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M SUPERGIANTS AND STAR FORMATION AT THE GALACTIC CENTER

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ABSTRACT

High resolution spectra of six sources at the galactic center demonstrate that these objects are M supergiants. The dramatic concentration of such stars is interpreted as evidence for a recent burst of star formation which may also correctly model the ionization and energetics of the galactic center.

Subject headings: galaxies: Milky Way — galaxies: nuclei — stars: formation — stars: late-type — stars: supergiant

I. INTRODUCTION

The presence of luminous, late type stars at the galactic center has been known for some time—e.g., Neugebauer *et al.* (1976) and Treffers *et al.* (1976). More recent work (Wollman, Smith, and Larson 1982) has investigated a few of the M supergiants, notably Source 7, in more detail, confirming that these objects are oxygen-rich stars and derived a relatively large velocity for Source 7 (170 ± 50 km s^{-1}). Photometry and polarimetry were used recently (Lebofsky *et al.* 1982) to suggest that about 12 M supergiants (Sources 7, 11, 12, 17, 19, 22–27; note that 26 is double) lie within a radius of about 1'.5 of the galactic center; if this conclusion could be confirmed, the remarkable concentration of M supergiants would have widespread implications for our understanding of the processes in this area. This paper presents high-resolution spectroscopy ($R \sim 1000$–2000) of six of these sources, and uses this new information to derive accurate spectral types and extinction values for these stars. Together with previous work, there is now definitive spectroscopic confirmation for the presence of seven M supergiants in the galactic center. To account for this result, we suggest that a burst of star formation occurred at the galactic center $\sim 10^7$ years ago; this star burst also appears to dominate the currently observed level of ionization and the energetics of the galactic center.

II. DATA

All of the spectra were acquired using the Steward Observatory Fourier Transform Spectrometer (S.O.F.T.S.) (Thompson and Reed 1975) on the University of Arizona Observatories' 2.25 m telescope. A pair of liquid-helium cooled indium antimonide detectors were used for all of the measurements. An 8" aperture and 30" reference beam spacing in right ascension were also used.

Special care was taken during the acquisition of these spectra with regard to standard star observations. Whenever possible, equal altitude transfers were made to ensure accurate and complete removal of atmospheric features.

Table 1 is a log of the observations and includes both the original and apodized resolutions of the spectra shown in Figure 1. Since these objects are such luminous late type stars, they are probably variable, although the only magnitude difference noted during the acquisition of these spectra was that Source 11 always appeared substantially fainter (~ 0.5 mag) than reported by Becklin and Neugebauer (1975). Clearly visible in all spectra in Figure 1 are the prominent CO bands, originally suspected to be present in sources 7, 11, and 12 by Neugebauer *et al.* (1976) and confirmed for Source 7 by Treffers *et al.* (1976) and for Source 12 by Wollman, Smith, and Larson (1982). However, the extremely deep CO reported by Neugebauer *et al.* for Source 11 is not confirmed—only CO appropriate to about spectral type M0 is seen. The spectra of Sources 7 and 19 are in good agreement with those in Wollman, Smith, and Larson (1982): the Source 7 spectrum presented here is of the same resolution but higher signal-to-noise ratio than that in Wollman, Smith, and Larson whereas the Source 19 spectrum is at twice the resolution of the Wollman, Smith, and Larson spectrum. The spectral type of Source 12 was derived from Wollman, Smith, and Larson's spectrum with the atmosphere ratioed out. Source 9 was also observed to have weak CO bands and strong Brγ emission; it is not likely to be an M supergiant. Its CO bands may come from the stellar background or may result from its being a composite of a cool star and a hot star which fills in the CO absorption.

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TABLE 1

LOG OF OBSERVATIONS

Source	R_{obs} (cm^{-1})	R_{apo} (cm^{-1})	Date (mo/day/yr)
7	2.5	3.7	6/15/79, 6/16/79
11	5.3	7.8	5/4/80, 4/1/80
19	2.5	3.7	3/22/81, 5/13/81
22	2.5	3.7	7/5/79
23	2.5	3.7	5/12/81
24	2.5	3.7	5/13/81

As is readily apparent from published work (e.g., Johnson *et al.* 1968), 1.9–2.5 μm spectra can be used to classify red stars with regard to both spectral type and luminosity (e.g., supergiants have much stronger CO absorption at a given effective temperature than do giants). To make full use of these data in assigning spectral types, a suite of comparison objects selected from lists of White and Wing (1978) and Smolinski (1972) were also observed. Table 2 lists all of the comparison objects; several of these spectra are included in Figure 2. It became apparent early in this project that the galactic center stars are much more luminous than M giants, both on spectroscopic grounds (deep CO) and on the basis of bright absolute magnitudes. Therefore supergiant comparison objects were emphasized, although spectra of a few giants (o Vir [G8 III], α Cas [K0 II–III], δ Tau [K0 III], 20 Boo [K3 III], μ UMa [M0 III], α Her [M4 II–III]) were also acquired.

III. SPECTRAL TYPES AND EXTINCTIONS

Spectral types were derived using an iterative process based on ratioing spectra against comparison star spectra. Initial estimates for A_V were made, spectra dereddened, and then ratioed. The process was repeated until it converged—which it did rapidly in all cases. The assumed extinctions for the comparison stars are given in Table 2 while Table 3 lists the derived spectral types, extinctions, and absolute magnitudes for the galactic center sources.

Figure 2 shows the result of ratioing Source 7 to BD+24°3902 and to AZ Cep. In the ratio to BD+24°3902, the CO bands and atomic features are still in absorption, indicating that Source 7 is later than M1.1. In the ratio against AZ Cep, the absorption features appear in emission, demonstrating that Source 7 must be earlier than M1.6. Ratioing of the various comparison stars against one another indicates that an accuracy of about 0.5 in the spectral type can be expected from this technique. An accuracy of at least 2 mag in A_V is given by this method—if the dereddening is incorrect, the continuum in the ratio spectrum will show a slope. The technique will be less accurate for low signal-to-noise ratio spectra, but the limits quoted should apply for all of the galactic center spectra presented here.

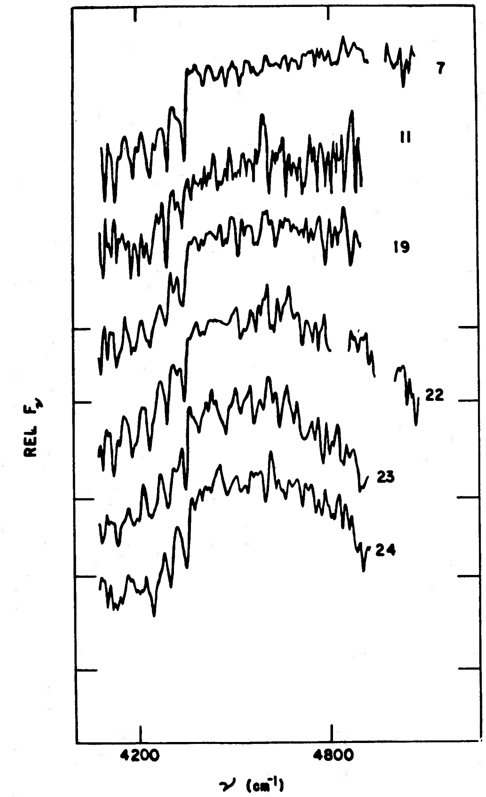

FIG. 1.—Two-micron spectra of galactic center M supergiants. The zero points for each spectrum are indicated with zero for Source 24 at the bottom of the frame. These spectra have been dereddened by the amounts listed in Table 2 and are apodized to the resolutions listed in Table 1.

Sources 22–24 have spectral types later than any of the comparison stars. These types were assigned by dereddening until the dereddened continuum slope appeared similar to those seen for o Cet (M5), R Hya (M6), and R Leo (M8) in Johnson *et al.* (1968). The spectral type was then estimated by comparison to these same spectra with particular attention given to the ap-

TABLE 2

COMPARISON STARS

Name	Spectral Type	Ref.	A_V	Ref.
RW Cep	G8 Ia	1	3.30	2
ϵ Gem	G8 Ib	3	1.1	4
HD 221861 ...	K0 Iab	1	2.0	4
ξ Cyg	K5 Ib	3	0.2	4
HD 163428 ...	M0.6 Iab$^-$	5	3.5	6
Case 75	M2.7 Iab	5	5.33	2
PZ Cas	M2.8 Ia	5	3.02	2
BC Cyg	M3.2 Iab	5	5.44	2
KY Cyg	M3.9 Iab	5	6.88	2

REFERENCES.—(1) Smolinski 1972. (2) Humphreys 1978. (3) Tomkin, Luck, and Lambert 1976. (4) A_V estimated from colors. (5) White and Wing 1978. (6) Lee 1970.

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TABLE 3

DERIVED SPECTRAL TYPES AND EXTINCTIONS

Source	Sp	A_V	K	M_K	M_V	$H-K_{obs}$	$H-K_o$
7	M1.3 Ia	35.5	6.7	−11.9	−7.9	2.6	0.29
11	M0 Ib	29	9.5	−8.4	−4.6	2.1	0.22
19	M4 Ib	32	8.1	−10.1	−4.6	2.5	0.42
22	M6 II	23	7.8	−9.5	−2.2	2.0	0.50
23	M6 II	27.5	7.9	−9.9	−2.9	2.3	0.51
24	M6 II	31	7.9	−10.2	−3.2	2.4	0.49
12[a]	M4 Ib	30	8.1	−9.9	−4.4	2.2	0.35

[a] H. Larson provided an atmosphere-corrected version of the spectrum published in Wollman, Smith, and Larson 1982 for this analysis.

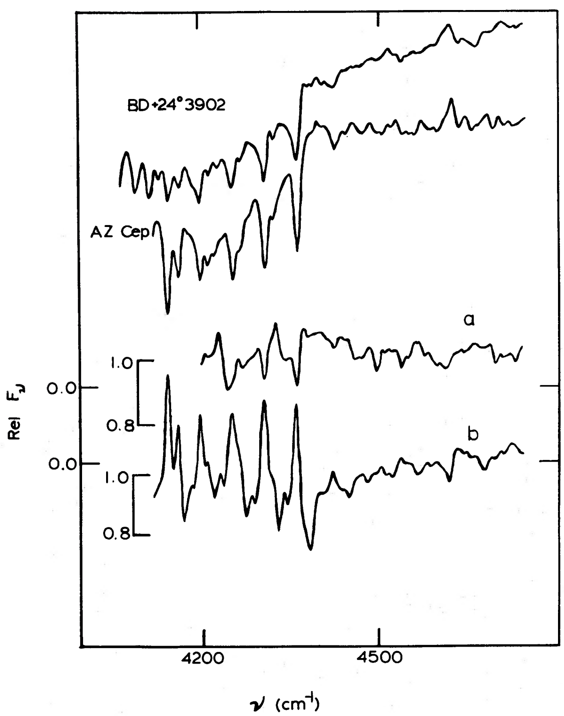

FIG. 2.—Comparison star spectra (BD +24°3902, M1.1 Ia; and AZ Cep, M1.6 Ia) and ratios to Source 7; (*a*) shows Source 7 divided by BD +24°3902, and (*b*) shows Source 7 divided by AZ Cep. Note that the CO bands, apparent for $\nu < 4360$ cm^{-1}, shift from being in emission in the ratio with BD +24°3902 to being in absorption in the ratio with AZ Cep. The zero points for the comparison star spectra are indicated by ticks while scales are shown by each ratio spectrum.

pearance of the steam depression near 2 μm. Because none of the observed comparison stars are of such late spectral type, the spectral classes assigned for these stars may be less accurate although the spectra are of high enough quality to assign accurate classes.

The observed $H-K$ and dereddened $H-K$ colors are listed in Table 3. Excellent agreement between the dereddened colors and those expected for these spectral types is seen, confirming the accuracy of the derived spectral types and extinctions.

From polarimetry Lebofsky *et al.* (1982) demonstrate that these stars probably lie close to the galactic center. The supergiant luminosities and A_V of about 30 required by both the spectra and photometry for Sources 7, 11, 12 and 19 confirm that these sources lie within the galactic center—if their angular separations are interpreted as spatial separations at a distance of 10 kpc, then all of the sources discussed here lie within 5 pc of the galactic center. If these objects were to be interpreted as M giants, they would be only 1 kpc distant and hence unlikely to have visual extinctions near 30 mag. Sources 22–24 have "bright" giant luminosities; if interpreted as normal giants with $M_V \sim -0.5$, they would be 4 kpc away and also rather unlikely to have such high extinctions.

IV. DISCUSSION

The presence of so many M supergiants is a strong indication of recent star formation at the galactic center. For comparison, in Humphreys's (1978) list of Milky Way OB associations, only 76 M supergiants are listed, with no concentrations as dramatic as that at the galactic center.

Before considering the star burst model further, a brief discussion of dynamical mechanisms that may alter the stellar densities at the galactic center is needed. The issue affecting the star burst model is whether or not the M supergiants are still near their formation sites or whether they have moved a considerable distance, thus creating the impression of an elevated star formation rate. The relevant dynamical processes are reviewed by Saslaw (1973), and have been suggested as possibly being important at the galactic center. The lifetimes of the progenitors of the M supergiants are $\sim 10^7$ years (if $M = 15\ M_\odot$) or less. Of the dynamical processes discussed by Saslaw, the "amplification" time which represents the time for a density enhancement to form caused by the settling of the most massive stars is most relevant, and is of the order of 10^8 years for the conditions

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present in the Galactic Center, or about 10 times too long to have a significant effect on the M supergiants. The time scales for other mechanisms such as relaxation are at least 5 times longer than the amplification time. Another indication that dynamical effects have not greatly modified the stellar distribution is that if Source 7's velocity of about 170 km s^{-1} (Wollman, Smith, and Larson 1982) is interpreted as radial motion away from the galactic center, the maximum distance that Source 7 can travel is about a parsec.

Working from the assumption that the current M supergiant distribution is representative of the spatial distribution of their formation sites, the number of M supergiants can be converted to star formation and mass consumption rates. These rates are model dependent in the sense that the current number of M supergiants has to be converted to an entire range of stellar masses formed in this burst, and a time scale for this activity needs to be determined. Note that Source 7 must have a $\sim 40\ M_\odot$ progenitor, Sources 12 and 19 have $\sim 20\ M_\odot$ progenitors, and Sources 11, 22, 23, and 24 may have $\sim$10–15 $M_\odot$ progenitors. If an initial mass function (IMF) ranging from 0.09 $M_\odot$ to 31 $M_\odot$ with a power-law slope of -2 (close to the Salpeter value of -2.35) is used, a total of $2\times10^3\ M_\odot$ in a volume with a radius of 1'.5 must be used in the current burst. This mass is reduced by a factor of 2 if the lower mass limit is raised to 1 $M_\odot$. This star burst mass is also uncertain from the standpoint that the range of progenitor masses almost certainly indicates that star formation has been occurring for some time rather than in a single, discrete burst.

The simplest choice for the time scale is the lifetime of the progenitors of the M supergiants, about 10^7 years. This time scale for the age of the burst is indicated by other lines of evidence such as the ionized helium abundance (Rodriguez and Chaisson 1979), the possible ejection of material causing the motion of the 3 kpc arm (van der Kruit 1971), and the ionization state of the galactic center clouds (Lacy, Townes, and Hollenbach 1982). Using an IMF cutoff at 1 $M_\odot$ yields a mass consumption rate of $1.4\times10^{-5}\ M_\odot\ yr^{-1}\ pc^{-2}$ as compared with a galaxy-wide average of 3–$7\times10^{-9}\ M_\odot\ yr^{-1}\ pc^{-2}$ (Miller and Scalo 1979) and $3.78\times10^{-7}\ M_\odot\ yr^{-1}\ pc^{-2}$ for a volume with an 800 pc radius at the galactic center found by Smith, Biermann, and Mezger (1978). Miller and Scalo (1978) consider the mass consumption rates in various regions such as OB associations, T associations, and clusters, and none of the rates compare with that found at the galactic center. Even if the three least luminous stars in this paper are not considered, the mass consumption rate is at least 20 times higher at the galactic center than elsewhere in the Galaxy. Perhaps this high rate is indicative of very efficient conversion of stars into gas, as has been suggested for the nucleus of M82 (Rieke *et al.* 1980), but more complete understanding of gas inflow/outflow processes at the galactic center is needed to test this conjecture.

The burst indicated by the M supergiant statistics can also provide the required ionization. As discussed in Rieke and Lebofsky (1982), Humphreys (1978) has tabulated the numbers of blue and red supergiants seen in Milky Way OB associations where she sees 11 times as many blue as red supergiants. This blue supergiant population could provide the required distribution of ionizing sources. Lacy, Townes, and Hollenbach (1982) have also proposed a burst of $4\times10^3\ M_\odot$ and 4×10^6 years old to explain the galactic center ionization, values which are essentially the same as those derived from the M supergiants considering the uncertainties (e.g., effect of metallicity).

Whether the current star burst is an isolated event or part of a series of bursts cannot be determined directly, although there is no evidence against bursts being recurrent, and the spread in stellar mass indicates a spread in formation times. If a burst with a lower mass cutoff of 0.09 $M_\odot$ and total mass of $2\times10^3\ M_\odot$ occurred every 10^7 years, then $8\times10^4\ M_\odot$ would be tied up in unevolved main sequence stars and remnants from massive stars after 10^9 years, which is only a small fraction of the 3–$10\times10^6\ M_\odot$ (Lacy, Townes, and Hollenbach 1982) at the galactic center. Bursts could not occur much more frequently than every 10^7 years without the main sequence and remnant mass becoming significant. Another constraint on cyclic bursts is the buildup of metals which would accompany many generations of stars. Argon and neon may have about twice their solar abundance values at the galactic center (Lester *et al.* 1981; Lacy, Townes, and Hollenbach 1982), but turning chemical evolution into a tight constraint involves unknown or speculative information such as the gas infall rate. Possible conditions for cyclic star formation at the galactic center are considered by Loose, Krugel, and Tutukov (1982), with the conclusion that repetitive star bursts are likely if the lower mass cutoff of the IMF is near 1 $M_\odot$.

V. CONCLUSIONS

The new results derived from high-resolution spectra of sources within 5 pc of the galactic center are the following:

1. Including Source 12, there are at least four late type stars with $M_V \leq -4.4$ and three late type stars with $-2.2 \leq M_V \leq -3.2$.

2. Source 7 is of spectral type M1.3 Ia with $M_V = -7.9$, making it one of the two or three most luminous M supergiants known in the Galaxy.

3. The extinction varies over $23 \leq A_V \leq 36$ within 30'' of the galactic center.

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4. The population of luminous red stars requires recent, rapid, and sustained star formation at a rate which must be at least 10^3 the mean rate for the Galaxy and at least 20 times the rate anywhere else in the Galaxy.

5. A consistent model to explain supergiants, ionization, and energetics is a star burst forming $1-2\times10^3$ $M_\odot$ of stars which ended 10^7 years ago.

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