analysis of this new data is consistent with that presented above; however, the preliminary maps presented in Figures 3 and 4 below show some interesting new details.

The new 100um map presented in Figure 3 and compared with the HCN and CO distributions shows two lobes symmetrically placed around the galactic center, consistent with the results in Figure 1. The overall symmetry of the central contours shows no evidence for the gap in the torus on the eastern edge suggested by the HCN observations. The outer contours of the 100um emission bend away from the galactic plane towards a more North-South orientation; this is similar to the curvature of the gas distribution inferred from comparison of the CO emission with the more centrally concentrated HCN emission.

The new 50um map is shown in Figure 4 and compared with the

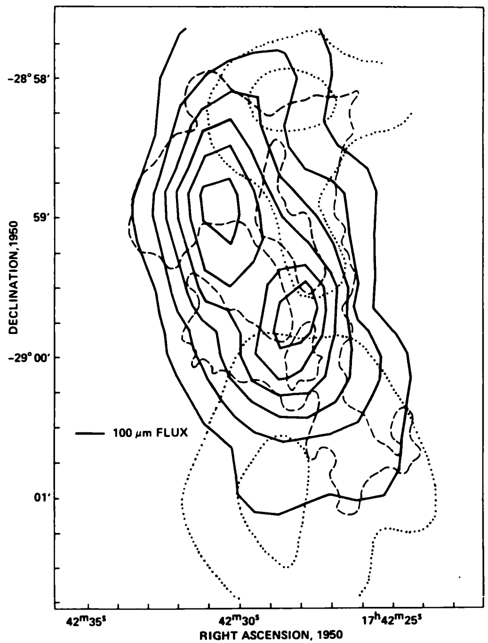

Figure 3. The new high-resolution 100um map of the galactic center (Davidson et al, 1988) is compared with the HCN (dashed) and CO (dotted) emission from this region (adapted from Gusten et al, 1987).

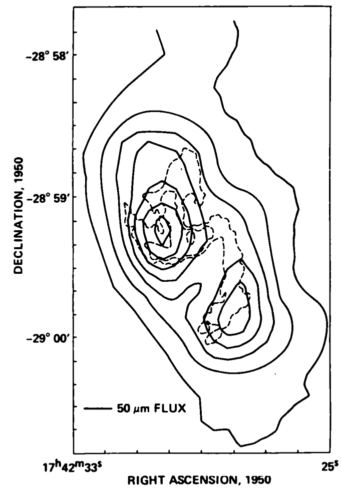

Figure 4. The new high-resolution 50um map of the galactic center (Davidson et al, 1988) is compared with the free-free emission from the Ionized plasma in the central cavity (adapted from Lo and Claussen, 1983).

distribution of the ionized gas determined from radio continuum measurements with the VLA. Two emission lobes are seen at 50um as well; however, the northern lobe clearly lies within the central cavity, between the two ionized streamers referred to as the Northern Arm and the Eastern Arm. A possible interpretation is that this 50um feature represents a finger of neutral matter (dust and gas) which protrudes into the cavity; the Northern and Eastern arms could be ionization fronts at the boundaries of this finger just as the Western arm is thought to delineate the inner edge of the dust ring in that direction. If this interpretation is correct, one might expect to see high velocity emission in the OI and CII lines from the neutral gas associated with the dust, which would lie in an intensely heated photodissociation region. Such emission is in fact apparent in the OI and CII profiles at this position (Genzel et al 1985), as has been previously pointed out by Serabyn and Lacy (1985).

7. COMPARISON WITH THE 30 DORADUS REGION

Because our direct view of the galactic center is obscured, it is useful to think of analogous regions which might provide interesting comparisons and contrasts. In the past, there has been a tendency to think of the galactic center as an HII region/star-formation complex perhaps similar to those seen in the spiral arms of the Galaxy. We suggest as an alternate point of view that the morphological similarities between the central few pc of the Galaxy and the innermost regions of the 30 Doradus complex in the Large Magellanic Cloud (recently discussed by Mathis, Chu, and Peterson, 1985; and by Moffat et al, 1987) are quite striking. These are summarized in Table 1.

Most of the differences between the two regions can be attributed to differences in overall scale and also to the fact that, as an irregular galaxy, the LMC does not have a central stellar condensation such as that which produces the deep gravitational potential responsible for the high velocities at the galactic center. Another significant difference is the much higher ionization state of the 30 Doradus nebula, which is consistent with the high luminosity and presumed high mass and extreme youth of its exciting stars.

In other regards, such as the presence of a central cavity within which the luminosity sources are located, the presence of ionized filaments, and the fact that the far infrared peaks are offset from the position of the principal heating sources (Werner et al, 1978), the regions are very similar. The fact that there appears to be a central dominant source in 30 Doradus - in contrast with the situation in our Galaxy - may be a bit misleading, as R136 is a compact cluster with several barely resolved components, as IRS16 would certainly appear to be at the LMC's distance of 55 kpc. However, it appears that the dominant object in the R136 cluster stands out rather more from its fellows than does any of the components of IRS16.

The 2.2um photometry of the 30 Doradus complex provided by McGregor and Hyland (1981) allows us to reassess the search for the smoking gun. They find that at 2.2um R136 is only 50% brighter than the next brightest early-type object in the region, the B9 supergiant R131, which lies 3 arcmin to the west. By comparison, these objects

TABLE I

Property	30 Doradus	Galactic Center
Scale	50 pc	3 pc
L(tot)	10^8 L_o	10^7 L_o
L(IR)	1/2 L(tot)	1/2 L(tot)
Ionization Rate	$>10^{51}$/sec	1.3×10^{50}/sec
Central Cavity?	Yes	Yes
Ionized Filaments?	Yes	Yes
Late-type Supergiants?	Yes	Yes
Early-type Supergiants?	Yes	Probably
Stellar Winds?	Yes	?
Ionization State	High	Low
High Stellar Velocities?	No	Yes
Dominant Central Object?	Yes (R136)	?

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differ in bolometric luminosity by a factor of about 50! The obvious conclusion is that determining the bolometric luminosity of peculiar early-type objects from near infrared observations is fraught with uncertainty, and the possibility of a dominant luminosity source at the galactic center remains open.

The morphological similarities lead one naturally to compare the stellar populations in the two regions, and here again there are some interesting similarities. For example, the brightest 2.2 micron source in each region is a late-type supergiant, IRS7 in the galactic center and the object known as Q in 30 Doradus. It is suggestive that the 13 early-type supergiants within the central 12 x 12 arcmin region surrounding 30 Dor measured by McGregor and Hyland have a median absolute magnitude of -8 at 2.2um; at the distance of the galactic center, including the 2.7 magnitudes of extinction, such an object would appear about half as bright as the components of IRS16. McGregor and Hyland estimate bolometric luminosities for ten of these supergiants; the median is -10.50, corresponding to $L = 1.2\times10^6\ L_o$, while several of the individual objects in addition to R136 have $L > 4\times10^6\ L_o$. A small number of objects of this type could in principle energize the galactic center, although it may still be difficult to reconcile the high ionization state of 30 Doradus with the low effective temperature of the ionizing sources in the galactic center.

One could easily go overboard with this type of comparison. However, it does suggest rather strongly that important clues to the nature of the galactic center may come from studies of the 30 Doradus region and of the similar regions in nearby galaxies which will become accessible for detailed study with the launch of the Hubble Space Telescope.

8. CONCLUSIONS:

In conclusion, we return to the questions posed in the introduction:

8.1. What is the luminosity of the central parsec of the Galaxy?

Probably within a factor of two of $10^7\ L_o$. The remaining uncertainties are primarily geometrical and may be reduced by modelling of newly-obtained far infrared data.

8.2. Which objects produce it?

The peculiar radio source Sgr A* shows no evidence of being a signficant luminosity source. Among the identified near-infrared point souces, the components of the IRS-16 complex are the most likely candidates for making substantial contributions to the luminosity of the region. Although there is no evidence for a single dominant luminosity source, the possibility is consistent with current data.

8.3. What sorts of object are they?

The example of the 30 Doradus region emphasizes the difficulty of deducing the properties of optical/ultraviolet sources from near infrared observations. Nevertheless, it is suggested that the early-type supergiants seen in 30 Doradus might serve as instructive examples of the types of objects responsible for energizing the galactic center.

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