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THE STELLAR POPULATION AT THE GALACTIC CENTER AND THE MASS DISTRIBUTION IN THE INNER GALAXY

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Robert David Blum

* * * * *

The Ohio State University

1995

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To Denise, of course. And, to Brian

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Fields of Study

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The Galactic Center	Profs. Sellgren & DePoy
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CHAPTER I

Introduction

The study of the inner regions of our galaxy, the Milky Way, is a young field. The Galactic center lies 7.7 ± 0.7 kpc from the sun (Reid 1989, $1 \text{ kpc} = 1000 \text{ pc} = 3.08 \times 10^{21} \text{ cm}$) and is obscured by large amounts of interstellar dust which lie along the line of sight (For simplicity, I adopt a sun to Galactic center distance of 8 kpc in what follows, unless stated otherwise).

The intervening dust attenuates the radiation from the inner Galaxy to such an extent at visible wavelengths that the first quantitative measurements of starlight from the Galactic center were not made until 1968 when infrared detectors became sufficiently sensitive. Because longer wavelength light is attenuated less by dust, infrared observations are effective for studying optically obscured stellar populations. By observing at near infrared wavelengths between $1.65 \mu\text{m}$ and $3.4 \mu\text{m}$, Becklin & Neugebauer (1968) were able to quantify, for the first time, the stellar luminosity emanating from the central $\sim 10 \text{ pc}$ of the Galaxy.

Since the intervening dust is confined to the Galactic plane, observations at higher latitudes will be less susceptible to extinction by dust, but regions within a few degrees of the Galactic plane are still generally inaccessible to optical investigations, particularly for spectroscopic studies. Not until the “windows” of low extinction

(due to the large variations in the column density of dust along the line of sight to the inner Galaxy) are reached along the minor axis of the Galaxy at $b \gtrsim 3^\circ$ (Baade 1963) are optical studies possible. And, here, of course, a great body of work has been established on the nature of the stellar population using optical astronomical observations (see Frogel 1988 for a recent review).

It is the region between these optical windows and the Galactic center that has remained largely unexplored (except the inner few pc of the Galaxy, but this region has been subject to new exploration with each advance in technology) and now stands to benefit the most from the advances in infrared detector technology that have occurred since the work of Becklin and Neugebauer. Single channel detectors like the one they used have given way to large format two dimensional arrays in the last 5–10 years. The advent of this array technology has made it possible to study the obscured regions of the inner Galaxy with techniques comparable to those used in optical astronomy, namely, high spatial resolution imaging ($\lesssim 1''$) and high resolution spectroscopy ($\lambda/\Delta\lambda \approx 500$ to 40000).

The present work exploits these new arrays to make detailed investigations of the stellar population in the Galactic center and the mass distribution of the inner Galaxy at $l, b \lesssim 2^\circ$. These two areas of investigation are briefly outlined below.

1.1 The Mass Distribution in the Inner Galaxy

The aim of the present work has been to obtain the kinematics for as large a number of stars as possible in a series of fields located within a few degrees of the Galactic center. The kinematics in these optically obscured regions are used to constrain the

mass distribution of the inner Galaxy at projected radii between 150–300 pc from the Galactic center where no previous measurements had been made. The kinematic results rely on measuring velocities of individual stars from the Doppler shift of the $2.3\ \mu\text{m}$ CO photospheric absorption feature which is strong in late type giant stars. The more luminous subset of stars with strong CO absorption, the M giants, are employed here since they are bright at near infrared wavelengths and so, are effective tracers of distant populations.

Explorations of the inner Galaxy are particularly relevant now since our view of the structure of the inner Galaxy has changed significantly in the past few years. The former view of an essentially independent oblate spheroidal component, the Bulge, which dominates the stellar density within ~ 1000 pc of the center and which may have formed and evolved independently of the disk, has given way to a model in which the Bulge is considered as a rotating stellar bar (a triaxial, non-axisymmetric shape). New infrared observations of the central $\pm 10^\circ$ of the Galaxy (Weiland et al. 1994, Dwek et al. 1995), and re-analysis of older ones (Blitz & Spergel 1991) demonstrate that the inner Galaxy surface brightness distribution is asymmetric. This asymmetry is believed to arise naturally from a bar shaped stellar distribution, whose formation and evolution could be strongly linked to the disk (e.g, Sellwood 1993). This new picture of the Galactic bulge is more fully described in the references given in the introductory material in Chapters 2–4.

Chapter 2 discusses results from the first set of kinematic observations and lays out, in detail, the observing techniques employed. Chapter 3 presents results for

three additional fields, reviews the results for all four fields, and compares these results to axisymmetric and barred dynamical models. Chapter 4 presents a simple dynamical model of the inner Galaxy (based in part on the present kinematic results, but also those of other investigators) which suggests that a barred stellar distribution in the inner Galaxy could lead to a significantly more massive Bulge than previously thought.

1.2 The Stellar Population at the Galactic Center

The remaining chapters are concerned with the massive stellar population at the Galactic center, by which I mean, the central few pc. The central region of the Milky Way provides the nearest galactic nucleus which is available for high spatial resolution investigations. Our Galactic center may thus lead to a better understanding of external galaxies which we observe through the integrated light of many stars. However, with high spatial resolution also comes great complexity, and the space of years since the observations of Becklin and Neugebauer (1968) has seen a tremendous volume of observational and theoretical work on many aspects of astrophysical interest at the Galactic center. These include, but are not limited to: the stellar population; the excitation, spatial distribution, and kinematics of ionized and molecular gas; far infrared dust emission, and black holes. Genzel, Hollenbach, and Townes (1994) present a comprehensive review of these research areas and others related to the Galactic center.

One subject of Galactic center research that has been historically active and remains so is the nature and extent of recent star formation there. Whether by “nor-

mal” processes (i.e. by collapse and coalescence from molecular gas) or by non-normal means, such as stellar mergers, it seems clear that star formation has occurred within the last 10^7 years at the Galactic center. Much of the evidence to support this result comes from the study of a cluster of emission-line stars, known as the Galactic center He I stars. Several sources were initially identified at different wavelengths by Forest et al. (1987) and Allen et al. (1990); later Krabbe et al. (1991) added a significant number of new members, demonstrating that the original sources were the brighter members of a He I emission-line star cluster. These stars are now thought to be massive, post-main-sequence stars, some of which are in evolutionary states related to Luminous Blue Variables and Wolf-Rayet stars.

Chapter 5 presents a detailed comparison of the H band ($1.65 \mu\text{m}$) and K band ($2.2 \mu\text{m}$) spectra of the Galactic center He I stars to a set of similar stars in Large Magellanic Cloud (LMC) and several from elsewhere in the Galaxy. This comparison shows that the Galactic center objects have several important differences from their LMC and galactic counterparts. The spectroscopic results are used to estimate the impact the He I stars have on the Galactic center environment through ionizing radiation and mass loss and to place them in a region of the HR diagram which shows they may have evolved from stars with initial masses between $\sim 30\text{--}100 M_{\odot}$.

Chapter 6 continues the discussion of star formation at the Galactic center by presenting a spectrum of the first Wolf-Rayet star discovered there. This discovery, when combined with previous data, suggests massive stars in a range of evolutionary states exist in the Galactic center as might be expected from a normal burst of star

formation. In any event, a complete census of the types of massive stars, like the Wolf-Rayet star described in Chapter 6 and the He I stars detailed in Chapter 5, will be needed to understand the character and extent of massive star formation at the Galactic center.

CHAPTER II

Radial Velocities of M Giants at 300 pc Projected Radius from the Galactic Center ¹

2.1 Abstract

We present radial velocities for 33 stars in an optically obscured field toward the Galactic bulge at $l=-1.14^\circ$, $b=1.81^\circ$. The radial velocities are derived from spectra of the $2.3\ \mu\text{m}$ CO bandhead that is prominent in late type giants. The heliocentric radial velocity and dispersion are $-75 \pm 24\ \text{km s}^{-1}$ and $127 \pm 16\ \text{km s}^{-1}$, respectively. Comparison to the axisymmetric mass model of Kent (1992) shows good agreement with the velocity dispersion, but there is some evidence (at the $2.1\ \sigma$ level) for a more negative mean velocity. The more negative mean velocity is suggestive of streaming motion in a rotating barred potential such as derived by Binney et al. (1991).

2.2 Introduction

Kinematic studies of stars in the inner Galaxy have been used to derive the mass distribution within 1000 pc of the Galactic Center (Kent 1992; Lindqvist et al. 1992; Sellgren et al. 1990; McGinn et al. 1989; Rieke & Rieke 1988). The most detailed model (Kent 1992) utilizes the kinematic data from all these papers as well as

¹This chapter appeared in its entirety as Blum et al. (1994)

kinematics in Baade’s Window (BW) and several other fields along the bulge minor axis from Rich (1990), Sharples et al. (1990) and Terndrup et al. (1993). These data represent a large number of observations of individual stars in the inner Galaxy. However, they are concentrated either near the Galactic Center (projected radius $R \lesssim 10$ pc) or in low-obscuration optical windows at $R \gtrsim 400$ pc along the minor axis. An exception is the OH/IR star investigation of Lindqvist et al. that measured 134 sources concentrated toward the Galactic plane extending to approximately $R = 100$ pc. A gap therefore exists in the observations at intermediate distances and in off-axis positions. The minor axis data ($R \gtrsim 400$ pc) sample only the inner Galaxy velocity dispersion; Kent’s model relies primarily on these data for the mass distribution at larger radii ($R \gtrsim 100$ pc). Mean velocities are available only near the Galactic Center ($R \lesssim 10$ pc) or on the major axis. Thus, as Kent points out, the mass models have not yet been adequately tested for mean velocities in the inner Galaxy due to a lack of observational data.

We have obtained radial velocities for a sample of late-type giants in a single field located at $l = -1.14^\circ$, $b = 1.81^\circ$ using the $2.3 \mu\text{m}$ CO bandhead. This is the first investigation of kinematics in this region of the inner Galaxy. These data begin to fill the observational gap that exists between the stars of the bulge minor axis fields and those of the Galactic Center.

2.3 Observations and Data Reduction

2.3.1 Imaging

The program stars were selected from the brighter stars on a K band ($\lambda=2.2 \mu\text{m}$, $\Delta\lambda=0.4 \mu\text{m}$) image (Figure 1) of the field obtained with the Ohio State Infrared Imaging System (OSIRIS) on the Perkins 1.8m telescope near Flagstaff, Arizona during May 1992. OSIRIS is described by Atwood et al. (1993). The scale in Figure 1 is $1.6 \text{ arcsec pix}^{-1}$. The brightest stars on the image were saturated since the response of the camera's 256×256 NICMOS array becomes non-linear for stars with $K \lesssim 8.5 \text{ mag}$ at the minimum integration time. In addition to the image shown in Figure 1, we obtained J ($\lambda=1.25 \mu\text{m}$, $\Delta\lambda=0.3 \mu\text{m}$) and K images of the field with a 10 % transmission neutral density filter yielding stellar images in the linear region for all but one of the program stars. These images were obtained in March 1993.

J and K magnitudes were derived from synthesized apertures (3 pixel radius) on the image shown in Figure 1 or from images taken with the neutral density filter. The overall flux calibration was obtained from images taken with OSIRIS on the CTIO 4m telescope during July 1993. The $0.4 \text{ arcsec pix}^{-1}$ scale resulted in a much smaller field of view. Seven stars in common to the large and small fields were used along with the flux standard HD 161743 (Elias et. al., 1982) to calibrate the photometry. The flux standard and seven calibration stars were observed at the same airmass, so no airmass correction was needed. The typical photometric uncertainty for the seven stars in the small field was 0.03 and 0.02 mag at J and K , respectively. Comparison of these magnitudes to the instrumental magnitudes in the larger field results in an

Fig. 1.— 2.2 μm image of the field located at $l = -1.14^\circ b = 1.81^\circ$. The numbers correspond to the stars in Table 1. The bright star at center is SAO 185534. The offsets in Table 1 are relative to this star and were determined from this image after a 1.9° rotation of the field; see discussion in text. North is up, East to the left.

uncertainty of 0.06 magnitude in both J and K . K magnitudes were obtained from Figure 1 by comparing a small set of stars whose response was linear on the image to the same stars from the neutral density filter frames. The $J - K$ color and K magnitude of each program star are given in Table 1.

2.3.2 Spectra

The spectroscopic observations were made on the CTIO 1.5m telescope during the nights of 1992 July 27 and 28 using the facility infrared spectrometer (IRS) which employs an SBRC 58×62 InSb detector. The IRS is described by DePoy et al. (1990). The $4.8'' \times 30''$ ($\alpha \times \delta$) slit and 632 line mm^{-1} grating combined to give a spectral resolution of 84 km s^{-1} at $2.2935 \mu\text{m}$, the rest wavelength of the CO 2-0 vibrational-rotational bandhead. The spectrometer was used in first order. The IRS spectra are Nyquist sampled, giving a total spectral coverage of approximately 2600 km s^{-1} ($0.02 \mu\text{m}$) at $42 \text{ km s}^{-1} \text{ pix}^{-1}$. The spatial scale along the slit is $2.39'' \text{ pix}^{-1}$.

We obtained spectra for 33 stars brighter than about $K = 9.0$ in the 42 arcmin^2 field shown in Figure 1. The field is centered on SAO 185534, located at $\alpha(1950) = 17^h 32^m 39.1^s$, $\delta(1950) = -28^\circ 54' 43''$. The locations of the program stars relative to SAO 185534 are shown in Table 1. The program stars were usually observed in a sequence of star-sky-sky-star, where the sky position was chosen from a blank point on the K band image. All reduction steps were done using IRAF².

The final spectra were obtained through the following procedure. The average of the two star frames was subtracted from the average of the two sky frames. After

²IRAF is distributed by the National Optical Astronomy Observatories.

TABLE 1
PROGRAM STAR POSITIONS AND MEASURED
PROPERTIES

Star	$\Delta\alpha$ (")	$\Delta\delta$ (")	V_r (km s ⁻¹)	K	$J-K$	CO
1	174	-147	140	8.71	—	0.31
2	-157	-155	-117	8.22	2.16	0.46
3	-105	-135	-126	8.19	2.19	0.36
4	135	-119	112	8.00	2.10	0.33
5	-40	-122	-315	8.91	2.15	0.30
6	8	-120	-158	9.22	1.98	0.33
7	-138	-112	-243	8.80	2.08	0.36
8	165	-84	-163	8.55	—	0.33
9	-45	-72	-7	8.68	2.20	0.31
10	75	-24	1	8.72	2.20	0.33
11	-34	-19	-80	8.20	2.22	0.39
12	108	-3	125	8.58	2.12	0.32
13	92	5	-224	7.93	2.18	0.27
14	37	31	-94	7.26	1.86	0.28
15	-176	33	-33	8.72	2.17	0.35
16	-102	43	130	8.69	2.11	0.40
17	123	98	-175	8.80	1.93	0.35
18	137	103	106	8.43	2.20	0.28
19	-16	115	-57	6.00	—	0.31
20	-24	126	-131	8.15	2.30	0.26
21	-109	149	41	8.77	2.12	0.35
22	-68	156	134	8.11	2.07	0.30
23	-177	154	-140	8.53	1.95	0.26
24	-202	155	1	7.69	—	0.35
25	-74	175	-225	7.61	2.16	0.31
26	-100	175	14	8.68	1.51	0.31
27	-139	-52	-27	6.50	2.17	0.34
28	157	-4	-42	8.09	2.09	0.29
29	153	-18	-222	8.24	2.28	0.32
30	120	-47	-205	7.43	2.05	0.34
31	124	-43	-95	7.50	2.29	0.31
32	-60	-65	-135	7.45	2.31	0.32
33	-99	-60	-271	7.60	2.16	0.36

NOTE.— Note to Table 1: All offsets are from SAO 185534 located at $\alpha(1950) = 17^{\text{h}}32^{\text{m}}39.1^{\text{s}}$, $\delta(1950) = -28^{\circ}54'43''$. The offsets were determined from the K band image in Figure 1 and have been corrected for a 1.9° counter-clockwise rotation of the field. The offsets are uncertain by approximately $\pm 1.5''$. The radial velocities, V_r , are heliocentric and have individual uncertainties of approximately ± 20 km s⁻¹. The K magnitudes and $J - K$ color are observed, not reddening corrected. The photometric errors in the J and K magnitudes are 0.06 mag. The K magnitude for star 19 is an upper limit. No J magnitudes were available for stars 1, 8, 19, and 24; see text. CO absorption strength is the relative flux in $0.005 \mu\text{m}$ bandpasses just shortward and longward of the bandhead.

being divided by dome flat-field images, the spectra were extracted from the images by synthesizing 2-D apertures, approximately 3 pixels wide, and collapsing the spatial dimension to form 1-D spectra using IRAF “apextract.” The spectra were wavelength calibrated by a Xe arc lamp image. In order to correct for the instrumental profile and telluric absorption, early type stars were chosen from the Bright Star Catalog and observed throughout the night. The program star spectra were then ratioed by these atmospheric standards.

A typical program star spectrum is shown in Figure 2. This spectrum, like all the program stars, shows the strong CO absorption characteristic of K and M giants (Kleinmann & Hall 1986). The CO absorption strength was computed by comparing the flux just shortward of the bandhead to the flux longward of the band minimum in $0.005\ \mu\text{m}$ bandpasses. The CO values are given in Table 1. The mean CO absorption strength for the sample is $33 \pm 4\%$.

2.3.3 Radial Velocities

The program stars were cross-correlated with the spectra from a single M8 III star of known radial velocity from Baade’s Window (Sharples et al. 1990, star 301 in their Table 1), using the fast fourier transform technique employed by the “RV0” package in IRAF. Sharples et al. estimate the error in an individual star to be $\pm 9\ \text{km s}^{-1}$. Observations of this star were made at roughly equal intervals three times each night. A spectrum of the velocity standard is shown in Figure 2. Cross-correlation of the multiple spectra of this star taken at different times on each night and between nights showed velocity differences of less than $10\ \text{km s}^{-1}$. This is equivalent to an error in

Fig. 2.— Spectra near the $2.3 \mu\text{m}$ CO bandhead. Points are plotted every 42 km s^{-1} ; the spectral resolution is 84 km s^{-1} . a.) Radial velocity standard taken from Sharples et al. b.) Program Star no. 9.

reproducing the standard velocity of 0.12 pixels, or 0.06 of a resolution element.

There are at least three sources of systematic uncertainty in the measurement of these radial velocities. These are shifts in wavelength along the spatial dimension of the slit, wavelength shifts due to observing stars at different positions across the dispersion dimension of the slit, and the uncertainty in the velocity of our standard.

The first two effects could be ignored if each star was precisely placed in the same position in the slit. This was not the case since the program stars are located in an obscured field, and we had no visual counterpart to aid in acquisition and guiding. Program stars were acquired by offsetting from SAO 185534. Uncertainties in the telescope pointing and our calculated offsets resulted in stars being placed at different positions in the slit.

Initially, before any spectra were obtained, we offset to a number of stars at the edge of the field. Comparison of the calculated offset from Figure 1 to the actual offset found by acquiring stars in the slit indicated that the image was rotated approximately 1.9° counter-clockwise. We have corrected for this rotation in the offset values given in Table 1. Each program star was acquired by first centering on the foreground SAO star, using a dichroic in the optical path allowing visual acquisition and guiding, and then offsetting by the amount indicated in Table 1. We relied on the calculated offsets to put the program stars in the slit in order to maximize observing efficiency and thus, the number of stars obtained.

Consider displacements along the spatial dimension of the slit. Positions in this direction were measured off the 2D spectral images using the “apcenter” routine in

IRAF. On the first night, the mean position of the program stars along the slit varied from that of the mean radial velocity standard position by only $0.45 \pm 1.49''$. On the second night the difference was $0.05 \pm 1.50''$. The relatively small displacements from slit center also indicate that our calculated offsets were uncertain by only $\pm 1.5''$ in declination. Throughout each night, OH airglow lines were observed in second order by changing the order sorting filter; the grating was not moved. Comparison of OH spectra separated by more than $10''$ above and below the slit center showed shifts of no more than a few km s^{-1} . Therefore, we are confident that there is no significant uncertainty in the radial velocity due to position along the spatial direction.

Next, consider displacements across the slit. A star which is observed alternately at each side of the slit will show a velocity difference due to the different incident angles on the grating. The difference is of order, but less than, the resolution. For the IRS, the $4.8''$ slit results in a calculated shift of 72 km s^{-1} for a point source. Observations of star 28 near either side of the slit showed a 42 km s^{-1} shift. We also stepped a bright star across the slit. These spectra show a 32 km s^{-1} shift. The difference in these two measurements indicates the difficulty of precise positioning within the slit. These measured velocity shifts are smaller than the calculated 72 km s^{-1} shift since the stars have finite width and could not be precisely located at the slit edge.

As long as the program stars were placed randomly in the slit with respect to the standard, no large systematic uncertainty is expected since the majority of stars would not be expected to fall at the slit edge. Only in the case where the majority of

program stars were observed on the opposite side of the slit from the standard would there be a large systematic error in the mean velocity for the sample. This is unlikely because the standard was placed in the slit by centering its visual counterpart on the marked boresight on the TV guider while the program stars were placed in the slit by offsetting from SAO 185534 after its visual counterpart was similarly centered on the TV guider. The TV guider reference for the slit was defined by observing a star (usually SAO 185534) on the visual display while peaking up the counts in the spectrometer. This alignment procedure was used to account for differences in the optical and infrared light paths such as might be caused, for example, by differential refraction. The alignment would systematically drift throughout the night until stars were no longer acquired in the slit and the boresight had to be redefined. Alignment was done 2–3 times per night. Since program stars and the standard were obtained at various times after re-alignment, with no preference for observing the standard right before or after re-alignment, we expect no systematic differences in the positions in the slit.

Finally, we consider uncertainties in the velocity of our standard. We obtained spectra of a sample of K giants from the Bright Star catalog (taken as part of a different program on the same nights as the bulge stars with the same setup) with known velocities that we attempted to use to verify the velocity of our standard. The K giants (BS numbers: 224, 296, 489, 8841, and 8924) cross-correlate with each other to a mean difference between measured and Bright Star Catalog velocities of $1.3 \pm 16 \text{ km s}^{-1}$. However, the K giants cross-correlate with our standard to a mean

difference between measured and Bright Star Catalog velocities of $-41 \pm 10 \text{ km s}^{-1}$, four times the uncertainty given by Sharples et al. (1990). We believe this systematic blue shift is due to either declination dependent instrument flexure or a significant shift in the boresight alignment with declination. The latter seems most likely as we also observed shifts in the boresight alignment while tracking our bulge field in hour angle. Since we did not originally intend to use the K giant velocities, we did not re-align the boresight later in the night when the K giant spectra were obtained. The K giants were 20–30 degrees further north than the radial velocity standard and program stars. This suggestion, that the difference in calculated velocities between the K giants and the Sharples et al. star was due to declination dependent flexure and/or boresight shift, was checked by comparing both the K giants and the standard to a spectrum of the M2 super-giant, IRS7, located near the Galactic Center. IRS7 is less than a degree away from the standard and program stars. The radial velocity of IRS7 (adjusted to the heliocentric frame of reference) was taken from Sellgren et al. (1987). Cross correlation with IRS7 gives a mean difference of $-32 \pm 8 \text{ km s}^{-1}$ for the K giants and 0.0 km s^{-1} for the velocity standard, in agreement with our supposition that the difference in velocities is due to flexure of the instrument and/or boresight shift.

We therefore take the heliocentric velocities for the program stars relative to the star from Sharples et al. to be correct and adopt an uncertainty in an individual measurement of $\pm 20 \text{ km s}^{-1}$, which is consistent with the analysis of the K giants and the systematic uncertainty due to slit positioning as determined from the measurements

of star 28.

Subsequent to these observations, we obtained 27 km s^{-1} resolution spectra ($3.34 \text{ km s}^{-1} \text{ pix}^{-1}$) of four of our program stars using the CSHELL spectrometer (Tokunaga et. al. 1990) at the NASA Infrared Telescope Facility on Mauna Kea. The difference between the CSHELL velocities and those reported above is consistent with the quoted uncertainties.

2.4 The Distribution of Stars Along the Line of Sight

To use the measured kinematics in a study of the inner Galaxy, we first need to estimate their distribution in space along the line of sight. In addition, a comparison of the observed kinematics to those predicted by the axisymmetric mass model of Kent (1992) requires not only that the stars be distributed along the line of sight at true galactocentric distances close to the projected radius, but that they also be uncontaminated by disk stars since these are not included in the model. The mean position can be estimated from our photometry and the spatial distribution and contamination can be estimated by construction of a bulge + disk galaxy model.

First of all, an estimate of the extinction to our field will be required for any photometric distance determination. This can be obtained from the J and K photometry of stars in our field. The mean $J - K$ for stars in the field as determined from aperture photometry was 2.11 ± 0.09 . The mean intrinsic $J - K$ can be estimated from the measured CO absorption strengths which are independent of reddening. Direct comparison of our mean CO strength with the disk M giant spectra in Kleinmann & Hall (1986) suggests a mean spectral type of M7 or later. The flux in the band and

continuum for the Kleinmann & Hall spectra are summed over the same bandpasses used in section 2.2; the resolution of the Kleinmann & Hall spectra is 106 km s^{-1} . Binning our spectra to this smaller resolution does not change the assignment of a mean spectral type for the program stars. The CO strength can also be compared to the spectra of bulge M giants from Terndrup, Frogel & Whitford (1991). Binning our spectra to wavelength bins $0.0023 \text{ } \mu\text{m}$ wide, corresponding to the 300 km s^{-1} resolution of the Terndrup et al. data, results in a mean CO strength of $26 \pm 3 \%$. Using the Terndrup et al. M6–M9 bulge giants (see their Table 5), we find a mean CO strength of $27 \pm 2 \%$. The mean CO strength for the three M6 and three M7 stars is $26 \pm 3 \%$, each separately and for the six stars combined. Here the CO absorption strengths are computed by comparing the flux shortward of the bandhead and longward of the band minimum, in bandpasses approximately $0.006 \text{ } \mu\text{m}$ wide.

Assignment of a mean spectral type is uncertain since the spectra all have different original resolutions and the comparison samples are small. We adopt a mean spectral type of M7 III; this corresponds to an intrinsic $J - K$ of 1.15 for the bulge stars in Terndrup, Frogel, and Whitford (1990) which were measured on the CTIO/CIT system. Color transformations between OSIRIS and CTIO/CIT do not yet exist, but we estimate that the correction for an M7 III would result in a $J - K$ bluer by 0.04 magnitude based on transformations of other NICMOS cameras (Rayner 1993). Since this correction is small and uncertain, we ignore it. Assuming the interstellar reddening curve of Mathis (1990) leads to $A_K = 0.59 \pm 0.06$, where the error is due to the photometric uncertainty.

An estimate of the positions and number of intervening disk stars was made by constructing a disk model based on the luminosity function of Garwood and Jones (1987). The luminosity function is subdivided by spectral class and is defined by star counts in the solar neighborhood. An exponential density distribution was taken in both the radial and disk normal directions. The vertical scale height for each class (the K and M giants have vertical scale heights between 200 and 300 pc) was also taken from Garwood and Jones. A radial scale length of 3 kpc was adopted from Kent et al. (1991), together with a sun to Galactic Center distance of 8 kpc.

A bulge model was also constructed in order to estimate the distribution of positions of bulge stars and the ratio of bulge to disk stars in the field. The space density distribution was adopted from Kent (1992), and the luminosity function was taken from Frogel & Whitford (1987). The bulge model was normalized such that the total number of stars from the bulge and disk combined, with $K \lesssim 9.0$ mag, equaled the number obtained from the $2.2 \mu\text{m}$ image of Baade's Window presented by DePoy et al. (1993). DePoy et al. find 483 stars in their image with $K \leq 9.0$ mag. The normalization does not depend heavily on extinction since the reddening toward Baade's Window at K is small ($A_K = 0.14$ mag, Frogel & Whitford 1987).

The total number of stars in our frame brighter than $K = 9.0$ as determined from aperture photometry was 72 ± 9 , where the uncertainty arises from the photometric error for a single star plus the zero point uncertainty in the magnitude scale due to airmass correction. Taking into account the small amount of extinction to BW and the extinction to our field, the bulge + disk model predicts 60 stars brighter than K

$= 9.0$ and disk contamination (disk stars/(disk+bulge stars)) of 29 %. Allowing for variations in the disk scale length (2500–3500 pc) and sun to Galactic Center distance (7500–8500 pc), the disk contamination in our field was predicted to vary from 21 % to 47 %, with the shortest scale length giving the largest disk contribution. Since the models are normalized by star counts toward BW, changing these parameters does not change the total number of stars predicted by more than a few.

The preferred model is in good agreement with the observed star counts to our field if the extinction toward BW and the field are accounted for. The bulge model predictions do not depend sensitively on the distribution of extinction along the line of sight since most of it is likely to arise in the disk. The measured extinction is less than that determined from the axisymmetric model of Kent et al. (1991) which relies on the radial distribution of gas in the Galactic disk. The smaller amount of extinction measured here may reflect the patchy nature of extinction toward the Galactic Center. It also suggests that the distribution of absorbers along our line of sight is different than the azimuthally averaged radial distribution in the disk. Therefore, the extinction is added at a single radius for the models described above. For radii where the extinction is introduced variously from 3500 to 8000 pc from the Galactic Center, the total number of stars and the disk contamination change by a few percent. The model quoted above uses an extinction introduced at 4000 pc, the distance at which the gas distribution peaks in the disk (Burton 1989).

Before using the derived models to predict the radial distribution of stars corresponding to our sample, it is first useful to estimate the distance of the program stars

along the line of sight by comparing their color magnitude diagram to that for the M giants in Baade’s Window. In Figure 3, we compare the K vs. $J - K$ diagram for the program stars to the mean and median relations for the BW M giants measured by Frogel & Whitford (1987) which we have reddened by the amount calculated for our field. No color corrections were applied to the intrinsic BW colors for consistency with the derived $E(J - K)$. No J magnitudes are available for stars 1, 8, and 24 because the J image was rotated slightly with respect to the K image shown in Figure 1, placing these stars off the J frame. These three stars all showed strong CO absorption indicating they are late type giants; none had K magnitudes which would suggest they were foreground objects. Star 19 was saturated on both J and K images, so its color is undetermined. The majority of our stars lie near the Frogel & Whitford relations, suggesting a mean distance that places them in the inner Galaxy. There are four stars (14, 19, 27, 30) with apparent brightnesses that suggest they are foreground disk giants; see Table 1. One star, 26, has significantly lower intrinsic $J - K$. It may be a foreground star, or the extinction may vary in the field. Its combination of K magnitude and CO strength suggest it is not a foreground star. We consider the effect of removing these five stars from the sample in the next section when we discuss the mean velocity and velocity dispersion of the program stars.

Using the observed magnitudes and colors, an estimate of the distribution of stars along the line of sight can be made from the previously described models. The observed CO strengths indicate that most of the stars are later than about M4–M5 III. Selecting such stars with observed K brighter than 9.0 from the disk + bulge

Fig. 3.— Comparison of the K vs. $J - K$ color magnitude diagram for the program stars (filled boxes) and the unbiased sample of Baade's Window M giants from Frogel & Whitford (1987) which have been corrected to the reddening in our field. Typical uncertainty in K and $(J - K)$ are ± 0.06 and ± 0.09 magnitude, respectively.

model, we find a distribution highly peaked about the point lying along the line of sight at a true distance from the Galactic Center of 300 pc. The distribution is shown in Figure 4, where the distance plotted is the true galactocentric distance to a point along the line of sight. Note that the double lines in this figure result from stars in front and back of the 300 pc point. The mean galactocentric distance to stars along the line of sight is 605, 1815, and 920 pc for the bulge stars, disk stars, and total, respectively. The predicted distribution shows that 50% of the stars are located at true distances less than 400 pc and 90% within 1300 pc. If the short and long scale length models are used, the mean distances change up to $\pm 10\%$ for the disk stars and total; the bulge mean distance remains unchanged.

Both Figures 3 and 4 indicate that the program stars are confined to true galactocentric radii near the center of the Galaxy.

2.5 Results and Discussion

The resulting velocity dispersion and mean heliocentric radial velocity for the sample of 33 stars are $127 \pm 16 \text{ km s}^{-1}$ and $-75 \pm 24 \text{ km s}^{-1}$. The velocities may be corrected to the LSR by adding 10 km s^{-1} to account for the earth's motion through the LSR toward the Galactic Center. A further correction of -4 km s^{-1} may be added to account for the projected component of the 220 km s^{-1} Galactic rotation rate at the solar radius. The quoted error in the dispersion is dominated by statistical uncertainty but includes the effect of a $\pm 20 \text{ km s}^{-1}$ systematic uncertainty in an individual measurement (consistent with the observed dispersion in measured K giant velocities and positioning uncertainties discussed in section 2.3). The determination

Fig. 4.— Model distribution of stars with respect to true galactocentric distance along the line of sight. The double lines indicate stars in front and back of the point along the line of sight located at 300 pc galactocentric radius.

of the statistical uncertainty in the velocity dispersion follows the discussion in Da Costa et al. (1977). The uncertainty in the mean radial velocity is the dispersion added in quadrature to the error for an individual measurement, divided by the square root of the the number of stars in the sample, plus the 9 km s^{-1} error in the velocity standard added in quadrature. The distribution of velocities was compared to a gaussian distribution with the observed mean velocity and velocity dispersion. Application of a Kolmogorov–Smirnov test shows that the distribution is statistically different from a gaussian at a confidence level of less than 80%; thus there is no statistical evidence that the velocity distribution is non-gaussian.

The observed kinematics in our field may be compared to Kent’s model, for which he reports (private communication) a velocity dispersion of 119 km s^{-1} and mean velocity of -25 km s^{-1} (here we have corrected Kent’s mean velocity to the heliocentric frame). The velocity dispersion is in good agreement. If the individual velocities have not been affected in a systematic way, as argued in section 2.3, then there is some evidence (2.1σ) for larger rotational support than predicted by Kent’s model. Indeed, Lindqvist et al. (1992) derive a dynamical model for the inner Galaxy that shows more rotational support (higher mean radial velocities) than Kent’s model. They derive the mass distribution from kinematics of OH/IR stars under an assumed spherical potential. At 104 pc, similar to the longitude of our field but along the major axis, they find a mean radial velocity of $97 \pm 14 \text{ km s}^{-1}$ and dispersion of $111 \pm 14 \text{ km s}^{-1}$. The mean radial velocity is much larger than given by Kent’s model which predicts a mean radial velocity of 40 km s^{-1} everywhere on the major axis. However, Lindqvist

et al. find that a sub-sample of their stars, which may be less concentrated toward the plane, shows lower mean velocities. The OH/IR stars, in general, are strongly concentrated toward the Galactic plane (approximately within ± 50 pc), so they may not be representative of stars at more extended latitudes.

The Kent dynamical model is a solution to the Jean's equations and as such, requires that the population used to trace the stellar space density distribution is the same as that from which the kinematics are obtained. Since the Kent model has no disk population included, we must account for the possibility that the observed kinematics do include disk stars. Our two component models indicate a disk contribution of 21 to 47% of the sample. Disk stars might be identified by their position on the color magnitude diagram in Figure 3. Stars 14, 19, 27, and 30 have similar color but brighter apparent magnitudes than those on the BW relations and may thus be foreground disk stars. Star 26 has lower intrinsic $J - K$ and may thus be in the foreground. If we remove these five stars (15% of the sample), the mean radial velocity and velocity dispersion are -75 ± 26 km s $^{-1}$ and 134 ± 17 km s $^{-1}$, respectively. Thus, there is no significant change in the result if these stars are excluded.

While including a dynamical disk model is beyond the scope of the present paper, the effects of contamination can be estimated from the observed disk star kinematics found by Lewis and Freeman (1989). Lewis and Freeman find a radial velocity dispersion of 89.3 ± 9.5 km s $^{-1}$ at a distance of 1400 pc and 94.8 ± 9.0 km s $^{-1}$ at 600 pc from the Galactic Center toward BW. They find mean radial velocities less than 20 km s $^{-1}$ toward BW at distances between 5 and 1 kpc from the Galactic Center.

Thus, we would expect that if stars such as these are, in fact, included in the present sample, removing them (assuming mean kinematics) from the bulge sample would result in an increase in the dispersion and a more negative mean velocity. Thus, we would expect a correction for disk contamination to increase the discrepancy in mean radial velocity between our measurements and the Kent axisymmetric model; the velocity dispersion would still be in good agreement. More importantly, given that the disk increases in temperature toward the center and that most of the stars intervening along the line of sight are expected to be close to the bulge (a consequence of the space distributions assumed in our models along with the magnitude limit), separation of the stars into distinct components can not be easily done kinematically and would be difficult even with accurate distance indicators.

We believe the velocity dispersion estimate is probably robust, because the kinematics remain essentially unchanged if we exclude the stars most likely to be disk stars, the disk itself increases in temperature at small galactocentric radii, and the stars appear to be distributed close to the point along the line of sight at galactocentric radius 300 pc. The large (negative) mean radial velocity measured here and also those measured by Lindqvist et al. (1992) suggests that the mass distribution still remains uncertain in this region of the inner Galaxy.

An interesting final note is that the large negative mean velocity found for this sample is suggestive of the streaming motions of stars moving in a barred potential seen at a small angle relative to its major axis. Binney et al. (1991) infer a rotating bar from the inner Galaxy gas kinematics which has a major axis inclined to our line

of sight by $16 \pm 2^\circ$. Blitz and Spergel (1991) derive strong evidence for a nuclear bar from asymmetries in the $2.4 \mu\text{m}$ surface brightness distribution in the first and fourth Galactic quadrants. This near infrared surface brightness distribution asymmetry is confirmed by the COBE observations of Weiland et al. 1994 who used multi-color data to correct for extinction. The mean velocity found in our sample is in the same sense as the gas moving on closed orbits in the Binney et al. potential, and the longitude and latitude of our field are well within the angular scale lengths of the bar derived by Blitz & Spergel.

Two cautionary notes are in order. The orientation of the bar is well constrained by the gas kinematics but the analysis of the stellar surface brightness distribution does not tightly constrain the orientation to be close to the line of sight. Also, since we have measurements in only one field, the large mean radial velocity, which differs from Kent's axisymmetric model only at the 2.1σ level, could result from systematic errors. Our recent observations in two other fields at similar radii should help resolve these questions as well as the uncertainty in the mass distribution in this region.

2.6 Summary

We have obtained radial velocities for a sample of 33 late type stars in a 42 arcmin^2 field distributed near 300 pc projected radius from the Galactic Center. Analysis of the 84 km s^{-1} resolution spectra centered on the CO bandhead at $2.3 \mu\text{m}$ results in a mean velocity of $-75 \pm 24 \text{ km s}^{-1}$ and a dispersion of $127 \pm 16 \text{ km/s}$. Comparison to the axisymmetric mass model of Kent (1992) shows good agreement with the velocity dispersion but some evidence (2.1σ) for a more negative mean velocity than expected.

The large (negative) mean velocity is suggestive of streaming motion in a rotating barred potential such as derived by Binney et al. (1991) for the inner Galaxy.

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CHAPTER III

M Giant Kinematics in Off-Axis Fields Between 150 and 300 Parsecs from the Galactic Center¹

3.1 Abstract

We present radial velocities for approximately 40 stars in each of three optically obscured, off-axis, fields toward the Galactic bulge. Combined with the data presented by Blum et al. (1994), we now have mean radial velocities and radial velocity dispersions in four fields towards the Galactic bulge. These four fields lie nearly along an axis whose position angle from the major axis of the Galaxy is 55° . The observed kinematics generally match both Kent's (1992) axisymmetric and Zhao's (1994) barred dynamical model predictions, but are marginally better described by the latter.

The velocity dispersion in our innermost field is high, $153 \pm 17 \text{ km s}^{-1}$. Our data, combined with that from previous studies at larger radii, suggest that the stellar velocity dispersion is flat or still rising at projected radius $R \lesssim 150 \text{ pc}$.

3.2 Introduction

Recent photometric studies and star count data have produced strong evidence that the inner Galaxy, or bulge, is bar shaped (Blitz & Spergel 1991, Nakada et al. 1991,

¹This chapter appeared in its entirety as Blum et al. 1995a

Weinberg 1992, Whitelock & Catchpole 1992, Weiland et al. 1994, Stanek et al. 1994, and Dwek et al. 1994). Dynamical modeling of the observed gas kinematics also indicates that the inner Galaxy is non-axisymmetric (Binney et al. 1991), a result first suggested by de Vaucouleurs (1964), who compared the non-circular gas motions of the inner Galaxy to those in external barred galaxies.

Surprisingly, clear signs of a non-axisymmetric potential have not been found in the observed stellar kinematics (de Zeeuw 1993). Recent stellar kinematic studies have been completed at a number of positions projected onto the Galactic bulge. The majority of these have been in the optical windows, regions of lower interstellar extinction, along the bulge minor axis ($b \gtrsim 3^\circ$), and several have explored the bulge kinematics at larger longitudes (e.g. Minniti et al. 1992 and Harding & Morrison 1993). Kent (1992) and de Zeeuw (1993) provide recent compilations of the locations and results of these bulge kinematic studies. At radii inside the optical windows, the majority of stellar kinematic work has been done at the Galactic center (GC) ($R \lesssim 10$ pc; see Genzel, Hollenbach, & Townes 1994 for a recent review) and along the major axis between $\sim 10 - 100$ pc (Lindquist et al. 1992). Our data, combined with that of Blum et al. (1994), explore the inner Galaxy stellar kinematics at radii which are intermediate between the Galactic center and optical windows. To search for evidence of triaxiality and to better constrain the inner Galaxy mass distribution at these intermediate radii, we have obtained radial velocities for stars in each of four fields located at off-axis positions between 150 and 300 pc projected radius from the GC. The results for one of these fields were previously given by Blum et al. (1994).

The large amount of interstellar extinction toward the GC at optical wavelengths requires spectroscopic observations at near infrared or longer wavelengths. The radial velocities presented here were obtained from spectra centered near the $2.3\ \mu\text{m}$ CO bandhead, a strong photospheric absorption feature in M giants. Where required, we adopt a distance of 8 kpc to the GC (Reid 1993).

3.3 Observations and Data Reduction

The observational data are a combination of three distinct sets: J and K band images from which the program stars were selected, spectra obtained with the CTIO grating spectrometer, IRS, and spectra obtained with the IRTF echelle spectrometer, CSHELL. These three data sets and their reduction procedures are discussed separately below. For all three data sets, the basic image processing tasks were performed using IRAF²

3.3.1 Imaging

The program stars are located in four fields which lie along a “slit” projected across the bulge (approximately intersecting $l = b = 0^\circ$) and oriented at an angle of $\sim 55^\circ$ with respect to the bulge major axis. The field locations were chosen to coincide with foreground SAO stars so that accurate offsets could be calculated to the program stars for use in obtaining the program star spectra (see below). The locations of all four fields are indicated in Table 2.

²IRAF is distributed by the National Optical Astronomy Observatories.

TABLE 2
M GIANT FIELDS AND MEAN PROPERTIES

Field	l°	b°	$R^a(\text{pc})$	CO_{sp}^b	CO_{ph}^c	$(J - K)_o^d$	A_K^e	$\bar{V}_r^f(\text{km s}^{-1})$	$\sigma(\text{km s}^{-1})$
1	-0.59	0.98	160	0.30	0.21	1.05	1.06	-31 ± 28	153 ± 17
2	0.85	-0.88	171	0.32 ^g	0.23	1.10	0.79	0 ± 23	128 ± 14
3	1.21	-1.67	288	0.29	.20	1.05	0.29	14 ± 23	128 ± 14
4 ^h	-1.14	1.81	299	0.33	0.24	1.10	0.63	-75 ± 24	127 ± 17

^aProjected distance from the Galactic center, assuming $R_0 = 8$ kpc

^bObserved mean spectroscopic CO strength

^cPhotometric CO index converted from spectroscopic CO strength; see text

^dintrinsic color based on CO index vs. intrinsic $J - K$ of FW; see text.

^eDerived using the extinction law of Mathis (1990) and intrinsic color based on CO strength; see text. Uncertainty in A_K is ~ 0.01 mag from photometric uncertainty alone.

^fHeliocentric radial velocity

^gCO converted to lower resolution measure; see text.

^hCO and observed colors taken from Blum et al. (1994), but intrinsic colors and extinction derived here

The program stars were selected from the brighter and redder stars on J ($\lambda=1.25 \mu\text{m}$, $\Delta\lambda=0.24 \mu\text{m}$) and K ($\lambda=2.2 \mu\text{m}$, $\Delta\lambda=0.4 \mu\text{m}$) band images obtained with the Ohio State Infrared Imaging System (OSIRIS) on the Perkins 1.8m telescope near Flagstaff, Arizona in 1993 May. OSIRIS employs a 256×256 NICMOS III array. The images were taken in low resolution mode which results in a spatial scale of $\sim 1.5'' \text{ pix}^{-1}$ on the Perkins telescope. OSIRIS is more fully described by DePoy et al. (1993).

All of the J and K images were taken through a 10 % transmission neutral density filter so that the brighter stars would not saturate the detector. A typical exposure time with the neutral density filter was 3 seconds for each filter. Each J and K image was sky subtracted with frames obtained at nearby positions off the bulge, then flattened using dome flats. Several of the sky images used were taken without the 10% transmission neutral density filter. These were scaled appropriately before subtraction. Low order variations due to scattered light differences may exist between images with and without the neutral density filter, but any residual background should be accounted for by local background values determined when the photometry was obtained for the stellar images (see below).

J and K magnitudes were obtained from the reduced images by synthesizing circular apertures (3 pixel radius) about each star. A local background, or sky, component (determined from an annulus extending 5 pixels from the aperture edge) was subtracted before the magnitude determination. Magnitudes were typically obtained for each program star from three frames each at J and K . Scatter between measurements

of the same star from the different frames suggests typical photometric uncertainties of ± 0.05 mag and ± 0.02 mag at J and K , respectively.

The photometry was calibrated using stars of known magnitudes from Baade's window ($l, b = 1^\circ, -4^\circ$) (stars 107, 108, B 28, and B 66 from Frogel and Whitford 1987; hereafter FW) and the flux standards HD 162208, HD 106965, and HD 136754 (Elias et al. 1982). These stars have magnitudes given on the CTIO/CIT system. The scatter between different measurements (typically 3 to 5 frames for each filter) of the same flux standard was $\lesssim 0.03$ mag and 0.02 mag at J and K , respectively. There is an additional uncertainty of $\sim \pm 0.04$ mag due to uncertain airmass correction between the standards and program stars.

Adding the above photometric uncertainties in quadrature results in a typical uncertainty for an individual program star of 0.07 mag and 0.05 mag at J and K , respectively. The true uncertainty may be larger than this due to image crowding in the field. However, the effects of crowding should be less for the brighter stars which we are concerned with here.

Transformations between the OSIRIS photometric system and other systems do not yet exist, but the color transformation between the standard OSIRIS system (no neutral density filter) and the CTIO/CIT system is estimated to be less than the observational uncertainties reported here and is not included (Blum et al. 1994; Tiede & Frogel 1994). However, there may be a systematic color correction for the neutral density filters. Sufficient data are not yet available for OSIRIS to determine whether a transformation exists between the standard and neutral density filter systems.

The observed K and $J - K$ for each star in fields 1, 2, and 3, for which spectra were obtained, are given in Table 3.

3.3.2 CTIO Spectra

The spectroscopic observations for fields 1 and 3 were made on the CTIO 1.5m telescope in 1993 July using the facility infrared spectrometer (IRS) which, at that time, employed an SBRC 58×62 InSb detector. The spectral resolution was 84 km s^{-1} ($42 \text{ km s}^{-1} \text{ pix}^{-1}$) at $2.3 \text{ } \mu\text{m}$, the position of the CO bandhead. The IRS had a spatial scale of $2.39'' \text{ pix}^{-1}$ and a $4.8'' \times 30''$ N-S oriented slit. A detailed description of the IRS may be found in DePoy et al. (1990).

The instrument set up and data taking mode were the same as that for field 4, as described in Blum et al. (1994). Briefly, program stars were acquired by offsetting from a visible star in the field using calculated offsets (Table 3) from a K band image. The visible stars from which program stars were located for fields 1 and 3 were SAO 185604 ($\alpha(1950)=17^h 37^m 13.48^s$, $\delta(1950)=-28^\circ 53' 50.0''$) and SAO 185927 ($\alpha(1950)=17^h 51^m 48.83^s$, $\delta(1950)=-28^\circ 44' 53.7''$), respectively. After offsetting, spectra were obtained in a star-sky-sky-star sequence.

The data reduction for these spectra was identical to that described by Blum et al. (1994), including wavelength calibration and correction for telluric absorption features, with one minor exception. Instead of combining both star and sky frames from a given star-sky-sky-star sequence resulting in a single spectrum for each program star, only the sky frames were combined. Each star frame was reduced and analyzed separately. This allowed for a first order check on the accuracy of the radial velocities

by directly comparing the values from the two spectra.

3.3.3 IRTF Spectra

The spectra for stars in field 2 were obtained in July 1994 using the IRTF 3m infrared telescope and facility echelle spectrometer, CSHELL (Tokunaga et al. 1990 and Greene et al. 1993). CSHELL employs a 256×256 InSb array and has a plate scale of $0.2'' \text{ pix}^{-1}$. The slit width was set at $2''$, giving a spectral resolution of 25 km s^{-1} ($2.5 \text{ km s}^{-1} \text{ pix}^{-1}$). The $30''$ long slit was oriented E-W.

Field 2 was centered on SAO 185837 ($\alpha(1950)=17^h 47^m 53.3^s$, $\delta(1950)=-28^\circ 38'46.8''$). CSHELL has a flip-in mirror which allows for imaging the field without moving the grating. This mirror was used to center each program star in the slit after offsetting from SAO 185837. Corrections made to the initial offsets for program stars suggest that the offsets given in Table 3 are accurate to about $1'' - 2''$. The higher spatial resolution of CSHELL allowed for a more efficient data taking mode since crowding is less at this scale. Each program star was observed in two positions, $\sim 7'' - 8''$ E and $\sim 7'' - 8''$ W of the slit center. In this way, star and sky measurements were made with two instead of four frames.

The final spectrum for a typical program star was obtained in the following way. The initial images were flat-fielded using continuum lamp images. Bad pixels were linearly interpolated across and replaced. The resulting two images for each star were then subtracted from each other. Two spectra were then extracted from the subtracted image using the IRAF “apextract” package. Each one-dimensional spectrum resulted from synthesizing 10 pixel wide apertures which had been traced along the

spectral dimension and which included a background aperture on each side of the spectrum located 13 pixels from the spectrum center. These spectra were ratioed by the spectrum of a hot star (spectral types O, B, or A) chosen from the Bright Star catalog to cancel telluric absorption features. Finally, the spectra were wavelength calibrated using Ar and Kr lamp lines.

The wavelength response changes slightly along the spatial dimension of the CSHELL array. Therefore, hot stars, radial velocity standards, and wavelength calibration images were taken at both of the spatial positions corresponding to the program stars. When determining velocities (see below), the IRTF/CSHELL data were always compared to standards taken at the same spatial position on the array.

Figure 5 shows the spectra of a radial velocity standard and two program stars measured on the CTIO/IRS and IRTF/CSHELL systems.

3.4 Spectral Analysis

3.4.1 Radial Velocities

Radial velocities were obtained for the program stars in all three fields by cross correlation with stars of known velocity using the “RV” package in IRAF. Typically all three, but at least two, of the following stars from the Bright Star catalog were observed each night on both the CTIO/IRS and IRTF/CSHELL systems: BS 6459 (K5 III), BS 7323 (M0 III), and BS 5192 (M5 III). In addition, we observed the velocity standard used by Blum et al. (1994), star 301 from Sharples, Walker, & Cropper (1990).

No systematic changes in velocity were observed for a given standard taken at

Fig. 5.— Spectra of the 2.3 μm CO bandhead. Upper panels, CTIO IRS spectra: resolution = 84 km s^{-1} ($42 \text{ km s}^{-1} \text{ pix}^{-1}$). Lower panels, IRTF CSHELL spectra: resolution = 25 km s^{-1} ($2.5 \text{ km s}^{-1} \text{ pix}^{-1}$). A typical radial velocity standard (BS 5192, M5 III) is shown along with program stars 1–32 and 2–48.

different times during a given night. Typical differences in multiple measurements of the same standard were less than 10 km s^{-1} , so all spectra of a given standard were averaged together on each night. Cross correlating the different standards on each night resulted in measured differences between the heliocentric velocities of less than 10 km s^{-1} compared to the differences in the published values (including star 301) in all cases except one, in which the difference between BS 6459 and BS 7323 on one night was 14 km s^{-1} .

For all nights, two standards (of the 2 or 3 available) were chosen to cross correlate with the program stars. In each case standards were used whose measured heliocentric velocity difference compared to the difference in the published values was less than 5 km s^{-1} . For one night on the CTIO/IRS system, this included star 301. Combined with the two measurements of each program star, this procedure resulted in four measured velocities for a typical program star. We adopt the average of these (typically) four velocities as the velocity for a given program star (Table 3). The standard deviation for a program star velocity calculated in this way was less than 10 km s^{-1} for 95 % of the program stars; the maximum deviation was 21 km s^{-1} .

A small number of stars measured on the IRTF/CSHELL system had radial velocities large enough that the bandhead was nearly shifted off the array. For these stars (indicated in Table 3), the velocity was estimated by measuring the shift in the bandhead position relative to the bandhead position for the standard. Because the CSHELL resolution is quite high (25 km s^{-1}) and a resolution element is well sampled (10 pixels), this should give a velocity estimate within the quoted uncertainty

(see below). Comparing the velocity measured in this way and that measured by cross-correlation for a number of stars indicates that this is the case.

An overall uncertainty in the measurement of a program star velocity was estimated by comparing the velocities determined for a subset of program stars on both the CTIO/IRS and IRTF/CSHELL systems. The difference between velocities measured for 15 stars in all four fields on both systems was $12 \text{ km s}^{-1} \pm 15 \text{ km s}^{-1}$, in the sense that the CTIO/IRS velocities are more negative. We adopt a typical error of $\pm 15 \text{ km s}^{-1}$ for the measurement of a single program star velocity. We discuss the effects of a possible systematic offset below.

3.4.2 CO Strengths

Measurement of the strength of the $2.3 \mu\text{m}$ CO bandhead leads to an estimate of the intrinsic, or de-reddened, color of the program stars. This combined with the observed $J - K$ color yields the reddening to each field. The CO feature is sensitive to both temperature and gravity, becoming stronger in lower gravity and cooler stars (Baldwin et al. 1973; Kleinmann & Hall 1986; hereafter KH). CO strengths in excess of 20 % (as measured by KH and here; see below) are characteristic of late K and M giants and supergiants. The difference in strength between dwarf and giant M stars is large, so they are easily distinguished from each other. The similar effects of lower gravity and lower temperature which both result in increased CO strength mean that K supergiants could have as strong a CO strength as later M giants. The more luminous K supergiants, located near or in front of the GC, would be conspicuous by their brightness and color and would not have been selected (see below). It is possible

that K supergiants, located behind the GC, could be confused with M giants closer to the GC. However, luminosity class I stars are expected to be much more rare, so we assume that the program stars are giants.

We define the measured CO strength as $1 - F_{CO}/F_{con}$, where F_{CO} and F_{con} are the total flux in bands just longward and shortward of the bandhead, respectively. For the CTIO/IRS data, the band passes were $0.005 \mu\text{m}$ wide. This value was chosen so a comparison could be made with the giant stars of known spectral type in KH. For the IRTF/CSHELL data, the total wavelength coverage was small ($\approx 0.005 \mu\text{m}$) and a direct comparison could not be made in this way. For these stars, the CO strength was measured in band passes $0.001 \mu\text{m}$ wide. The CO strengths (Table 3) were calculated using the LINER spectral analysis program in use at Ohio State (written by Richard Pogge).

The stars measured with the CSHELL/IRTF system (field 2) were first converted from a measured CSHELL/IRTF CO strength to a CTIO/IRS one based on the measurements of the subset of stars which were measured on each system (16 stars including the radial velocity standards). A linear fit to the data suggest a CO strength for field 2 of 0.29 ± 0.03 . The large uncertainty results from the considerable scatter in the measured CO strengths. About $1/2$ of these stars were taken under cloudy conditions, and their signal-to-noise ratio is much lower. Fitting the higher signal-to-noise data only, suggests a CO strength of 0.32 ± 0.02 . We adopt this value for the CTIO/IRS CO strength of field 2.

The mean CO strengths in fields 1,2, and 3 were found to be, respectively, $0.30 \pm$

0.01, 0.32 ± 0.02 , and 0.29 ± 0.01 , where the quoted uncertainty is the uncertainty in the mean (except for field 2). The CO strengths in fields 1, 2, and 3 are similar to that found for field 4 (0.33 ± 0.01) by Blum et al. (1994).

The measured CO strengths for the velocity standards on the CTIO/IRS system can also be compared to the CO strengths for stars of the same spectral type given in KH. The KH spectral resolution and band passes are similar to those used here for the CTIO/IRS data, so a direct comparison can be made. The CO strengths are in excellent agreement for BS 6459 ($0.23 \pm .01$, K5 III) and BS 7323 (0.25 ± 0.02 , M0 III) and reasonable agreement for BS 5192 (0.30 ± 0.01 , M5 III). We therefore conclude that no transformation is necessary between our data and KH.

The mean CO strength can be used to estimate the mean intrinsic $J - K$ color in each field. The difference between the observed and intrinsic color yields the color excess. The color excess and an assumed interstellar extinction law lead directly to the extinction (A_K) for each field. At least two factors could limit the accuracy of this approach. First, the relationship between CO strength and intrinsic $J - K$ has been found to be different for different stellar populations. FW measured photometric CO indices (a measure of the CO absorption strength over a $0.08 \mu\text{m}$ wide wavelength interval compared to a similar continuum band using narrow-band filters) for M giants in Baade's window and found that these stars had stronger indices (i.e. stronger CO absorption) than disk M giants of the same $J - K$. The relationship between CO and $J - K$ may also change systematically with latitude in the bulge (Frogel et al. 1990). The second limiting factor is the significant scatter in the measured CO index

versus spectral type or $J - K$ for the latest type bulge and disk M giants (Frogel et al. 1978, FW).

To estimate the intrinsic $J - K$ in our fields from CO indices and $J - K$ for either the field giants (Frogel et al. 1978) or bulge giants (FW), we must first convert our spectroscopic CO strength to a CO index. KH showed that the CO index employed by Frogel et al. (1978) for disk M giants is strongly correlated with the spectroscopic CO strength. Assuming this same relationship holds for our stars, we can assign CO indices to the measured spectroscopic CO strengths and use the CO index and $J - K$ data for bulge giants (FW) and disk giants (Frogel et al. 1978) to estimate the intrinsic color for stars in our fields.

The intrinsic $J - K$ for each field was obtained by averaging the bulge (FW) and disk (Frogel et al. 1978) $J - K$ values over a range of CO indices which corresponded to the mean CO indices $\pm$ one standard deviation in each of our fields. The intrinsic $J - K$ and A_K (determined with the interstellar extinction law of Mathis 1990) are similar for both the disk and bulge determinations. We adopt the bulge values to determine the unreddened color and K magnitude in the program star fields. The CO index, mean intrinsic color, and A_K for each field are given in Table 2.

3.4.3 Color Magnitude Diagram

In Figure 6, we plot the de-reddened color magnitude diagram (CMD) for all four fields using the intrinsic $J - K$ and A_K estimated above from the bulge giant (FW) CO indices and $J - K$ values. The left panel shows the CMD for all stars with observed $K \lesssim 9$ mag. The right panel shows those stars for which we obtained spectra. There

appears to be a clear sequence in the CMD, which we take to be the bulge or inner Galaxy giant branch. The relation for Baade’s window giants is also plotted from the data in FW. The CMD for the stars which we observed spectroscopically, appears to have a slightly bluer component than the M giants in Baade’s window. This could result from the uncertainties in the derived intrinsic $J - K$, a potential unknown color transformation (see §2.1), or from physical differences in the populations observed.

The data for Baade’s window suggest that the CMD has larger width in $J - K$ at its bright end. Our data also show this trend, but seem to be even broader. Part of the spread in our data may be due to differential reddening within a given field and uncertain reddening corrections between fields. The stars in Figure 6 which contribute the most to the width in the CMD are from fields 1 and 2 which are located at lower latitude. The images of Glass, Catchpole, & Whitelock (1987) show that the extinction inside a few degrees of the GC is both strong and variable on small spatial scales. Our inner fields are more crowded than Baade’s window which could also increase the scatter in our aperture photometry.

Some of the stars in the right panel of Figure 6 may be foreground or background stars. We have computed the distribution of stars along the line of sight for a simple two component bulge/disk model for each field with the same model described by Blum et al. (1994). The relative disk to bulge contamination for fields 1,2, and 3 (25%–29%) is quite similar to that reported for field 4 (28%) by Blum et al. (1994). In these simple models, which employ an exponential disk (Garwood & Jones 1987) and axisymmetric bulge (Kent 1992), many of the disk stars would still be at dis-

Fig. 6.— De-reddened color-magnitude diagram for the four program star fields. The extinction correction assumes the interstellar relation from Mathis (1990) and relies on using the mean CO strength to determine intrinsic color; see text and Table 2. The left panel depicts the CMD for stars in the four fields with observed $K \lesssim 9$ mag. The right panel shows the stars observed spectroscopically which were selected based on color and magnitude. The open circles in the right panel represent the data for Baade’s window M giants taken from FW.

tances making them co-spatial with bulge stars. We also note that while there is substantial evidence for an asymmetric light distribution in the inner Galaxy, which argues against using this simple two component axisymmetric model, none of the non-axisymmetric models are fit to the near infrared light distribution inside $b \lesssim 3^\circ$.

TABLE 3
M GIANT OBSERVED MAGNITUDES AND RADIAL
VELOCITIES

<i>Star</i>	$\Delta\alpha(^{\prime\prime})^a$	$\Delta\delta(^{\prime\prime})^a$	$V_r^b(\text{km s}^{-1})$	K^c	$J - K^c$	CO^d
1- 1	123	19	-63	8.04	2.59	0.24
1- 2	-95	-15	113	8.06	2.76	0.32
1- 3	-83	20	-69	8.20	2.66	0.32
1- 4	-67	-51	-282	8.24	2.89	0.35
1- 5	-66	-161	26	8.26	2.96	0.28
1- 6	-17	17	80	8.29	2.66	0.30
1- 7	90	179	19	8.32	2.52	0.28
1- 8	74	42	-92	8.38	2.82	0.27
1- 9	-92	-69	-85	8.39	2.92	0.35
1-10	-40	67	-88	8.40	2.71	0.32
1-11	-158	86	-142	8.42	2.56	0.24
1-12	-96	-89	142	8.42	2.77	0.34
1-13	-14	-117	-71	8.46	2.81	0.29
1-14	-166	-104	-224	8.49	2.77	0.30
1-15	-85	117	272	8.50	2.68	0.19
1-16	-93	145	-163	8.50	2.61	0.22
1-17	-163	-119	-6	8.53	2.75	0.29
1-18	-104	-41	-363	8.53	2.50	0.36
1-19	78	103	210	8.59	2.59	0.28
1-20	-138	111	116	8.63	2.62	0.32
1-21	-85	-112	-87	8.68	2.73	0.28
1-22	-82	-18	-84	8.70	2.51	0.27
1-23	132	63	-28	8.73	2.67	0.30
1-24	10	95	9	8.76	2.73	0.24
1-25	31	-103	-98	8.78	2.71	0.27
1-26	-120	-100	-35	8.80	2.71	0.34
1-27	80	-134	198	8.80	2.97	0.30
1-28	-2	-167	-175	8.80	2.93	0.34
1-29	34	-112	-93	8.82	2.86	0.32
1-30	-140	118	-17	8.82	2.65	0.32
1-31	186	-23	270	8.83	3.17	0.25
1-32	49	-90	-176	8.86	2.86	0.30
1-33	184	-97	-316	8.94	3.14	0.32
1-34	-29	-86	281	8.96	2.67	0.32
1-35	-72	-115	-104	8.98	2.51	0.17
1-36	-151	-134	58	8.99	2.78	0.26
1-37	-119	149	5	9.00	2.78	0.40
1-38	69	-85	-28	9.02	2.83	0.39
1-39	-106	57	-100	9.03	2.55	0.21
2- 1	-36	-130	58 ^e	7.86	2.26	0.34
2- 2	-156	-73	-23	7.88	2.80	0.48
2- 3	146	87	-192	7.91	2.26	0.58
2- 4	147	108	-77	7.91	2.19	0.48
2- 5	-150	-46	-268	7.91	2.57	0.43
2- 6	-54	-67	252 ^f	7.94	2.23	...
2- 7	-83	126	24	7.99	2.69	0.55
2- 8	139	-158	-108	8.01	2.36	0.48
2- 9	85	-32	-56 ^e	8.01	2.18	0.11

TABLE 3—*Continued*

Star	$\Delta\alpha(^{\circ})^a$	$\Delta\delta(^{\circ})^a$	$V_r^b(\text{km s}^{-1})$	K^c	$J - K^c$	CO^d
2-10	-4	-18	-232	8.02	2.33	0.51
2-11	-88	92	68	8.04	2.34	0.53
2-12	-41	-87	-136	8.11	2.18	0.57
2-13	-33	-53	158	8.13	2.31	0.51
2-14	-15	153	237 ^f	8.15	2.27	...
2-15	1	27	-30	8.17	2.32	0.56
2-16	-136	97	-20	8.18	2.41	0.46
2-17	-121	167	-18	8.22	2.34	0.41
2-18	138	-98	216 ^f	8.22	2.21	...
2-19	2	66	-172	8.23	2.23	0.52
2-20	-35	126	52	8.26	2.21	0.50
2-21	40	187	-64	8.30	2.54	0.53
2-22	-176	35	53	8.32	2.55	0.50
2-23	-62	117	278 ^f	8.36	2.50	...
2-24	15	153	-82	8.37	2.39	0.53
2-25	70	-97	113	8.41	2.18	0.52
2-26	-62	-106	-109	8.42	2.41	0.52
2-27	-136	181	-8	8.45	2.36	0.50
2-28	-139	-93	-105	8.47	2.50	0.52
2-29	-165	-97	-130	8.53	2.19	0.41
2-30	-144	133	74	8.55	2.36	0.48
2-31	-92	131	29	8.57	2.43	0.56
2-32	57	-74	182 ^f	8.58	2.23	...
2-33	25	-26	22	8.59	2.20	0.48
2-34	145	-78	-83	8.61	2.34	0.52
2-35	-90	192	22	8.62	2.31	0.52
2-36	-40	63	4	8.63	2.37	0.48
2-37	137	135	20	8.71	2.37	0.44
2-38	-143	112	48	8.72	2.22	0.42
2-39	-27	40	1	8.77	2.20	0.48
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3-1	-52	140	76	7.38	1.68	0.32
3-2	-102	-34	182	7.44	1.67	0.26
3-3	139	31	-152	7.57	1.60	0.32
3-4	130	10	-104	7.66	1.69	0.32
3-5	62	-131	210	7.67	1.64	0.32
3-6	3	-165	-183	7.68	1.73	0.27
3-7	60	-164	140	7.85	1.58	0.30
3-8	-146	-23	-18	7.92	1.53	0.25
3-9	-94	-45	-50	7.97	1.62	0.32
3-10	-18	-156	-17	8.00	1.53	0.29
3-11	11	54	-10	8.15	1.51	0.29
3-12	76	128	58	8.16	1.50	0.20
3-13	17	26	254	8.17	1.53	0.30
3-14	-154	160	56	8.21	1.61	0.26
3-15	-15	166	0	8.26	1.73	0.36
3-16	107	-66	18	8.27	1.65	0.33
3-17	-105	-175	-134	8.28	1.44	0.35
3-18	-165	-110	132	8.35	1.49	0.34
3-19	5	-11	18	8.36	1.66	0.25
3-20	-114	-159	-187	8.38	1.39	0.27
3-21	-57	101	-128	8.43	1.65	0.31

TABLE 3—*Continued*

Star	$\Delta\alpha(^{\prime\prime})^a$	$\Delta\delta(^{\prime\prime})^a$	$V_r^b(\text{km s}^{-1})$	K^c	$J - K^c$	CO ^d
3-22	53	-174	220	8.46	1.50	0.35
3-23	-118	169	10	8.47	1.57	0.25
3-24	22	12	78	8.48	1.40	0.30
3-25	-181	-98	-38	8.52	1.42	0.24
3-26	146	-92	-136	8.54	1.44	0.27
3-27	156	-7	-102	8.55	1.41	0.27
3-28	-153	103	59	8.55	1.52	0.26
3-29	-27	-103	180	8.56	1.49	0.32
3-30	42	-5	-20	8.56	1.59	0.33
3-31	-122	-93	-4	8.59	1.42	0.30
3-32	-35	-116	66	8.60	1.45	0.31
3-33	29	-110	-282	8.65	1.43	0.28
3-34	-57	-186	140	8.68	1.50	0.34
3-35	-166	-135	68	8.72	1.31	0.26
3-36	-63	-54	-168	8.75	1.47	0.32
3-37	89	-4	85	8.78	1.32	0.21
3-38	22	63	166	8.80	1.44	0.30
3-39	46	158	146	8.81	1.35	0.20
3-40	-155	-104	-87	8.81	1.35	0.21

^aOffsets are from SAO 185604 ($\alpha(1950)=17^h 37^m 13.48^s$, $\delta(1950)=-28^\circ 53' 50.0''$), SAO 185837 ($\alpha(1950)=17^h 47^m 53.3^s$, $\delta(1950)=-28^\circ 38' 46.8''$), and SAO 185927 ($\alpha(1950)=17^h 51^m 48.83^s$, $\delta(1950)=-28^\circ 44' 53.7''$) for fields 1, 2, and 3, respectively; see text. The offsets are accurate to $\sim 1'' - 2''$.

^bHeliocentric radial velocity. Velocities are uncertain by approximately $\pm 15 \text{ km s}^{-1}$; see text.

^cObserved magnitudes, uncorrected for interstellar extinction. The K and J magnitudes have photometric uncertainties of 0.07 and 0.05 mag, respectively.

^dThe CO strength is defined as $1 - F_{CO}/F_{con}$, where F_{CO} is the flux in a band just longward of the bandhead and F_{con} is the flux in a similar band just shortward of the bandhead. The band width was $0.005 \mu\text{m}$ for fields 1 and 3 and $0.001 \mu\text{m}$ for field 2.

^eHeliocentric velocity and CO strength measured on CTIO/IRS system.

^fHeliocentric velocity estimated from position of the bandhead, not by cross-correlation, and no measured CO strength because the large velocity shifted part of the CO band off the array.

3.5 Discussion

The mean heliocentric radial velocity and radial velocity dispersion for each field are given in Table 2. The quoted uncertainties are dominated by statistical uncertainty due to the small number of stars in each field, but they include the effects of measurement error (the uncertainties were determined as shown in Blum et al. 1994). These values may be compared to the predictions of dynamical models to help constrain the inner Galaxy mass distribution. In light of the photometric and gas kinematic observations, noted above in §1, we expect the inner Galaxy mass distribution may be strongly barred.

A range of bar models fit the observed near infrared light distribution about equally well (Dwek et al. 1994). These models have rather large differences in some of their characteristics, particularly in the orientation of the bar to our line of sight. To determine how sensitive the predicted kinematics are to the different mass models, we will compare our observed kinematics to predictions from two models which take quite different forms for the inner Galaxy mass distribution: the axisymmetric model of Kent (1992) and the triaxial bar model of Zhao (1994). The Kent model is an oblate, isotropic rotator. The velocity dispersion is assumed to be the same in any direction; the bulge appears flattened in this model due to net rotation about the axis normal to the plane of the Galaxy. Zhao's model is triaxial. It employs one of the best fit (Gaussian) density distributions found by Dwek et al. (1994) to the near infrared surface brightness distribution as observed by the DIRBE experiment on board COBE. The semi-major axes are 1.49:0.58:0.40 kpc (scaled from 8.5 kpc as

adopted by Dwek et al. to 8 kpc). The major axis of the bar is oriented at an angle to our line of sight of 13.4° . Both models assume a constant stellar mass to light ratio.

We note that the surface brightness asymmetry, which leads to the consideration of triaxial models for the bar in the first place, is constrained only with data at $b \gtrsim 3^\circ$. Zhao (1994) employs an axisymmetric density component similar to Kent (1992) within this distance of the Galactic center. This means that Zhao’s model is more similar to Kent’s model in the region where the present observations are taken. However, even though the density distribution is similar, other characteristics, like the velocity dispersion isotropy are not.

Within the framework of its assumptions, the Kent (1992) model should make quite accurate predictions. The Zhao (1994) model is the most realistic attempt at modeling the Galactic bulge as a triaxial stellar system; however, more work will be needed to explore the effects of varying the bar parameters.

We discuss the observations and models within the context of the velocity dispersions, mean velocities, and velocity distributions. We conclude our discussion by considering new types of observations which will further establish the bulge mass distribution.

3.5.1 Velocity Dispersion

Figure 7 shows a plot of our inner Galaxy dispersion measurements compared to the model results of Kent (1992) and Zhao (1994). The figure also shows observational results from the optical windows near the minor axis. The Kent prediction is for a “slit” projected across the bulge at an angle of $\sim 55^\circ$ from the major axis. Kent

generously made available his code to us so that these predictions could be made. The code is the same one that produced the Kent (1992) bulge model, with minor modifications. We reproduced the results of Kent (1992) to within a few km s^{-1} at all radii with this code. The slit nearly encompasses all our positions. The model prediction changes by only a few km s^{-1} at all radii for position angles from 45° to 90° , so a single position angle is sufficient for comparison to the observations (ours and previous observations made on the minor axis). The bar model prediction for the minor axis was taken directly from a figure presented by Zhao (1994). The bar model reaches slightly higher dispersions and reaches its maximum dispersion at a smaller radius than the axisymmetric model. Both models generally fit our data.

It is interesting to note that the N body simulation of Sellwood (1993), which forms a bar through a disk instability, also predicts higher velocity dispersions in our fields ($140 - 150 \text{ km s}^{-1}$, if his model is scaled to give a dispersion of 113 km s^{-1} in Baade's window). This result is for the end state of Sellwood's simulation. We are grateful to Sellwood for providing us with the results of his simulation which we "observed" along lines of sight to our fields (the bar major axis was aligned at $\sim 20^\circ$ to the line of sight). It is difficult to assess the significance of this result since the Sellwood model employs a rigid spherical mass distribution (30 % of the total mass) in addition to the distribution defined by the end state of the mass particles.

Previous kinematic results for minor axis fields at larger b (Rich 1990; Sharples et al. 1990; Terndrup, Frogel, & Wells 1994) and for fields at larger l (Minniti et al. 1992; Harding & Morrison 1993) are also roughly consistent with the kinematics predicted

by both the Kent (1992) and Zhao (1994) models (the mean radial velocity in Harding & Morrison's field is better matched by the Zhao model predictions discussed below).

The dispersion in our innermost field is $153 \pm 17 \text{ km s}^{-1}$, higher than either model prediction and higher than observed anywhere else in the inner Galaxy. This means that we have yet to observe the predicted velocity dispersion turnover and decrease toward smaller radii. Both models discussed here predict this, largely as a result of their adopted density profiles which are similar inside about 400 pc (minor axis distance). An average value for the dispersion in the central pc of the Galaxy is 125 km s^{-1} (Sellgren et al. 1990) and in the central 10 pc may be as low as 75 km s^{-1} (Rieke & Rieke 1988). If the bulge population joins onto the nuclear population, then we should expect to see the bulge dispersion turn over. We plan to obtain the kinematics for stars inside about 70 pc in an upcoming observing run to address this question.

Although not statistically significant (at least for the Zhao 1994 model), the inner field data point is 1 to 2 sigma above either model prediction. If the dispersion continues to rise or remain flat inside this position, the stellar mass to light ratio might not be constant. Kent (private communication) has made a preliminary check of the $3.5 \mu\text{m}$ and $4.8 \mu\text{m}$ COBE surface brightness distributions. These longer wavelength measurements should be less susceptible to uncertainties caused by interstellar extinction. While the spatial resolution is low (0.7° beam), Kent finds that the amount of light observed is consistent with his model (Kent 1992) and thus also with that of Zhao (1994). If the the velocity dispersion does not fall inside 100 pc, then a higher

Fig. 7.— Comparison of observed and model projected velocity dispersions. The solid box data points are from the present paper, except the one at the largest radius which is taken from Blum et al. (1994). The data point at ~ 500 pc (open triangle) is taken from the M giant study by Sharples et al. (1990) in Baade’s window. The remaining two points (also open triangles) are from minor axis optical windows (Terndrup et al. 1994). The solid line represents the prediction from the Kent (1992) dynamical model (private communication; see text). This prediction is for a “slit” oriented at 55° which is similar to the distribution of our four fields (solid boxes); see text. The dashed line represents the minor axis prediction of Zhao (1994) as scaled from one of his figures.

mass may be required, but the observed amount of near infrared light would remain unchanged.

Lindquist et al. (1992) have obtained velocities for OH/IR stars at projected radii between 10 and 100 pc. They find dispersions between about $50 - 100 \text{ km s}^{-1}$ suggesting that the dispersion does fall in this range. However, the OH/IR stars also have considerable rotational velocities (up to 100 km s^{-1} at 100 pc, much higher than the two models discussed here predict; see the next section) and so probably represent a different stellar population than the stars and models depicted in Figure 7.

3.5.2 Mean Radial Velocities

The mean radial velocities in our four fields are compared to the predictions for both dynamical models in Figure 8. All velocities in this figure are for the *galactocentric* reference frame. The axisymmetric prediction is again along a slit whose position angle is about 55° from the major axis. The dotted line in this figure is an estimate of the projected velocity as a function of l assuming $V_r(-l) = -V_r(l)$, which is a good approximation (Zhao, private communication). A detailed map of $V_r(l, b)$ for the bar model (Zhao 1994) shows essentially cylindrical rotation (the projected velocity is constant with latitude) with a linear dependence on longitude for the region of the inner Galaxy shown here.

The mean velocity in field 4 is significantly more negative than either model prediction. Part of this discrepancy may be due to the adopted correction to the galactocentric frame. A linear fit to the four data points suggests that the mean galactocentric velocity is -15 km s^{-1} at $l = 0^\circ$. This is nearly the same amount as

Fig. 8.— Comparison of observed and model mean velocities. All velocities in this figure are galactocentric. The solid boxes represent the four inner Galaxy fields discussed in this paper and Blum et al. (1994). The solid line is from Kent's (1992) model. The dashed line is an estimate from the Zhao (1994) model. The open triangles represent the effect of a possible systematic offset for the fields observed at CTIO based on a small sample of program stars which were observed on both the CTIO/IRS and IRTF/CSHELL systems. Here we assume the absolute velocity for the higher resolution IRTF/CSHELL data is correct; see text.

the difference between the IRTF/CSHELL and CTIO/IRS velocities for a sub-set of stars measured on both systems (§3.1). If we correct for this offset by adding 12 km s^{-1} to the mean velocities in fields 1,2 and 4 (they were measured on the CTIO/IRS system), then the mean velocities (open triangles in Figure 8) would match the Zhao bar model quite well. The results are also consistent with the Kent (1992) model.

3.5.3 Velocity Distributions

The axisymmetric model and bar model both predict distributions of observed velocities which are quite similar to a Gaussian distribution for certain fields. Kuijken (1994) has derived the phase space distribution function for the Kent (1992) model. He finds that the predicted distribution of observed velocities towards Baade's window is well approximated by a Gaussian distribution. The detailed distribution function, which Kuijken derives numerically, fits the Baade's window M giant kinematics (Sharples et al. 1990). The Zhao (1994) model predicts an observed velocity distribution which is nearly Gaussian for l near zero degrees but which can become strongly asymmetric at larger l ($\sim 7^\circ$).

The observed *heliocentric* distribution of velocities for each field is shown in Figure 9. Kuijken has kindly provided us with predictions for our fields from the same model as described in Kuijken (1994); these are shown in Figure 9 for comparison. We have arbitrarily shifted the model predictions to the mean observed velocity; here we are only comparing the relative numbers of stars at each velocity. The mean velocities predicted by Kuijken's distribution function for our fields are similar to those of the Kent model which were discussed in the previous section. The Kuijken

distributions were renormalized to give the same number of stars as observed in each field. The Kuijken (1994) model results are well fit by Gaussian distributions, but they have slightly lower dispersions than the Kent model ($\sim 10 \text{ km s}^{-1}$), and thus our observations. This is perhaps due to a truncation of high angular momentum stars which had to be made for computational reasons, or a slightly different disk model used than for the Kent model (Kuijken, private communication).

If we compare the observations to Gaussian distributions of the observed width and mean velocity (also shown in Figure 9), we find no statistical evidence that any of the observed distributions is different from Gaussian (by application of a Kolmogorov-Smirnov [KS] test to each field; the KS test does not depend on binning the data).

Zhao has also provided us with the predicted distribution in one of our fields (field 4, $l, b = -1^\circ, 2^\circ$) from his model (Figure 9). The model results were shifted and normalized as described above. Again, this distribution is well fit by a Gaussian and is quite similar to the Kuijken result. Zhao was forced to cut off the highest velocity stars due to storage requirements when producing the velocity distribution; this results in a reduced dispersion as computed from the distribution (the actual dynamical model calculation predicts a higher dispersion in this field as discussed above).

Due to the small number of stars in each field, we do not attempt to uniquely determine the form of the velocity distributions; however, the model results and KS tests suggest that a Gaussian is a good representation.

Fig. 9.— Comparison of observed and model velocity distributions. The model distributions have been arbitrarily shifted to the mean heliocentric velocity observed in each field. The solid histograms are for the four inner Galaxy fields discussed in this paper and Blum et al. (1994). The observations have been placed in 100 km s^{-1} bins. The dashed histograms are Gaussian curves of the same observed full width and mean heliocentric velocity, binned to the same 100 km s^{-1} as the observed data. The solid curves are predictions from the same distribution function as Kuijken (1994) which is based on the Kent (1992) model; see text. The dashed line for field 4 is the distribution from the model of Zhao (1994). Both model predictions are well represented by a Gaussian.

3.5.4 Other Models and Constraints

Our observed velocity dispersions and mean velocities appear to be marginally better fit by the Zhao (1994) bar model. This may be reassuring when we consider the photometric evidence that points to a non-axisymmetric stellar distribution. However, both the non-axisymmetric and axisymmetric models we have discussed here have similar axisymmetric components inside a minor axis distance of about 400 pc (3°), so a more stringent test of the axisymmetric *vs.* bar models in the innermost part of the bulge must await models with non-axisymmetric mass distributions there. Such models must still be consistent with the observed light distribution. Since it is very difficult to uniquely determine the unreddened surface brightness distribution and separate the bulge and disk in this region (Arendt et al. 1994), finding convincing non-axisymmetric models from the observed surface brightness distribution seems unlikely. Perhaps the M giant kinematics which we plan to obtain and/or a better understanding of the OH/IR star kinematics inside 100 pc will settle the question.

The Kent (1992) and Zhao (1994) models predict similar total masses for the bulge: $1.8 \times 10^{10} M_\odot$ *vs.* $2 \times 10^{10} M_\odot$ for the Kent and Zhao models, respectively. The Kent (1992) value follows from direct integration of the model luminosity profile and derived mass-to-light ratio (Blum 1994). The total mass of the bulge may be even greater than these models imply. Blum (1994) has calculated the bulge mass using the tensor virial theorem with the global observed kinematics, the pattern speed determined by Binney et al. (1991), and the same Dwek et al. (1994) model employed by Zhao (1994). Blum (1995) finds the bulge mass could be as high as $2.8 \times 10^{10} M_\odot$ if

the bar major axis is aligned at 20° to our line of sight and the pattern speed is $81 \text{ km s}^{-1} \text{ kpc}^{-1}$. The uncertainty in the total bulge mass is represented by the differences in these three determinations. The Kent model applies to an axisymmetric system; Zhao's model is complex, and he has not yet fully explored the available parameter space for barred models; and Blum's estimate is sensitive to the bar orientation and pattern speed, neither of which is precisely known.

Self consistent bar models are difficult to construct due to their complexity and computational requirements. When a series of dynamical models can be constructed which account for the range of bar models which fit the light distribution, the wealth of kinematic data that now samples essentially all of the inner Galaxy may narrow the choice of models (and hence the bulge mass).

On the other hand, new types of observations may help to constrain the mass distribution. Three dimensional space motions of bulge stars offer the possibility of more stringent constraints on the determination of the inner Galaxy mass distribution (Spaenhauer, Jones, & Whitford 1992). For example, Zhao et al. (1994) have noted that by including the transverse components of velocity for the bulge stars one can definitively show whether or not the stars move on orbits which result from a non-axisymmetric potential. They analyzed a sample of K giants in Baade's window which have both radial velocities and proper motions. From these, they compute the off-diagonal terms to the velocity dispersion tensor and find that the observed velocity ellipsoid is not aligned with the spatial directions (line of sight and l) as it should be if the mass distribution were axisymmetric. Their result depends on breaking the

sample of stars in to metal rich and metal poor subsamples. The observed “vertex deviation” is not present in the combined sample. Rich, Terndrup, & Sadler (1994) have three space motions for a much larger sample of bulge K giants. Analysis of this data set will more clearly demonstrate whether vertex deviations are present.

The bulge mass distribution may also be constrained by observations of microlensing events. Such events occur when a foreground object passes near in projection to a background star and “focuses” the background star light due to its gravitational field, creating a magnification of the background star which can be detected. Approximately 60 microlensing events have been detected by the two groups searching for them toward the bulge (The Optical Gravitational Lensing Experiment, Udalski et al. 1994; Massive Compact Halo Object collaboration, Bennett et al. 1994). The total number of events observed is better explained by a barred model of the bulge than an axisymmetric one (e.g. Han & Gould 1995a). The total number of events observed so far is still small enough to allow for a range of bar models to fit the data (Han & Gould 1995a).

3.6 Summary

We have obtained radial velocities for approximately 120 M giant stars in three fields at projected radii between 150 and 300 pc. Combined with the data presented by Blum et al. (1994), we have a total of about 150 stars in four fields.

The mean velocities, velocity dispersions, and velocity distributions of the observed samples agree favorably with available axisymmetric (Kent 1992) and barred (Zhao 1994) dynamical models. Figures 7 and 8 suggest a slightly better representa-

tion of the observed kinematics by the bar model.

The velocity dispersion in our innermost field is $153 \text{ km s}^{-1} \pm 17 \text{ km s}^{-1}$, 1 to 2 σ ($\sim 15 - 30 \text{ km s}^{-1}$) higher than either model prediction and higher than observed anywhere else in the inner Galaxy. This means that we have yet to observe the dispersion begin decreasing toward smaller radii as we might expect if the bulge and GC populations are to join smoothly together.

We are indebted to Stephen Kent, Konrad Kuijken, Jerry Sellwood, and Hong-Sheng Zhao for making available to us model predictions as well as for helpful discussions. We thank R. Pogge for use of his spectral line analysis program, LINER. This work was supported by a grant from National Science Foundation (AST - 9115236).

CHAPTER IV

Figure Rotation And The Mass of the Galactic Bulge¹

4.1 Abstract

The mass of the Galactic bulge, M_B , is estimated from the tensor virial theorem. By including the effects of a barred stellar distribution and figure rotation ($81 \text{ km s}^{-1} \text{ kpc}^{-1}$) and by assuming that the bar is oriented at $\theta = 20^\circ$ to our line of sight, M_B is found to be as high as $2.8 \times 10^{10} M_\odot$. This estimate is in good agreement with the total mass inferred from the observed optical depth to microlensing for stars toward the inner Galaxy. For larger angles, $\theta \sim 40^\circ$, or smaller pattern speeds ($20 \text{ km s}^{-1} \text{ kpc}^{-1}$), M_B is found to be $\sim 1.7 - 1.9 \times 10^{10} M_\odot$, similar to previous estimates for a barred bulge ($2 \times 10^{10} M_\odot$) and axisymmetric bulge ($1.8 \times 10^{10} M_\odot$).

4.2 Introduction

Until recently, the axisymmetric mass model of Kent (1992) was viewed as the standard Galactic bulge model; it successfully fits observed kinematics and the near infrared surface brightness distribution over the inner few kpc of the bulge. However, analysis of existing and new photometric observations show that the bulge may be

¹This chapter appeared in its entirety as Blum (1995)

strongly triaxial. Blitz & Spergel (1991) found that the near infrared surface brightness distribution is asymmetric about $l = 0^\circ$. Data from the DIRBE experiment on board the Cosmic Background Explorer (COBE) confirmed this result (Weiland et al. 1994). The light asymmetry has been interpreted as an asymmetry in the stellar distribution. Dwek et al. (1994) fit triaxial models to the light distribution and find that the bulge is strongly barred and has its long axis oriented at an angle θ of $\sim 10^\circ$ to 40° to our line of sight. Dynamical modeling of observed gas kinematics in the inner Galaxy (Binney et al. 1991) also points to a barred mass distribution with $\theta \sim 16^\circ$.

In addition to its inability to account for the observed light asymmetry, the Kent (1992) axisymmetric model appears to significantly underestimate the optical depth to microlensing for stars observed toward the inner Galaxy (Paczynski et al. 1994; Han & Gould 1995a; Zhao, Spergel, & Rich 1995). The Kent (1992) model leads to a prediction for the optical depth to microlensing which is a factor of 3–4 lower than the observed optical depth reported by the Optical Gravitational Lensing Experiment (OGLE) (Udalski et al. 1994) and the Massive Compact Halo Object (MACHO) experiment (Bennett et al. 1994). A barred geometry increases the bulge’s optical depth to self-lensing because the optical depth scales as the distance from source to lens. A barred geometry naturally places large numbers of stars at the near end of the bar (lenses) in front of stars at the far end of the bar (lensed sources). Accounting for a barred bulge increases the predicted optical depth by a factor of nearly 1.5 compared to the value for the Kent (1992) axisymmetric model (Han & Gould 1995a).

Barred models of the bulge produce predictions for M_B which bracket the estimate for an axisymmetric bulge. Zhao (1994) and Han & Gould (1995a) estimate M_B to be $2 \times 10^{10} M_\odot$ and $1.6 \times 10^{10} M_\odot$, respectively, for barred models of the bulge. This may be compared to $M_B = 1.8 \times 10^{10} M_\odot$ for the Kent (1992) model (Kent does not state a value for M_B , but using his density law and derived mass to light ratio leads directly to this value). In this *Letter*, I demonstrate that a triaxial model of Dwek et al. (1994), but modified to account for the excess luminosity in the central 3° , and a predicted value of the bar pattern speed (Binney et al. 1991) lead to a bulge mass which may be a factor of 1.4 higher than that of Zhao (1994). In what follows, I adopt a value for the distance between the sun and Galactic center ($R_\odot$) of 8 kpc.

4.3 Mass Estimate

Given a density model and observational estimates of the kinetic energy and pattern speed of a rotating, barred stellar system, an estimate of the system's mass can be made from the tensor virial theorem. In the case of the Galactic bulge, sufficient kinematic observations exist to estimate the global kinetic energy of the system (see below), recent density models have been computed from the observed light distribution (Dwek et al. 1994), and an estimate of the pattern speed of the bulge potential has been made from observations of gas kinematics (Binney et al. 1991).

For a steady state, rotating, triaxial system, the tensor virial theorem results in the following balance between the system's kinetic and potential energy (Binney 1982):

$$-W_{xx} = 2T_{xx} + \Pi_{xx} + \omega^2(I_x - I_y) \quad (1a)$$

$$-W_{yy} = 2T_{yy} + \Pi_{yy} - \omega^2(I_x - I_y) \quad (1b)$$

$$-W_{zz} = \Pi_{zz} \quad (1c)$$

where W_{ii} , T_{ii} , and Π_{ii} ($i = x, y, z$) are the components of the potential energy tensor, ordered motion kinetic energy tensor, and random motion kinetic energy tensor, respectively. These equations are for an inertial reference frame with the major axis along the x axis and figure rotation with pattern speed ω about the z axis. The ω^2 term arises because the moments of inertia, I_x and I_y are not constant in time with respect to the inertial frame. This rotation adds an effective kinetic energy along the major axis, and takes an equal amount away from the intermediate axis. I have assumed there is no ordered motion in the z direction.

I define the density distribution as $\rho = M_B \xi(x, y, z)$, where M_B is the system mass and ξ is the normalized density distribution. I ignore the disk mass; the effect of this is discussed in the next section. Next, I use the following results from Binney & Tremaine (1987):

$$I_x = \int \rho x^2 dV \quad (2a)$$

$$W_{xx} = -\frac{1}{2}G \int \int \frac{\rho(\mathbf{r})\rho(\mathbf{r}')(x - x')^2}{|\mathbf{r}' - \mathbf{r}|^3} dV' dV \quad (2b)$$

where V is the volume, $\mathbf{r}$ and $\mathbf{r}'$ are spatial position vectors, and analogous equations hold for y and z . Equation (1) may then be written as,

$$-\frac{1}{2}GM_B^2 w_{xx} = M_B(\bar{\sigma}_{xx}^2 + \bar{V}_x^2) + M_B\omega^2(i_x - i_y) \quad (3a)$$

$$-\frac{1}{2}GM_B^2 w_{yy} = M_B(\bar{\sigma}_{yy}^2 + \bar{V}_y^2) - M_B\omega^2(i_x - i_y) \quad (3b)$$

$$-\frac{1}{2}GM_B^2 w_{zz} = M_B\bar{\sigma}_{zz}^2 \quad (3c)$$

where $w_{ii} = W_{ii}/(0.5GM_B^2)$ and $i_i = I_i/M_B$. Note that the w_{ii} and i_i depend only on the adopted $\xi(x, y, z)$. The kinetic energy terms have been replaced by terms involving the system mass and mass weighted mean and random velocities ($\Pi_{ii} = \int \rho \sigma_{ii}^2 dV = M_B \bar{\sigma}_{ii}^2$; $2T_{ii} = \int \rho \bar{v}_{ii}^2 dV = M_B \bar{V}_i^2$).

To estimate the total mass, I adopt one of the best fitting triaxial distributions to the near infrared surface brightness distribution of the bulge from Dwek et al. (1994). This is their G2 (Gaussian) model which has principal axis scale lengths of 1487, 584, and 405 pc (for $R_o = 8$ kpc). This model is modified inside a major axis radius of 680 pc (415 pc minor axis radius) to include an axisymmetric density distribution as defined by Kent (1992). This hybrid model, similar to one employed by Zhao (1994), accounts for the higher observed luminosity in the central bulge which the G2 model does not. The two density laws were not smoothly joined, but agree reasonably well at the 680 pc radius. Numerical integration yields the values of the w_{ii} and i_i .

The pattern speed has been estimated by Binney et al. (1991) to be $81 \text{ km s}^{-1} \text{ kpc}^{-1}$ from observations of the inner Galaxy gas kinematics.

The bulge mass is calculated from equation (2) after rotating from the x, y, z frame to our line of sight. The angle between the bar major axis and our line of sight is taken as $\theta = 20^\circ$, a value consistent with the G2 model of Dwek et al. (1994). Other models which also fit the light distribution well have inclinations up to $\theta \sim 40^\circ$ (Dwek et al. 1994). Binney et al. (1991) derive a best fit value of 16° . After rotation, all that remains is to adopt a suitable value for the line of sight kinetic energy. Observations at angular distances from the Galactic center of $2^\circ - 7^\circ$ show a large velocity dispersion between about 90 km s^{-1} and 130 km s^{-1} (Rich 1990; Sharples, Walker, & Cropper 1990; Terndrup, Frogel, & Wells 1994; Blum et al. 1994). The mean velocities are generally observed to be small in comparison, except at larger longitudes ($8^\circ - 10^\circ$) where they rise (Minniti et al. 1992; Harding & Morrison 1993) to $50 - 80 \text{ km s}^{-1}$. This increase is compensated for by a decrease in dispersion; the total kinetic energy at larger radii appears to remain at $\sim (100 \text{ km s}^{-1})^2$. I adopt an average of the observed dispersion, $(110 \text{ km s}^{-1})^2$, for the line of sight kinetic energy.

The above assumptions lead to a total bulge mass of $M_B \approx 2.8 \times 10^{10} M_\odot$. The estimate is most sensitive to the adopted angle (θ) between the line of sight and bar major axis and the pattern speed. The ω^2 term is proportional to $\cos(2\theta)$ when rotated from the x, y, z frame to the line of sight. If θ is taken as 40° , the mass estimate falls to $1.9 \times 10^{10} M_\odot$. If the pattern speed is 20 km s^{-1} (and $\theta = 20^\circ$), $M_B = 1.7 \times 10^{10} M_\odot$.

4.4 Discussion

The derived bulge mass is about 1.4 times larger than previous estimates based on a variety of techniques. The Kent (1992) dynamical model, which fits nearly all of the existing kinematic observations, results in a $1.8 \times 10^{10} M_{\odot}$ bulge. The non-axisymmetry of the bulge coupled with rapid figure rotation allows for a much increased mass. I have ignored the disk contribution, which might result in an overestimate of the bulge mass. Applying the tensor virial theorem to the Kent (1992) density distribution and using the same observed kinetic energy estimate as for the bar model above, I find an axisymmetric bulge mass of $2.3 \times 10^{10} M_{\odot}$. This suggests that ignoring the disk contribution can lead to a somewhat higher mass estimate, 20% in the axisymmetric case. The bar model is more compact than the Kent model, so the disk contribution may be less in that case. It is also possible that the adopted line of sight kinetic energy is too high. This is less likely since the observed kinetic energy appears to be $\gtrsim (100 \text{ km s}^{-1})^2$ out to $\sim 1500 \text{ pc}$ (major axis radius), as discussed in the previous section.

Dwek et al. (1994) derive a stellar mass to light ratio for their bar model of the bulge using assumptions about the initial mass function and evolutionary history for bulge stars. Combined with their (luminosity) density distribution this gives a bulge mass of $1.15 \times 10^{10} M_{\odot}$ ($R_0 = 8 \text{ kpc}$). Zhao (1994) constructed a self consistent dynamical model based on the same Dwek et al. (1994) triaxial distribution used in this paper (and similarly modified in the central region). Zhao's dynamical model also fits a number of kinematic observations for a total bulge mass of $2 \times 10^{10} M_{\odot}$.

Part of the difference between Zhao's model and the virial estimate presented in this work is likely due to the fact that Zhao used a lower value of ω ($60 \text{ km s}^{-1} \text{ kpc}^{-1}$) which significantly reduces the ω^2 term in equation 2. Han & Gould (1995a) also used the virial theorem to estimate the bulge mass (again, using the same modified Dwek et al. 1994 density distribution). However, they obtained a lower value ($1.6 \times 10^{10} M_{\odot}$) because they did not include the effect of figure rotation ($\omega = 0$ in their model). The ω^2 term in equation 2 is approximately as large as the kinetic energy term if the pattern speed is $81 \text{ km s}^{-1} \text{ kpc}^{-1}$. Wada et al. (1994) have recently modeled the inner Galaxy with a bar potential and run SPH simulations of the gas behavior under this potential. They derive a significantly lower pattern speed ($\sim 20 \text{ km s}^{-1}$) than Binney et al. (1991). In this case, the present mass estimate would be reduced to $1.7 \times 10^{10} M_{\odot}$, a value comparable to that found by Han & Gould (1995a) and slightly less than that found by Zhao et al. (1995).

Since the predicted optical depth to microlensing is proportional to the total bulge mass (see, for example, Han & Gould 1995a), the mass estimate derived in section 2 would result in a predicted optical depth consistent (within the uncertainties) with the observed optical depth reported by OGLE (Udalski 1994) and MACHO (Bennett et al. 1994). For example, Han & Gould (1995a) report a predicted optical depth of $\tau = 0.95 \times 10^{-6}$ for a barred bulge. Increasing this value by the ratio of bulge masses (1.75) and adding the amount due to disk lensing ($\sim 0.5 \times 10^{-6}$, Paczyński 1991, Griest et al. 1991) results in $\tau = 2.2 \times 10^{-6}$. This value may be compared to the observed optical depth, $\tau \approx 3 \times 10^{-6}$, reported by Udalski et al. (1994) and Bennett

et al. (1994). The observed optical depth may be uncertain by as much as 24 % (Han & Gould 1995b), so the prediction from the bar model is consistent with the observations.

Finally, note that the mass estimate made from the observed line of sight kinematics may be used to estimate the transverse kinematics. These estimates may be compared to existing observations. The longitudinal kinetic energy is predicted to be $(153 \text{ km s}^{-1})^2$. The proper motion study of Spaenhauer, Jones, & Whitford (1992) results in a longitudinal velocity dispersion of $119 \text{ km s}^{-1} \pm 4 \text{ km s}^{-1}$ ($R_0 = 8 \text{ kpc}$) for stars observed toward Baade's window ($l, b = 1^\circ, -4^\circ$). The predicted value appears rather high even though the observed value does not include the effects of mean motion (there was no proper motion standard to calibrate the zero point of the measurements). The latitudinal dispersion from Spaenhauer et al. (1992), which likely has a small mean motion, is $104 \text{ km s}^{-1} \pm 4 \text{ km s}^{-1}$. This may be compared to the global prediction of 101 km s^{-1} from the tensor virial theorem.

4.5 Summary

The main objective of this *Letter* is to demonstrate that the bulge mass may be higher than previously thought and that if the bulge is strongly barred, its total mass will depend sensitively on the amount of figure rotation (pattern speed) and its orientation to our line of sight.

For the parameters adopted here, the mass of the Galactic bulge is estimated to be $2.8 \times 10^{10} M_\odot$, about 1.4 times higher than previous bar model estimates. The mass estimate is consistent with the mass which would be inferred from the observed

optical depth to microlensing for stars in the bulge. The mass estimate may be slightly overestimated since I have ignored the contribution of the disk in the calculation. A similar calculation by the tensor virial theorem for the Kent (1992) model results in a mass estimate which is 20% higher than Kent's dynamical estimate.

The bulge mass derived here depends on factors which are not precisely known, but which are observationally constrained. The particular density distribution that I have used is only one of a number which fit the observed near infrared surface brightness distribution. The mass estimate is most sensitive to the pattern speed and angle between the line of sight and bar major axis. The adopted pattern speed is not directly observed through the motion of stars, but it results from a dynamical model which fits the observed gas kinematics well. If the pattern speed is significantly less than the value adopted here ($81 \text{ km s}^{-1} \text{ kpc}^{-1}$) or the angle between the line of sight and bar major axis is significantly larger than 20° , then the mass estimate would be similar to previous estimates for a barred bulge ($1.6 - 2.0 \times 10^{10} M_\odot$).

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CHAPTER V

A Comparison of Near Infrared Spectra of the Galactic Center Compact He I Emission Line Sources and Early Type Mass Losing Stars ¹

5.1 Abstract

We present $R \approx 570$ resolution K band spectra of eight sources in the Galactic Center, including four sources within the IRS 16 cluster, IRS 13, IRS 1W, and the compact He I emission line sources AF (also known as AHH) and AHH NW. We also present $R \approx 570$ H and K band spectra of the AF source and nine galactic and LMC early type mass losing stars, including Ofpe/WN9, WN, and LBV stars. The spectra of both the Galactic Center sources and the comparison stars show a wide range of behavior in the He I ($1.70 \mu\text{m}$, $2.06 \mu\text{m}$, $2.11 \mu\text{m}$) and H I (Brackett series) lines. While the Galactic Center and comparison star spectra show some morphological similarities, we find significantly larger He I equivalent widths in the AF source and two galactic early type mass losing stars than in any of the LMC stars. Several of the Galactic Center He I sources are found to have higher He I velocity widths than any of the galactic or LMC early type mass losing stars. At least one source, IRS 13, shows significant emission to the red of the He I $2.06 \mu\text{m}$ line emission, which may be a red

¹This chapter appeared in its entirety as Blum et al. (1995b)

wing to this line or a blend of other unidentified lines.

We also rule out the Galactic Center He I sources being normal OB giant/supergiants, WC, or WN7-8 stars based on a comparison of our spectra to published spectra of these types. We estimate the $BC_K = M_{bol} - M_K$ for the Galactic Center sources as a function of effective temperature from published data on LBV, WN9, and Ofpe/WN9 stars, and use limits on the effective temperature to place the GC sources in the HR diagram.

5.2 Introduction

What is the source of radiation that ionizes the gas and powers the dust emission at the Galactic Center? Two models are debated: (1) accretion onto a massive black hole and (2) young ($\lesssim 10^7$ yr) massive stars. Genzel and Townes (1987) and Genzel, Hollenbach, and Townes (1994) present extensive reviews. Lebofsky, Rieke, & Tokunaga (1982) identified M supergiant stars in the Galactic Center (GC), supporting the recent star formation model. More recently, Forrest et al. (1987), Allen, Hyland, and Hillier (1990), and Krabbe et al. (1991) have identified compact He I sources and/or Br α emission sources with no radio counterparts in the GC. Allen et al. (1990) and Krabbe et al. (1991) interpreted the He I and accompanying H I emission as arising in the extended mass-losing envelopes of hot massive post-main-sequence stars. This interpretation is based on the similarity of the K band ($\lambda \approx 2.2 \mu\text{m}$) spectrum of the most prominent GC He I source (known as the AF star or the AHH star) and the relative He I to Br γ line measurements of other GC He I sources compared to similar spectra of optically classified stars in the Large Magellanic Cloud. In particular, the

AF source has been classified as an Ofpe/WN9 star based on its K band spectrum as compared to similar spectra of a number of optically classified LMC stars with this classification (Allen et al. 1990). If correct, this interpretation provides the most substantial evidence to date for the star formation model.

Two alternate models for the IRS 16 sources have been proposed. Morris (1993) proposed these sources formed by collisions between stellar remnants and late type stars. Tamblyn and Rieke (1993) interpret the IRS 16 sources as young stars but cooler F or G supergiants, as opposed to the hotter post main sequence stars discussed above. The He I emission would then arise in gas which is in close proximity to the IRS16 sources (i.e., the winds from cool stars which are ionized by external sources).

Optical classification of the GC sources is impossible due to the large extinction from interstellar dust along the line of sight. It is therefore important to acquire as wide a range of spectroscopic and broad band measurements as possible at longer wavelengths in order to understand the underlying physics of the GC He I sources. In this paper, we compare near infrared (NIR) spectra of the GC He I sources with those of the early type mass losing stars in the LMC and representatives from the Galaxy. We present H ($\lambda \approx 1.65$) and K spectra of the AF source, seven other GC He I sources (K band only) and nine early type emission line stars from the Galaxy and LMC. The LMC stars include five of those observed by McGregor, Hillier, and Hyland (1988; hereafter MHH); here we extend these spectra to the H band and include the LMC luminous blue variable (LBV) S Dor. The galactic sources include two Ofpe/WN9 stars (WR85a and WR122, van der Hucht et al. 1988) and the only galactic WN9

star (WR108) which have no previously published NIR spectra. Periodic observation of these sources is important: we find large variations in the K band spectrum of at least one of the Ofpe/WN9 stars observed by MHH.

In what follows, we briefly review the Ofpe/WN9 class, make direct comparisons between the observed spectra of these stars and the GC sources, compare the GC sources to observed spectra of other types of massive evolved stars from the literature, and attempt to place the GC sources in the HR diagram.

Libonate et al. (1995) have also recently obtained K band spectra for nine GC sources, including seven of the eight sources we have observed at K , and H band spectra for three GC sources, including the AF source which we have observed at H . Our K band spectra are higher spectral resolution and higher signal-to-noise than the spectra they present for five of the seven sources observed in common.

5.2.1 The Ofpe/WN9 Class

The LMC Ofpe/WN9 stars were first classified by Walborn (1977) and they now number ten stars in all (Bohannon and Walborn, 1989; hereafter, BW). These stars are believed to be precursors to the Wolf-Rayet stage and hence are likely to be helium enriched and massive (it is thought that the LBV, Ofpe/WN9, and Wolf-Rayet (WR) classes form an evolutionary sequence; see BW and Humphreys and Davidson 1994, for example). P-Cygni profiles in the optical spectra clearly indicate massive out-flows from the LMC objects. In addition, the LMC sources have bolometric luminosities and temperatures that place them among the most massive stars ($> 30 M_{\odot}$) in the H-R diagram (MHH). The K band spectra of the present LMC stars are a subset

of those first presented by MHH and include three Ofpe/WN9 stars and two early supergiants with $\text{He I } 2.06 \mu\text{m} / \text{Br}\gamma > 1$. H and K spectra were also presented by McGregor, Hyland, and Hillier (1988, MHH2) for a number of early-type galactic emission-line stars. Several of these stars appear similar to the LMC Ofpe/WN9 stars in the K band. Indeed, one of them, AG Car, may be classified as Ofpe/WN9 by its optical spectrum (Stahl 1986). These NIR spectra are the basis for classification of the GC sources as “He I stars.”

Recently, Crowther et al. (1994) have completed detailed wind (WR like) models for four of the LMC Ofpe/WN9 stars (none from the present sample) and the galactic WN9 star WR108. The detailed spectral types of the LMC stars are changed by Crowther et al. based on new optical spectra, to WN9–10 types. While important for understanding the precise links between evolutionary phases of massive stars, these changes do not affect our comparative analysis of the GC sources. The model results of Crowther et al. are in general agreement with the previous work presented by MHH.

The defining characteristic of the Ofpe/WN9 stars in the K band has been taken as a $\text{He I } 2.06 \mu\text{m} / \text{Br}\gamma$ integrated line flux ratio greater than one, sometimes accompanied by $\text{He I } 2.11 \mu\text{m}$ emission. Beyond this simple criterion, what more can quantitatively be said regarding the nature of the GC sources in the absence of optical and UV spectra? To answer this question, we have analyzed the H I and He I emission lines in the LMC stars and those in the GC for a direct comparison.

5.3 Observations and Data Reduction

The majority of the observations were obtained on the nights of 11 and 12 July, 1993 and 6 and 22 September, 1993 on the CTIO 4m telescope. The observations were made using the Ohio State Infrared Imager/Spectrometer (OSIRIS; DePoy et al. 1993) in low resolution mode ($R \approx 570$). OSIRIS employs a 256×256 HgCdTe array and may be used in cross-dispersed mode (simultaneous coverage of J , H and K bands). The GC sources were observed solely in the K band (except AF) with a $120'' \times 1.3''$ slit. The AF source and comparison stars were observed in cross-dispersed mode with a $20'' \times 1.3''$ slit. The spatial scale was $0.45'' \text{ pix}^{-1}$.

In July, we observed the seven GC He I sources listed in Table 4 with a critically sampled ($\text{FWHM} \approx 2 \text{ pix}$) spectral coverage of approximately $1.9\text{--}2.4 \mu\text{m}$ ($19.4 \text{ \AA} \text{ pix}^{-1}$). The data were taken by first centering on the source IRS16 SW. The E-W oriented slit was then stepped N-S across the central $15''$ in $1.5'' - 2''$ increments. OSIRIS can be easily switched from spectroscopic to imaging mode in real time at the telescope. We recorded several H and K band images during the course of obtaining spectra in order to effectively identify individual sources in the long slit spectral images. In September, we observed the AF source and the representatives of galactic and LMC emission line stars listed in Table 5. In the present work, we discuss only the H ($1.45\text{--}1.84 \mu\text{m}$) and K ($1.9\text{--}2.4 \mu\text{m}$) spectra for the sources in Table 5, as our goal is to investigate the NIR spectra of the GC sources for which we have no data shortward of H due to interstellar extinction. Each of these sources was individually centered in the cross-dispersed slit.

An additional high resolution ($R \approx 1350$ at $2.2 \mu\text{m}$) spectrum of the GC He I source IRS 13 was obtained in June 1994 with OSIRIS on the CTIO 4m telescope. The high resolution slit is approximately $0.5'' \times 45''$. The spatial scale in high resolution was approximately $0.17'' \text{ pix}^{-1}$.

Basic data reduction tasks were accomplished with standard packages included in IRAF². Each image was sky subtracted and then flat-fielded using appropriate domeflats.

After flat-fielding, the GC K band (non-cross-dispersed) spectra were corrected for anamorphic demagnification by using IRAF "GEOMAP" and "GEOTRAN." This effect, in which the spectrum shifts in the wavelength dimension as a function of spatial position along the slit (resulting in a maximum shift of 5 pixels from slit center to end) was corrected for by deriving a map from the measured positions of OH sky lines along the spatial and spectral dimensions. The transformation from this map to a uniform spectral response along the slit was then applied to each image.

After transformation, each image was ratioed by a secondary flat field image to remove low order variations (peak amplitude approximately 30 %) due to scattered light in the domeflats. The scattered light remains constant to a few percent from night to night in the domeflats; therefore, all the GC non-cross-dispersed K band spectra were ratioed by the same secondary flat. This flat was constructed by building a two dimensional image from 22 spectra of SAO 191522 taken over a roughly uniform grid along the spatial dimension. Each spectrum was fitted with a low order polynomial. These low order fits were combined into a single image and a two dimen-

²IRAF is distributed by the National Optical Astronomy Observatories.

sional surface fit to them, resulting in the secondary flat field. Comparison of different measurements of the same star taken at different positions along the slit shows that the low order variations introduced by the scattered light are reduced from about 30 % to about ± 5 %.

The cross-dispersed slit is much smaller than the normal low resolution slit so no correction for anamorphic demagnification is required. In addition, all the objects observed in cross-dispersed mode were measured approximately 8 to 10 times uniformly spaced along the slit. Averaging these measurements effectively removed any low order variations due to scattered light in the dome flats.

Source spectra were extracted by synthesizing apertures traced along the spectral dimension and then summing the flux in 4-5 pixels along the spatial dimension to form one dimensional spectra. This aperture size ($\approx 2.3''$) may be compared to the typical seeing which was generally between $1'' - 2''$. The *K* band cross dispersed spectral features can be broadened by about 10% by this procedure. The *H* band spectra are broadened by less than this amount. In addition, each spectrum had “background apertures” located approximately $1.5'' - 5''$ on one or both sides of the source spectrum. An average background was determined from these 1-2 pixel wide apertures at each wavelength and subtracted from the source spectrum. Determination of this background is critical in assessing the spectral properties of the GC sources which are contaminated by nearby diffuse emission and unresolved stellar light.

Each spectrum was ratioed by the spectrum of a hot star, or atmospheric standard star, to remove telluric absorption features. $\text{Br}\gamma$ ($2.16 \mu\text{m}$) absorption in the

standards was corrected by estimating a linear continuum across the feature. The H I Brackett series absorption lines in the H band spectra of the atmospheric standards were removed before ratioing by fitting the profiles and strengths of the three strongest features (Br10, Br11, and Br12) and extrapolating to the higher order lines assuming similar profiles and relative strengths estimated from Kurucz (1979). The correction of the higher order lines is imperfect and affects the derived strengths of the H I emission (for Br13 and higher order) in the observed sources at a level $\sim 5\%$ of the continuum.

For the GC *K* band spectra (non-cross-dispersed) a wavelength shift of 0–0.5 pix was made before ratioing to adjust the object spectra to the wavelength zero-point of the standard. The shifts in the object spectra result from slit positioning differences between the atmospheric standards (centered in the slit) and the GC spectra which were positioned randomly in the slit as the slit map of the GC region was obtained by uniformly stepping the slit. The positioning differences lead to wavelength shifts because the incident angle on the diffraction grating is different. The magnitude of the shift was estimated by cross-correlating the object vs. the atmospheric standard using only the region of the spectra where strong telluric features dominate ($\lambda > 2.26 \mu\text{m}$). This shift was found to be consistent with the value derived by minimizing the residual features in the strong telluric CO₂ near $2 \mu\text{m}$ by trial and error shifting and ratioing. These small shifts were then used to interpolate the object spectrum to the zero-point of the atmospheric standard which was set by the standard’s intrinsic Br γ absorption. This procedure was not used for the cross-dispersed data since the

sources were centered in the slit.

The object spectra were flux calibrated by multiplication of a blackbody spectrum appropriate to the atmospheric standards and by setting the $2.2\ \mu\text{m}$ and $1.65\ \mu\text{m}$ flux densities equal to the values derived from broad band photometry. The photometry and references are given in Table 7. Wavelength calibration was determined from analysis of OH sky lines of known wavelength (Oliva and Origlia, 1992). The relative line positions are accurate to $\lesssim 40\ \text{km s}^{-1}$, but the zero point for any given night is certain only to $\sim \pm 200\ \text{km s}^{-1}$ due to uncertainty in accounting for slit positioning differences discussed above and uncertainty in measuring the zero-point for any particular atmospheric standard.

The high resolution spectrum of IRS 13 was reduced similarly to the low resolution data except that no secondary flat field was used, nor were any shifts made to the spectrum before ratioing by the atmospheric standard star. These additional steps were not required since a series of measurements were made uniformly along the slit, and IRS 13 was centered in the slit. The high resolution spectrum was wavelength calibrated like the low resolution data with the zero point set so that Br γ had the same observed wavelength as the low resolution spectrum.

The final spectra are shown in Figures 10–13. The low amplitude periodic modulation of the continuum evident in some of the spectra is due to fringing inherent to OSIRIS (see IRS 16 SW, for example). The fringe pattern is inclined relative to the wavelength dimension (i.e. the fringes change phase as a function of position along the image spatial dimension). The fringe period is approximately $2\text{--}4\ \text{pix}^{-1}$ in the

wavelength dimension and decreases from blue to red wavelengths. The fringes in Figures 10–12 result from a combination of fringing observed in both the object and atmospheric standards. The fringing amplitude can be as high as 3% of the continuum, but is typically less for two reasons. First, fringes in the atmospheric standards tend to average out when multiple measurements are co-added and second, fringes in the atmospheric standard may cancel out fringes in the object.

The emission lines in each spectrum were analyzed with the LINER program (written by Richard Pogge of OSU), an interactive spectral line analysis program in use at Ohio State. For each line, a best fit Gaussian is determined from a least squares fit. The analysis includes a low order polynomial fit to the continuum which is made independently of individual line fits by selecting continuum points clear of features over a 0.1–0.2 μm range. Derived quantities from the best fit for each line are shown in Tables 4–6.

The line FWHM’s are the best fit values to the observed profiles, uncorrected for instrumental broadening. We estimate the uncertainty in a derived FWHM to be approximately $\pm 50 \text{ km s}^{-1}$ from the scatter about the expected instrumental width for a number of unresolved, or marginally resolved He I 2.06 μm and Br γ lines. Some lines have no quoted FWHM. These are typically those with small equivalent width where the signal to noise was inadequate to yield a FWHM. Several stronger lines also had FWHM which were about 2σ smaller than the instrumental width, which is possibly due to the atmospheric correction for these stars.

The line fluxes are corrected for interstellar extinction. We adopt $A_K=3.0 \text{ mag}$

Fig. 10.— K band spectra of He I emission line sources in the Galactic Center showing the He I 2.06 μm and Br γ (2.17 μm) emission lines. The resolution ($\lambda/\Delta\lambda$) is approximately 570 at 2.2 μm . Several sources also show He I emission at 2.11 μm . The lines near 2.15 μm , 2.22 μm , 2.24 μm , and 2.35 μm in IRS 13 are due to [Fe III]. These spectra were extracted from $\approx 1.8'' \times 1.4''$ apertures and include background subtraction from nearby ($\lesssim 2''$) apertures. The low amplitude periodic modulation of the continuum evident in some of the spectra is due to fringing inherent to OSIRIS (see IRS 16 SW, for example). Note that the emission lines in several of the sources are resolved (He I 2.06 μm FWHM $> 565 \text{ km s}^{-1}$).

Fig. 11.— H and K band spectra of He I emission line sources in the Galaxy showing the He I $1.70\ \mu\text{m}$ and $2.06\ \mu\text{m}$ lines and Brackett series emission lines. Reliable detections are made for $\text{Br}\gamma$ ($2.17\ \mu\text{m}$), $\text{Br}9$ ($1.82\ \mu\text{m}$), $\text{Br}10$ ($1.74\ \mu\text{m}$), $\text{Br}11$ ($1.68\ \mu\text{m}$), and $\text{Br}12$ ($1.64\ \mu\text{m}$). The weaker Br lines may be due to imperfect correction of intrinsic H I absorption in the standards used to correct for atmospheric absorption. The spectra for WR85a and WR122 are shown twice with two different scales for clarity. The lines near $1.69\ \mu\text{m}$ and $2.09\ \mu\text{m}$ in WR85a and WR122 are due to Fe II. The line present at $2.32\ \mu\text{m}$ in WR85a and WR122 is unidentified. These spectra were extracted from $\approx 2.3'' \times 1.4''$ apertures and include background subtraction from nearby ($\lesssim 5''$) apertures. The resolution ($\lambda/\Delta\lambda$) is approximately 570 at 1.65 and $2.2\ \mu\text{m}$.

Fig. 12.— Same as Figure 11 but for He I Emission Line Sources in the LMC. Spectra of the Luminous Blue Variable, S Dor, which shows no He I, is shown for comparison. The lines near $1.69 \mu\text{m}$, $1.74 \mu\text{m}$, and $2.09 \mu\text{m}$ are due to Fe II. The Na I ($2.21 \mu\text{m}$) and CO ($2.3 \mu\text{m}$) emission reported by MHH for HD 37836 are seen in our spectrum. The Na I line may also be present in the spectrum of HD 268840.

TABLE 4
GALACTIC CENTER LINE MEASUREMENTS

Object	Line (μm)	FWHM ^a (km s^{-1})	W_λ ($\text{\AA}$)	Line Flux ^b	Line/Br γ	$\dot{M}^c$
AF	Br12 1.6412	1200	23	1.5E-12	0.55	1.00
	Br11 1.6810	850	15	1.1E-12	0.39	
	He I 1.7007	750	38	2.5E-12	0.92	
	Br10 1.7367	1000	31	2.0E-12	0.71	
	He I 2.0587	800	249	8.0E-12	2.88	
	He I 2.1127	700	29	8.8E-13	0.32	
	Br γ 2.1661	1000	98	2.8E-12	1.00	
AHHNW	He I 2.0587	1200	109	1.8E-12	2.87	0.33
	He I 2.1127	1150	37	5.8E-13	0.91	
	Br γ 2.1661	1200	42	6.3E-13	1.00	
IRS 16 C	He I 2.0587	700	17	1.5E-12	2.08	0.37
	Br γ 2.1661	800	9	7.4E-13	1.00	
IRS 16 NE	He I 2.0587	550	17	4.1E-12	3.43	0.53
	Br γ 2.1661	600	6	1.2E-12	1.00	
IRS 16 NW	He I 2.0587	750	11	7.9E-13	1.89	0.24
	Br γ 2.1661	900	7	4.2E-13	1.00	
IRS 16 SW	He I 2.0587	700	8	2.0E-12	2.03	0.46
	Br γ 2.1661	...	4	9.8E-13	1.00	
IRS 1 W	Br γ 2.1661	550	4	4.8E-13	1.00	
IRS 13	He I 2.0587	950	37	4.2E-12	1.19	1.19
	He I 2.1127	1800	22	2.5E-12	0.71	
	Br γ 2.1661	750	31	3.5E-12	1.00	

^aObserved Full Width at Half Intensity, uncorrected for instrumental broadening. Instrumental width $\approx 565 \text{ km s}^{-1}$ at $2.06 \mu\text{m}$, 515 km s^{-1} at $1.70 \mu\text{m}$. No values appear for lines for which the derived value was significantly less than the instrumental width; see text.

^b $\text{Erg cm}^{-2} \text{ s}^{-1}$. Corrected for adopted reddening shown in Table 7. Estimated uncertainties are $\approx \pm 30 \%$ for He I $2.06 \mu\text{m}$ and 30 to 80 % for the Br lines; see text.

^cMass loss relative to AF. See text.

for the GC He I sources so a direct comparison can be made with the results of Krabbe et al. (1991). For the other sources, the adopted extinction follows from the $E(V - B)$ given in the reference cited in Table 4 and a power law fit to the interstellar extinction curve of Rieke and Lebofsky (1985). The uncertainties for the line fluxes are dominated by systematic effects which include fringing inherent to OSIRIS, using published photometry for the flux calibration (several of the sources are known variables, and most are expected to vary), incomplete cancelation of telluric features near the $2.06 \mu\text{m}$ He I line, and errors in correction of the intrinsic spectral features of the atmospheric standards. Comparison of our $2.06 \mu\text{m}$ He I line fluxes to the published values for the LMC stars (excluding HD 269582, see §3.3 below) shows typical agreement to $\pm 30\%$. The H I lines measured at H are more uncertain. A typical uncertainty in the Br10, 11 and 12 lines ranges from 10% to 80%, due mainly to errors in the correction to the same features in the atmospheric standards. Br13 can be off by a factor of 2 and is not reliably detected in the majority of sources. The uncertainty arising due to correction of Br γ in the atmospheric standard is less because Br γ is well defined and unblended by other intrinsic features in the standard star continuum. Comparison to the Br γ line fluxes given in MHH for the same stars we have observed shows agreement to better than a factor of two.

TABLE 5
GALACTIC AND LMC STAR LINE MEASUREMENTS

Object	Line (μm)	FWHM ^a (km s^{-1})	W_λ ($\text{\AA}$)	Line Flux ^b	Line/ $\text{Br}\gamma$	$\dot{M}^c$
WR122	Br12 1.6412	950	11	1.6E-12	0.36	
	Br11 1.6810	750	11	1.7E-12	0.38	
	He I 1.7007	500	113	1.7E-11	3.82	
	Br10 1.7367	750	12	1.9E-12	0.43	
	He I 2.0587	600	715	1.5E-10	33.94	
	He I 2.1127	500	26	5.8E-12	1.29	
	$\text{Br}\gamma$ 2.1661	900	20	4.5E-12	1.00	
WR85a	Br12 1.6412	800	8	8.6E-13	0.52	
	Br11 1.6810	800	8	9.2E-13	0.56	
	He I 1.7007	600	34	3.8E-12	2.27	
	Br10 1.7367	700	8	9.4E-13	0.57	
	He I 2.0587	650	300	3.6E-11	21.79	
	He I 2.1127	550	11	1.3E-12	0.79	
	$\text{Br}\gamma$ 2.1661	1000	14	1.7E-12	1.00	
HD269445	Br12 1.6412	950	10	1.5E-13	1.24	1.36
	Br11 1.6810	1100	9	1.3E-13	1.02	
	He I 1.7007	550	7	8.9E-14	0.73	
	Br10 1.7367	950	10	1.3E-13	1.04	
	He I 2.0587	600	37	3.2E-13	2.63	
	He I 2.1127	...	5	4.3E-14	0.35	
	$\text{Br}\gamma$ 2.1661	1100	16	1.2E-13	1.00	
HD269582	Br12 1.6412	600	9	3.7E-14	0.32	1.31
	Br11 1.6810	700	14	5.3E-14	0.46	
	He I 1.7007	500	23	8.2E-14	0.71	
	Br10 1.7367	750	20	7.0E-14	0.61	
	He I 2.0587	550	19	3.5E-14	0.30	
	He I 2.1127	600	21	3.5E-14	0.31	
	$\text{Br}\gamma$ 2.1661	850	71	1.2E-13	1.00	
HD269687	Br12 1.6412	700	5	1.3E-14	1.11	0.23
	Br11 1.6810	...	2	4.2E-15	0.36	
	He I 1.7007	...	4	9.3E-15	0.79	
	Br10 1.7367	500	3	6.9E-15	0.59	
	He I 2.0587	450	30	3.5E-14	3.02	
	He I 2.1127	900	4	4.6E-15	0.39	
	$\text{Br}\gamma$ 2.1661	550	11	1.2E-14	1.00	
HD37836	Br12 1.6412	700	9	1.4E-13	0.90	1.61
	Br11 1.6810	500	7	9.8E-14	0.64	
	He I 1.7007	...	6	7.6E-14	0.49	
	Br10 1.7367	...	7	9.2E-14	0.60	
	He I 2.0587	450	39	3.4E-13	2.21	
	He I 2.1127	900	3	2.7E-14	0.18	
	$\text{Br}\gamma$ 2.1661	450	20	1.5E-13	1.00	

TABLE 5—*Continued*

Object	Line (μm)	FWHM ^a (km s^{-1})	W_λ ($\text{\AA}$)	Line Flux ^b	Line/Br γ	$\dot{M}^c$
HD268840	Br12 1.6412	750	14	2.7E-14	1.34	0.36
	Br11 1.6810	550	9	1.9E-14	0.91	
	He I 1.7007	500	10	1.9E-14	0.93	
	Br10 1.7367	600	12	2.1E-14	1.04	
	He I 2.0587	550	47	5.1E-14	2.49	
	He I 2.1127	...	3	4.3E-15	0.21	
	Br γ 2.1661	650	19	2.0E-14	1.00	
WR108	Br12 1.6412	1100	5	1.1E-12	0.46	0.45
	Br11 1.6810	1000	3	6.7E-13	0.28	
	He I 1.7007	950	7	1.5E-12	0.62	
	Br10 1.7367	1100	9	1.6E-12	0.68	
	He I 2.1127	850	15	1.5E-12	0.61	
	Br γ 2.1661	1100	26	2.4E-12	1.00	
S Dor	Br12 1.6412	800	12	6.2E-13	0.77	5.59
	Br11 1.6810	850	16	7.6E-13	0.94	
	Br10 1.7367	550	14	6.0E-13	0.75	
	Br γ 2.1661	450	50	8.1E-13	1.00	

^aObserved Full Width at Half Intensity, uncorrected for instrumental broadening. Instrumental width $\approx 565 \text{ km s}^{-1}$ at $2.06 \mu\text{m}$, 515 km s^{-1} at $1.70 \mu\text{m}$. No values appear for lines for which the derived value was significantly less than the instrumental width; see text.

^b $\text{Erg cm}^{-2} \text{ s}^{-1}$. Corrected for adopted reddening shown in Table 7. Estimated uncertainties are $\approx \pm 30 \%$ for He I $2.06 \mu\text{m}$ and 30 to 80 % for the Br lines; see text.

^cMass loss relative to AF. See text.

TABLE 6
IRS 13 HIGH RESOLUTION LINE MEASUREMENTS

Line (μm)	FWHM ^a (km s^{-1})	W_λ ($\text{\AA}$)	Line Flux ^b	Line/Br γ
He I 2.0587	1030	38	4.7E-12	1.07
? 2.1045	990	4	4.7E-13	0.11
He I 2.1127	850	14	1.6E-12	0.37
[Fe III] 2.1457	380	2	2.6E-13	0.06
Br γ 2.1661	570	37	4.4E-12	1.00
He I ? 2.1851	520	1	1.4E-13	0.03
He II ? 2.1891	420	1	1.2E-13	0.03
[Fe III] 2.2178	420	6	6.1E-13	0.14

^aObserved Full Width at Half Intensity, uncorrected for instrumental broadening. Instrumental width $\approx 240 \text{ km s}^{-1}$ at $2.06 \mu\text{m}$.

^b $\text{Erg cm}^{-2} \text{ s}^{-1}$. Corrected for adopted reddening shown in Table 7. These measurements are consistent with the low resolution measurements in Table 1; see text.

The line measurements for the high resolution spectrum of IRS 13 show excellent agreement with those from the low resolution data. The flux measurements made with quite different spatial scales and slit widths are within 10% and 25% for He I $2.06\ \mu\text{m}$ and $\text{Br}\gamma$, respectively.

We have compared our dereddened line fluxes for the AF source, AHH-NW, IRS 13, IRS 1W, IRS 16NE, IRS 16C, and IRS 16SW with the results of Krabbe et al. (1991), and our equivalent widths and line fluxes for AF, IRS 13, IRS 1W, IRS 16NE, IRS 16NW, IRS 16C, and IRS 16SW with the results of Libonate et al. (1995). The comparison shows modest agreement. Our fluxes agree to 50% or better with those of Krabbe et al. for AF, AHH-NW, IRS 13, IRS 16NE, and IRS 16SW; the two remaining sources, IRS 1W and IRS 16C do not agree well. Our fluxes agree with those of Libonate et al. to better than a factor of two for only IRS 16C and IRS 16SW, while our equivalent widths agree to better than a factor of two with those of Libonate et al. for only IRS 13, IRS 16NE, and IRS 16C. Different choices of background apertures and beam sizes will affect both the line fluxes and equivalent widths. Which of these will be more affected will depend on the source being compared and the particular choices made.

Line and continuum variations are expected for mass losing stars, but differences in the placement and size of source and sky apertures are more likely the cause of differences in the observed line fluxes and equivalent widths in the Galactic Center, where source crowding is a serious problem.

TABLE 7
HOT STAR PHOTOMETRY AND PARAMETERS

OBJECT	TYPE	K	H	$H - K$	A_K^a	$(H - K)_0$	$D(\text{kpc})$	M_K	M_{bol}	BC_K	T_{eff}	References ^b
HD269445	Ofpe/WN9	9.56	9.98	0.42	0.20	0.30	46.8	-8.99	-11.60	-2.61	4.46	1,5,5,5,19,5,5
HD269687	Ofpe/WN9	11.58	11.65	0.07	0.06	0.03	46.8	-6.83	-9.80	-2.97	4.47	1,5,5,5,19,5,5
HD269582	Ofpe/WN9	11.08	11.24	0.16	0.06	0.12	46.8	-7.33	-9.25	-1.92	4.40	1,5,5,5,19,5,5
SK 67-266	Ofpe/WN9	11.88	12.02	0.14	0.05	0.11	46.8	-6.52	-9.62	-3.10	4.48	1,5,5,5,19,5,5
Hen S9	Ofpe/WN9	11.47	11.85	0.38	0.09	0.33	46.8	-6.97	-8.87	-1.90	4.46	1,5,5,5,19,22,22
HD37836	O8	9.40	9.73	0.33	0.03	0.31	46.8	-8.98	-10.50	-1.52	4.45	2,6,6,5,19,5,5
HD268840		11.49	11.88	0.39			46.8	-6.86				5,5,19
S Dor	LBV	8.61	8.4	-0.21	0.02	-0.22	46.8	-9.76	-9.80	-0.04	4.25	3,7,7,7,19,7,7
P Cyg	LBV	3.34	3.51	0.17	0.21	0.05	1.8	-8.15	-9.90	-1.75	4.28	3,8,8,16,16,16
HR Car	LBV	5.34	5.51	0.17	0.4	-0.06	5.0	-8.55	-8.90	-0.35	4.15	3,9,9,9,20,20,20
He3-519 ^c		7.42	7.63	0.21	0.46	-0.06	8.0	-7.56	-10.80	-3.24	4.50	3,10,10,3,21,3,3
Eta Car	LBV	1.14	2.58	1.44	0.4	1.21	2.5	-11.25	-11.5	-0.25	4.4	3,8,8,9,9,3,3
AG Car	LBV	5.76	6.11	0.35	0.2	0.23	6.0	-8.33	-10.80	-2.47	4.48	3,9,9,17,17,17,17
WR108	WN9	7.13	7.4	0.27	0.45	0.01	5.0	-6.81	-9.9	-3.09	4.48	4,11,11,11,22,22,22
WR122	Ofpe/WN9	6.45	8.49	2.04	0.81	1.57						4,11,11,11
WR85a	Ofpe/WN9	6.96	8.55	1.59	0.64	1.22						4,11,11,11
AF		10.95	12.71	1.76	3.00	0.01	8.0	-6.57				12,12,18,23
AHHNW		11.60	13.61	2.01	3.00	0.25	8.0	-5.92				12,13,18,23
IRS16 C		9.78	11.82	2.04	3.00	0.29	8.0	-7.74				14,14,18,23
IRS16 NE		8.76	10.83	2.07	3.00	0.32	8.0	-8.76				14,14,18,23
IRS16 NW		10.07	11.93	1.86	3.00	0.10	8.0	-7.45				14,14,18,23
IRS16 SW		8.67	11.5	2.83	3.00	1.08	8.0	-8.85				14,14,18,23
IRS1 W		9.20	11.17	1.97	3.00	0.22	8.0	-8.32				15,24,18,23
IRS13		9.40	11.17	1.77	3.00	0.01	8.0	-8.12				15,24,18,23

^a A_K determined from $E(V - B)$ or A_V assuming $R=3.1$ and the interstellar reddening curve of Rieke and Lebofsky (1985)

^bReferences are listed in order of TYPE, K , H , A_K , D , M_{bol} , and T_{eff} : 1.) BW, 2.) Hutchings 1980, 3.) Humphreys and Davidson 1994, 4.) van der Hucht 1988, 5.) MHH, 6.) Stahl 1985 7.) Leitherer et al. 1985, 8.) Allen 1973, 9.) MHH2, 10.) Allen and Glass 1974, 11.) Williams et al. 1987, 12.) DePoy, private communication, 13.) Present work, 14.) DePoy and Sharp 1991, 15.) Simon et al. 1990, 16.) Lamers et al. 1983, 17.) Humphreys et al. 1989, 18.) Wade et al. 1987, 19.) Reid and Strugnell 1986, 20.) van Genderen, 1991, 21.) Davidson et al. 1993, 22.) Crowther et al. 1994, 23.) Reid 1989, 24.) Rieke et al. 1989

^cPossible LBV (Humphreys and Davidson 1994)

5.4 Discussion

The fundamental problem in assessing the nature of the He I sources at the GC is that we can observe only the red end (NIR wavelengths or longer) of their spectra. If these objects are massive evolved stars which live in the upper part of the HR diagram, we may expect significant differences among their observed spectra based on experience with WR, LBV, and Ofpe/WN9 stars which have much more extensive spectral coverage (see the review of LBV's by Humphreys and Davidson 1994, for example). The task then, is to discern the nature of the GC He I sources using only a fraction of the wavelength coverage available when studying their visible (proposed) counterparts.

The following sections explore the similarities and differences between the comparison stars and GC He I sources. We first discuss the H I lines to establish more firmly the wind nature of the GC sources. We then move to the He I lines which provide the most dominant features in the GC spectra. We end with discussions of the mass-loss rates for the GC sources and their location in the HR diagram.

5.4.1 H I Lines: AF v. Galactic and LMC Stars

The Brackett line equivalent widths (W_λ) are consistently larger in AF (this paper, Table 4; Libonate et al. 1995) than any of the comparison stars (this paper, Table 5). The Brackett line to Br γ ratios for the comparison stars show a large range of values which encompass the ratios for AF. We find no relationship between the observed line ratios and the known physical parameters of the comparison stars. The

line ratios in the LMC stars and galactic source WR85a are larger than predicted for case B recombination (Hummer and Storey 1987; $T_e=10^4$ °K, $n_e > 10^4$ cm $^{-3}$). This suggests that the lines are optically thick (MHH2; Simon et al. 1983). WR122 is consistent with either high density ($n_e > 10^9$ cm $^{-3}$) case B or optically thick line ratios depending on the reddening.

The AF source is consistent with optically thick Brackett line emission if the adopted reddening is large ($A_K \approx 3$) as is typically taken for the GC. It is important to point out that we should expect some NIR excess to be associated with the AF source if it is an Ofpe/WN9 star. The LMC stars are generally consistent with an excess due to free-free emission (MHH), while the two galactic Ofpe/WN9 stars are associated with circumstellar dust (Williams et al. 1987) as can be seen from their rising continua (Figure 11) and spectral energy distributions given by Williams et al. (their Figure 13; note that WR85a=LSS 4005). This means any interpretation of the AF emission lines or NIR colors will be subject to considerable uncertainty. However, it is possible to rule out case B line ratios for AF based upon the measurements of Br γ and Pa α reported by Najarro et al. (1994), which indicate that the ratio of Br γ to Pa α could only be case B if the extinction at K is significantly *larger* than 3.0 mag. Such a large value is ruled out by the NIR colors of AF (our own unpublished colors: $J = 15.74 \pm 0.06$, $H = 12.71 \pm 0.07$, $K = 10.95 \pm 0.11$, and $L = 9.14 \pm 0.06$), which would then be bluer than a black body of any temperature.

5.4.2 The Galactic Center He I Emission Line Sources

The AF, AHH NW, WR85a, and WR122 stars have about an order of magnitude greater He I 2.06 μm equivalent width than the LMC stars. The W_λ ranges from 109 Å to 715 Å for these stars (this paper, Table 4; Libonate et al. 1995) which may be compared to the average $W_\lambda = 34 \pm 10$ Å for the LMC stars (this paper, Table 2). The four galactic/GC sources also show larger W_λ in the 1.700 μm line with the galactic/GC objects exhibiting $W_\lambda \gtrsim 20$ Å (this paper, Tables 1 and 2; Libonate et al. 1995) while the LMC stars show $W_\lambda \lesssim 10$ Å (this paper, Table 5). The He abundance predicted by Najarro et al. (1994) for AF is larger than the values derived by Crowther et al. (1994) for the LMC stars: He/H by number of 1.3 ± 0.3 compared to 0.3 ± 0.1 . Theoretical models for massive stars (Maeder 1990) predict that He/H at the surface will change by large amounts over short evolutionary periods, so this difference may not be significant. The observed difference in W_λ 's between the spectrum of AF (and the other galactic sources) and the LMC comparison stars, may also point to differences in the mass loss rate, ionization structure, effective and temperature, as well as the He/H abundance ratio. All of these strongly affect the He I 2.06 μm line flux (Najarro et al. 1994; see also Shields 1993). Accurate W_λ 's provide strong model constraints since they are not directly affected by reddening.

The remainder of the GC sources have much smaller equivalent widths, on average a factor of 2 less than the LMC stars (this paper; Libonate et al. 1995). Eckart et al. (1993) have proposed that the IRS 16 cluster is composed of about 25 stars. However, the lunar occultation results of Simon et al. (1990) and Simons et al. (1990) indicate

IRS 16 C, NE, SW, and NW emit the majority of the flux observed and are compact objects less than 200 AU in size. If the He I emission is in fact associated with fainter objects near the bright IRS 16 components, then the lower W_λ compared to AF, AHH NW, and the other comparison stars could result from source crowding. However, if the He I sources (coincident with IRS 16) are to have similar equivalent width as AF ($\sim 10\times$ lower continuum) then they would tend to be under-luminous at K , compared to the LMC stars (Table 7), since this would require reducing the continuum flux substantially for the same observed line flux. The observed continuum would then be due to the He I source and other, bright, non-emission line sources combined.

The level of HeI emission in the two galactic WN9/Ofpe stars, WR85a and WR122, is remarkable. The HeI lines are at least an order of magnitude stronger relative to $\text{Br}\gamma$ than in the other emission line stars we observed and other emission line objects in general (e.g. DePoy & Shields 1994). This suggests that regardless of the physical conditions in these two sources, the He to H abundance ratio must be significantly different from the solar value (~ 0.1). For example, the ratio of $\text{Br}\gamma$ to the sum of the singlet and triplet transitions producing HeI 2.113 μm emission is expected to be ~ 0.03 for a helium to hydrogen abundance ratio of 0.1, based on recombination rates appropriate for 10^4 K and 10^6 cm^{-3} from Brockelhurst (1972) and Hummer & Storey (1987) and HeI branching ratios of Wiese, Smith, & Glennon (1966). Although the applicability of this calculation is difficult to determine given the likelihood the sources have optically thick line emission (see §3.2), the observed values of the HeI

2.113 μm to $\text{Br}\gamma$ emission in WR122 (~ 1.3) and in WR85a (~ 0.8) suggests that the He/H abundance ratio in these objects is >1 . (Note that we have elected not to base our abundance estimates on the strength of the HeI 2.06 μm line emission, which is strongly affected by resonant scattering of the HeI $2^1P \rightarrow 1^1S$ 584 $\text{\AA}$ line and hence sensitive to geometry, density, dust content, and velocity structure, as well as abundance; see Shields 1993).

Comparison of Tables 1 and 2 shows another difference between the GC and individual sources: all the highest velocity widths are observed in the GC; the galactic and LMC emission-line stars are unresolved at our resolution. The observed He I velocity widths (uncorrected for the instrumental profile) range from unresolved to approximately 1200 km s^{-1} (excluding the 2.11 μm line for IRS 13; see below) for the GC sources, while the galactic and LMC comparison stars are unresolved ($\text{FWHM} \lesssim 565 \text{ km s}^{-1}$ at 2.06 μm , $\text{FWHM} \lesssim 513 \text{ km s}^{-1}$ at 1.70 μm). The measured widths of several comparison stars (WR122, WWR85a, and HD269445) appear marginally resolved, but this is likely due to the extraction technique described above which may broaden the lines by $\sim 10\%$. Our conclusions on the line widths are most firm for the He I widths since the H I lines may suffer from systematic uncertainty due to the reduction procedure as described above and also may be broadened by He I emission and so are not representative of the wind velocity (Najarro et al. 1994). For widths greater than our instrumental resolution, our results for the He I 2.06 μm line width are in good agreement with Krabbe et al. (1991) and Libonate et al. (1995).

Crowther et al. (1994) measure the wind terminal velocity for four of the ten LMC

Ofpe/WN9 stars from He I P Cygni profiles in the UV and IR. All four stars show terminal wind velocities less than 500 km s^{-1} , consistent with our measurements of similar LMC stars. Higher velocities are expected for the hotter WR stars. We find that the highest velocity GC source is AHH NW which has a He I $2.06 \mu\text{m}$ FWHM of 1200 km s^{-1} , similar to the terminal velocity reported for WR108 by Crowther et al. (1994). AHH NW is also the faintest He I source we observed. If it were hotter, its bolometric correction could be larger (see below) than the other GC sources. The K band spectra of AHH NW and WR108 are significantly different; WR108 shows no He I $2.06 \mu\text{m}$ emission. However, the models of Crowther et al. for one Ofpe/WN9 star indicate that changes in the ionization structure of the wind (which result from relatively small changes in the stellar input parameters) lead to significant changes in the $2.06 \mu\text{m}$ emission, causing it to range from essentially no emission to the amount indicated by the observed spectrum. However, the models which reproduce the observed $2.06 \mu\text{m}$ emission do not reproduce all the important features of the optical spectrum (Crowther et al. do not regard this as a serious problem; see their discussion of the models for the object Sk-66°40). Whether similar results would hold for WR108 is unclear. If large changes in the NIR spectra of these stars can result from small changes in the stellar parameters, the task of identifying the GC sources becomes even more difficult.

The significance of the observed differences in the NIR spectra of AF and AHH NW and the comparison stars is unknown. We might expect that differences in abundance and environment could lead to different physical conditions in the envelopes of these

stars. Abundance differences may play a key role since mass loss is expected to be metallicity dependent (Abbott 1982) and there are differences in abundances between the LMC, the Galaxy, and Galactic Center. The LMC is known to be metal poor relative to the Galaxy (eg, Dufour 1986 and references therein) and there is evidence that the Galactic Center may be metal rich (Lacy et al. 1980, Shields and Ferland 1994). Likewise, star formation and evolution may proceed differently in the GC where collisional/merger processes are thought to be important between stars and/or stellar remnants (Phinney 1989; Morris 1993).

We close our discussion of the GC K band spectra by pointing out several differences or extensions which our observations reveal relative to previous work. First, the spectral coverage is significantly greater than previous work. The He I 2.113 μm line and full K band continuum are included for eight GC sources. Full K band spectra are also presented by Libonate et al. (1995) for nine GC sources, but at lower spectral resolution than ours. We find no evidence for 2.113 μm emission in the IRS 16 sources with the possible exception of IRS16 SW, as is shown in Figure 10. Indeed, we may see small absorption at 2.113 μm in IRS16 NW and IRS 16 C. This is not expected for the Ofpe/WN9 stars, but if present, could be due to contamination by late O or early B stars (Hanson and Conti 1994). Libonate et al. (1995) do not see 2.113 μm emission or absorption in any of the IRS 16 sources.

The spatial scale on OSIRIS allows us to make background subtraction from nearby ($\lesssim 2''$) apertures for all the GC sources. This provides a more accurate estimate of the relative line to continuum flux for the compact point sources and eliminates

contributions to the line emission from the diffuse ionized gas. Note the spectrum of IRS1 W shown in Figure 10. We find no He I emission after background subtraction. The embedded source(s) suggested by Rieke and Lebofsky (1982) and Rieke, Rieke, and Paul (1989) in IRS1 W does not appear to be a He I emission-line source contrary to the results of Krabbe et al. (1991) who did not subtract a local background. Libonate et al. (1995), who do subtract a local background, also conclude that IRS 1W is not a He I emission line star.

Our observations reveal several important details which the Fabry-Perot data of Krabbe et al. (1991) do not. First, a number of sources show emission to the red of the He I $2.06 \mu\text{m}$ line, see IRS 13 in Figure 10 for the most prominent example, but IRS16 NW and SW may also exhibit this behavior. The spectral coverage of Krabbe et al. was insufficient to detect this emission which extends $\sim 5000 \text{ km s}^{-1}$ to the red in the case of IRS 13. This emission is not included in the line fluxes in Table 4 since it is not clear whether it is a blend of other lines or part of the He I emission. It amounts to 40 % of the He I line in IRS 13.

Hillier (1984 and 1991) attributed extended emission to the red of optical He II lines in the WN5 star HD50896 to electron scattering. Asymmetric (red wing) profiles are expected when the wind velocity becomes strong relative to the electron thermal velocity, as is the case for HD50896. For stars which have wind velocities much smaller than the electron thermal velocity, the profiles are symmetric. This is the case for P Cygni (Bernat & Lambert 1978). The fact that redward emission is not seen in Br γ and that the He I $2.11 \mu\text{m}$ line appears extended on both the red and

blue sides suggests that, at least for IRS 13, the emission might be due to unknown lines. To further investigate this unusual source, we obtained the high resolution ($\approx 120 \text{ km s}^{-1} \text{ pix}^{-1}$ at $2.06 \mu\text{m}$) spectrum shown in Figure 13. The line measurements are shown in Table 6.

The broad wing to the $2.06 \mu\text{m}$ line is not resolved into individual lines in the high resolution spectrum of IRS 13. The emission profile appears quite similar in the high and low resolution spectra. The broad emission near $2.11 \mu\text{m}$ does split up into two lines separated by about $0.01 \mu\text{m}$. The blue component is unidentified. The He I $2.11 \mu\text{m}$ line profile also appears to exhibit a red wing in the high resolution spectrum. This strengthens the possibility that a line formation mechanism intrinsic to the IRS 13 outflow is important for the He I lines. We can not say whether electron scattering is responsible for the formation of the He I red wings, and we note that the Br γ emission clearly does not exhibit profiles like the He I lines. Perhaps Br γ is still contaminated by emission not associated with IRS 13 which masks a red wing. [Fe III] emission (see below) may not be physically associated with the outflow from IRS 13, but does peak quite strongly along this line of sight (Lutz et al. 1993).

Two weak features appear at 2.185 and $2.191 \mu\text{m}$ in the high resolution spectrum of IRS 13. The longer wavelength line is possibly due to He II (10–7). This suggests that the effective temperature for IRS 13 may be similar to the Ofpe/WN9 stars. The Ofpe/WN9 star models of Crowther et al. (1994) for Sk–66°40 predict $T_{eff} \approx 29,000^\circ\text{K}$ with small W_λ ($1\text{--}6 \text{ \AA}$) in the He II $2.189 \mu\text{m}$ line. The line near $2.185 \mu\text{m}$ may be due to He I $4p^1P^o \rightarrow 7d^1D$.

Fig. 13.— High resolution ($R \approx 1350$, $120 \text{ km s}^{-1} \text{ pix}^{-1}$) spectrum of IRS 13. Note the emission to the red of the He I $2.06 \mu\text{m}$ and $2.11 \mu\text{m}$ lines. The lines at 2.15 and $2.22 \mu\text{m}$ are due to [Fe III]. This spectrum was extracted from a $\approx 0.5'' \times 1.0''$ aperture and includes background subtraction from nearby ($\lesssim 2''$) apertures on either side of it. All of the emission lines are resolved (observed FWHM $\gtrsim 240 \text{ km s}^{-1}$).

Extended emission from [Fe III] peaks near IRS 13 but may not be otherwise associated with it (Lutz et al. 1993). The lines identified by Lutz et al., ${}^3G_3 \rightarrow {}^3H_4$ 2.1457 μm , ${}^3G_5 \rightarrow {}^3H_6$ 2.2178 μm , ${}^3G_4 \rightarrow {}^3H_4$ 2.2437 μm , and ${}^3G_5 \rightarrow {}^3H_5$ 2.3485 μm due to [Fe III] (Sugar & Corliss 1985) are also clearly evident in our low resolution spectrum of IRS 13. The ratio of the emission from the 2.3485 μm line to that of the 2.2178 μm line measures the extinction to the line emitting region since both come from the same upper level. Assuming the Einstein A-values of Garstang (1957), the unreddened ratio should be 0.652; our measured ratio in the low resolution spectrum is 0.88 ± 0.16 , where we have estimated the uncertainty from the rms scatter in the nearby continuum. Assuming the extinction curve of Rieke and Lebofsky (1985) leads to a derived extinction of $A_K = 4 \pm 2$ mag, consistent with other estimates of the extinction to Galactic Center sources (i.e. Rieke, Rieke, & Paul 1989; Wade et al. 1987). We adopt $A_K = 3$ mag as determined by these other, more accurate, methods.

The ${}^3G_5 \rightarrow {}^3H_6$ 2.2178 μm and ${}^3G_3 \rightarrow {}^3H_4$ 2.1457 μm [Fe III] lines were also detected in the high resolution IRS 13 spectrum. These lines arise from closely spaced upper levels, so the ratio of the intensities is primarily density sensitive. Keenan et al. (1992) calculated collision strengths for Fe III and used the Einstein A-values of Garstang (1957) to produce relative level populations over a wide range of temperature and densities. The measured ratio of the two lines is 0.37 ± 0.1 . Assuming $A_K = 3$, this suggests an unreddened value of 0.50 ± 0.1 , which corresponds to $\log[n_e (\text{cm}^{-3})] = 5.8 \pm 0.2$. Densities this high have also been estimated from [FeII] lines in nearby regions by DePoy (1992).

At least one of the LMC Ofpe/WN9 class (HD 269858, not observed here) has been observed in transition to a spectrum like that of S Dor (Wolf et al. 1988). Our spectrum of HD 269582 shows an order of magnitude change in the He I 2.06 μm flux from that of MHH. Even with the potential uncertainties in our flux calibration, discussed above, the ratio of this line to Br γ has clearly changed from substantially greater than one in MHH to less than one in the present case. These two examples indicate an important area of investigation for the GC sources in the future: periodic observations showing spectral or continuum variations would provide strong links to the Ofpe/WN9 class.

5.4.3 What Are They Not?

The NIR spectra presented in Figure 10 can be used to eliminate several possibilities as to the nature of the GC He I sources. Comparison to the spectra in Figure 12 indicates that the GC sources have NIR spectra much different from the prototype LBV, S Dor, or the galactic WN9 star, WR108. The spectrum of WR108 shows no evidence of He I 2.06 μm emission but does show emission at 1.700 and 2.11 μm (although, see the discussion above regarding the modeling of Crowther et al. 1994). Werner et al. (1990) present longer wavelength spectra of WR108, IRS 16 NE, and AF which clearly show strong He II 3.09 μm emission in WR108 and no 3.09 μm emission in AF or IRS 16 NE. The spectrum of S Dor is clearly distinct from the Ofpe/WN9 stars and GC sources in that it shows no He I emission. This is expected since the LBV maximum light phase (which S Dor is in) is expected to be a lower excitation one (BW). Ofpe/WN9 star spectra may be similar to LBV minimum light

phase spectra. AG Car, a known LBV, has a K band spectrum with similar features as the LMC Ofpe/WN9 stars (MHH2) and was identified as Ofpe/WN9 at minimum by Stahl (1986) based on its optical spectrum. The well known LBVs η Car (Allen, Jones, & Hyland 1985, and MHH2) and P Cyg (Libonate et al. 1995) also show similarities to the LMC Ofpe/WN9 K band spectra (MHH2).

The GC spectra are also significantly different from the NIR spectra of WN7-8 stars (Hillier 1985) which show quite strong P Cygni absorption in the $2.06\ \mu\text{m}$ line, much weaker He I $2.06\ \mu\text{m}$ relative to $\text{Br}\gamma$, and also He II emission in the H and K bands (Hillier's Figures 2-8).

Earlier WR subtypes, i.e. WC5-9, can be ruled out by comparing the GC spectra to the observations of Eenens et al. (1991). All of these stars show strong C IV at $2.08\ \mu\text{m}$ which dominates the He I emission at $2.06\ \mu\text{m}$.

The AF and AHH NW sources show distinct differences from the more normal O and B giant and supergiant K band spectra presented by Hanson and Conti (1994). Many of these spectra exhibit absorption features at $2.06\ \mu\text{m}$ and $2.17\ \mu\text{m}$ corresponding to He I and H I. Only one spectrum, that of the O7.5 III star HD 155806, shows strong emission at $2.06\ \mu\text{m}$ relative to $\text{Br}\gamma$, but its He I $2.06\ \mu\text{m}$ W_λ ($7\ \text{\AA}$) is much smaller than the AF, AHH NW, WR122, WR85a, and LMC stars. The W_λ for HD 155806 is similar to IRS 16 NW and SW. These two GC sources are much brighter than HD 155806, if individual sources. As Hanson and Conti point out, the emission from HD 155806 is presumably due to a disk like structure analogous to the Be star phenomenon. The large observed line widths (and no evidence of double

peaked emission line profiles) for a number of the GC sources are more naturally associated with wind outflow than disk emission.

5.4.4 Mass Loss Estimates for the GC Sources

If we assume the $\text{Br}\gamma$ emission in AF and the other GC sources arises in an optically thick outflow, as shown in section 3.1, then we can follow MMH2 in making simple estimates of the mass loss from each source. By using the results of Simon et al. (1983) for a constant velocity, completely ionized wind, we can determine the relative mass loss compared to AF for each of the sources from the $\text{Br}\gamma$ integrated line fluxes. An estimate of the absolute mass loss can be obtained by taking the mass loss for AF as computed in the more detailed models of Najarro et al. (1994), which they give as $6.0\text{--}9.5 \times 10^{-5} M_{\odot}\text{yr}^{-1}$. This estimate assumes each of the sources has similar He abundance, since the mass loss rate for this model is proportional to the mean molecular weight (Krabbe et al. 1991). Assuming AF has the largest He abundance of the GC sources, based on the ratios of He I 2.06 μm and 2.11 μm to $\text{Br}\gamma$, then the mass loss rates for the remaining GC sources may be overestimated. The recent model results presented for LMC Ofpe/WN9 stars by Crowther et al. (1994) indicate that the LMC stars may have a He/H abundance (by number) a factor of three less than AF. In addition, most of the other GC sources exhibit little or no He I 2.11 μm emission, except AHH NW (see Table 4). Note that the increased He I abundance for AF may be countered somewhat by the fact that He I (7-4) will be added to the $\text{Br}\gamma$ line flux (Najarro et al. 1994). We find that the majority of the GC sources have somewhat smaller mass loss rates than AF, while the galactic and LMC stars fall in

a wide range above and below the mass loss rate for AF.

The values in Table 4 and range of model results for AF (Najarro et al. 1994) indicate a total mass loss rate from all the He I sources at the GC of $\lesssim 6.0\text{--}9.5 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ (accounting for a total of twice the number of sources in the GC that we have observed, roughly the number of He I sources reported by Krabbe et al. 1991), in agreement with Krabbe et al. (1991). We note that these values are a factor of 3–5 less than that required by Gatley et al. (1984, $3 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$) to collisionally excite the H_2 emission observed at the edge of the 2 pc molecular ring. The observed cometary tail of the red supergiant IRS 7 has been interpreted by Serabyn et al. (1991) and Yusef-Zadeh & Melia (1992) as arising from the impact of a wind from the IRS 16 vicinity on IRS 7. Both Serabyn et al. and Yusef-Zadeh & Melia argue for a wind mechanism instead of a drag force due to the motion of IRS7 through the GC interstellar medium, although neither of their results rule out the drag force scenario. Yusef-Zadeh & Melia fit the observed bow shock structure to simple models which result in a best fit required mass loss from the vicinity of IRS 16 of about $1.5 \times 10^{-3} M_{\odot} \text{ yr}^{-1}$. They can not rule out somewhat lower values of the required mass loss, which would be more consistent with the values presented here. Serabyn et al. compute models of the tail kinematics for various values of the ratio of the force on the tail due to an external wind, relative to the force of gravity due to the GC mass distribution. This parameter includes, but does not necessarily constrain the mass loss rate since it is also affected by the GC mass distribution and tail density; the implied mass loss rate in the wind could be consistent with the values reported here.

5.4.5 The HR Diagram

The ultimate goal of the analysis of the NIR spectra of the GC sources is to use the resulting spectral type information to assess the overall impact these objects have on the GC environment. Placing the GC sources in the HR diagram would result in firm estimates of the total ionizing flux and mass loss expected. The above results clearly indicate that we have not reached this point. However, the emission line spectra of the GC sources are at least suggestive that some of these objects are similar to very massive evolved stars. Therefore, we have used published data for WR, Ofpe/WN9, and LBV stars to compute K band bolometric corrections (BC_K) as a function of stellar effective temperature (Figure 14) which we apply to the GC sources. The resulting HR diagram is shown in Figure 15, where the GC sources are represented as line segments corresponding to different BC_K 's. The vertical error bar (± 0.71 mag) is an estimate of the uncertainty in the bolometric correction, estimated by the scatter in the best fit linear relation shown in Figure 14, added in quadrature to a ± 0.5 mag uncertainty in the adopted reddening.

The BC_K 's were determined from the photometry and stellar parameters given in Table 7. Reddening values were determined from the published $E(V - B)$ or A_V values and by assuming $R = 3.1$ and the interstellar reddening curve of Rieke and Lebofsky (1985). The BC_K 's were then fit to a line using a least squares analysis. The data and fit are shown in Figure 14. We take the average residual (0.5 mag) as an estimate in the uncertainty of the BC_K at any given T_{eff} . The BC_K relationship has a similar slope but is approximately 1 mag fainter than the same relation derived

Fig. 14.— Derived K band bolometric corrections (filled squares) for the early type mass losing stars listed in Table 7. The solid line is the best fit linear relation between the bolometric correction and effective temperature.

for a black body.

The GC source photometry are taken from the references given in Table 7. In the case of IRS 13 and IRS 1 W, the K magnitudes were taken from Simon et al. (1990). The results of Simon et al. (1990) are based on lunar occultations of the GC and indicate that IRS 1 W and 13 are composed of 2 dominant sources each. For purposes of including them in the HR diagram, we will take a K mag corresponding to the brighter of the two sources. The distance and reddening to the GC are taken as 8 kpc (Reid 1989) and $A_K = 3.0$ mag (Wade et al. 1987), respectively.

The NIR spectra of the GC sources indicate that none of them are consistent with WN8 or earlier type massive stars. The GC tracks in Figure 15 then suggest that none of the bright blue sources in the GC are as hot as the limiting T_{eff} ($\lesssim 35,000$ °K) for sources which ionize the diffuse gas in the central few pc (Serabyn and Lacy 1985). The similarity of the NIR spectra of the GC sources to several of the sources in Figure 12, but not the hotter WN7-8 stars suggests a limiting T_{eff} for the He I emission line stars of $\approx 30,000$ °K. If we assume all the GC sources are at their maximum M_{bol} , then they would produce $\approx 3.8 \times 10^{50} \text{ s}^{-1}$ Lyman continuum photons (accounting for twice the number of He I sources that we have observed, Krabbe et al. 1991, and including IRS 1 W). Here we have used the flux of ionizing photons from Panagia (1973) assuming $T_{eff} \approx 30,000$ °K and a stellar radius appropriate to the M_{bol} given in Table 7. This is just sufficient to account for the required H I ionizing flux in the GC (Serabyn and Lacy 1985, Mezger and Wink 1986).

It is likely that some of the GC He I sources are actually cooler and less luminous

than the maximum case shown in Figure 15. Krabbe et al. (1991) report that supergiant stars of $T_{eff} \approx 31,000^\circ\text{K}$ would produce 0.06 He I ionizing photons for each Lyman continuum photon. In this case, the total number of He I ionizing photons produced by the GC sources (using the maximum BC_K for each source) would exceed the number predicted by Krabbe et al. (1991) from analysis of the observed He I emission in the central few pc. The models of Najarro et al. (1994) estimate that AF has a $T_{eff} \approx 20,000^\circ\text{K}$ and that AF produces $\lesssim 10^{48} \text{ s}^{-1}$ H I ionizing photons and $\lesssim 10^{38} \text{ s}^{-1}$ He I ionizing photons. This T_{eff} (based on M_{bol} and radius at the base of the wind) is significantly less than the T_{eff} ($\approx 29,000^\circ\text{K}$) derived for the LMC Ofpe/WN9 stars modeled by Crowther et al. (1994; they call T_{eff} , as defined here, $T_\star$). The Najarro et al. results are shown by the box labeled N94 in Figure 15 and are consistent, within the estimated uncertainty, with the BC_K derived here.

The minimum T_{eff} used in determining the BC_K for the GC sources corresponds to $\approx 14,000^\circ\text{K}$. This is the value for HR Car and represents an approximate lower limit to the T_{eff} which can excite the observed He I emission. The K band spectrum of HR Car (MHH2) has essentially no HeI $2.06 \mu\text{m}$ emission.

The HR diagram suggests that all eight GC sources observed here may be massive post-main sequence stars with initial masses between ≈ 15 and $60 M_\odot$. Several of these sources may be near the Humphreys–Davidson limit (however, note that the K band spectrum of IRS 1 W is not similar to the spectra of the galactic and LMC comparison stars) while others have bolometric luminosities which overlap with those of late O and B supergiants.

Fig. 15.— HR diagram for the GC sources and early type mass losing stars. The GC sources are shown as solid lines using the bolometric correction v. effective temperature relationship shown in Figure 14. Data for the individual comparison sources (crosses) are taken from the references given in Table 7. The larger box (dashed lines) labeled “WR Stars” is reproduced from Humphreys and Davidson (1994). The smaller box (dashed lines) labeled “AF N94” depicts the model results of Najarro et al. (1994) for the AF source. The error bar shown is for the GC sources and corresponds to a ± 0.71 mag uncertainty in M_{bol} estimated from the residuals in the fit of Figure 14 added in quadrature to an assumed ± 0.5 mag uncertainty in the adopted reddening. The main sequence (Schmidt-Kaler 1982) is shown for comparison (filled triangles).

5.5 Conclusions

Direct comparison of the GC He I emission line source, AF, with representatives of the Ofpe/WN9 class shows that its NIR spectrum is morphologically similar to the spectra from these early type mass losing stars. However, we find significant evidence that the AF and AHH NW sources and galactic Ofpe/WN9 stars WR122 and WR85a may have substantial differences in the physical conditions in their mass losing envelopes relative to the LMC stars. They show an order of magnitude larger equivalent width in the He I 2.06 μm line than the LMC stars. In addition, we find larger velocity widths in the He I lines in the AF and other GC sources (observed widths up to 1200 km s^{-1}) than in any of the galactic or LMC Ofpe/WN9 stars, which are unresolved (or marginally resolved) at our resolution ($\lesssim 565 \text{ km s}^{-1}$ at 2.06 μm and 513 km s^{-1} at 1.70 μm). The observations of Crowther et al. (1994) are consistent with our finding that higher velocity outflows occur in the GC sources.

We point out that the models of Crowther et al. (1994) for a number of LMC Ofpe/WN9 stars result in significant differences from the predictions for AF of Najarro et al. (1994) for several of the derived stellar parameters. The He abundance predicted by Najarro et al. for AF is much larger than the values derived by Crowther et al. for the LMC stars: He/H by number of 1.3 ± 0.3 compared to 0.3 ± 0.1 . Evolutionary models for massive stars (Maeder 1990) predict that the surface abundance of He relative to H will change significantly over short evolutionary times, so the observed difference in He/H may not be significant. The temperature (based on M_{bol} and radius at the base of the atmosphere) is higher for the LMC stars modeled by Crowther et

al. compared to the Najarro et al. result for AF.

While in general agreement with previous work, the GC spectra presented here include several new important aspects. The long slit capability and spatial scale of OSIRIS allow us to determine the nearby background contribution to the GC sources. This is essential in eliminating emission from diffuse gas and in estimating the true underlying continuum for the GC sources. We find that the He I source IRS1 W has no emission at $2.06\ \mu\text{m}$ after background subtraction, consistent with it being an III region with an embedded source which has no compact He I emission.

Our spectra also greatly expand the wavelength coverage of the GC He I sources including the He I $2.113\ \mu\text{m}$ region. We find that the He I emission near 2.06 and $2.11\ \mu\text{m}$ may extend further to the red than previously found for some sources. IRS 13 is the most prominent example of this type. While we can not rule out that this emission is due to unidentified, unresolved lines, our high resolution spectrum of IRS 13 suggests the He I 2.06 and $2.11\ \mu\text{m}$ lines have continuous asymmetric emission profiles extending to the red of line center.

Finally, we point out that a large range of broad band and spectroscopic measurements should be used in modeling the GC sources. The NIR photometry and spectra (WR122 and WR85a in Figure 11 are extreme examples) indicate that we should expect an excess of continuum emission due to free-free and/or dust emission to be present in the GC sources if they are similar to the Ofpe/WN9 class. This is especially important in the GC where large observed colors are often attributed entirely to interstellar extinction.

The broad band fluxes and spectra of the GC sources should also be observed for evidence of variability. Several of the LMC stars are known variables and one of them, HD269582, showed a large variation in the He I 2.06 μm line in the present work, relative to the spectrum presented by MHH.

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CHAPTER VI

Discovery of a Possible Wolf-Rayet Star at the Galactic Center ¹

6.1 Abstract

We report the discovery of a possible Wolf-Rayet star located at 0.5 pc projected radius from the center of the Galaxy. A K band ($2.2\ \mu\text{m}$) spectrum of the Galactic Center object shows strong similarities with published K band spectra of WC9 stars, including emission lines due to He I at $2.06\ \mu\text{m}$, the C IV $3d\ ^2D-3p\ ^2P^\circ$ multiplet with components between $2.071\ \mu\text{m}$ and $2.084\ \mu\text{m}$, and a blend of two C III lines and He I near $2.11\ \mu\text{m}$.

6.2 Introduction

The discovery of a cluster of He I emission line stars at the Galactic Center (GC) by Krabbe et al. (1991) provides strong evidence of recent star formation in the region. The most prominent He I source was originally identified as a compact Br α source by Forrest et al. (1987) and as a strong source of He I $2.06\ \mu\text{m}$ emission by Allen, Hyland, & Hillier (1990). This source, now known as the Allen–Forrest or AF star, was classified as an Ofpe/WN9 star by Allen et al. The identification was based on

¹This chapter appeared in its entirety as Blum et al. (1995c)

the AF star's K band spectrum, which is similar to those of Large Magellanic Cloud (LMC) Ofpe/WN9 stars (McGregor, Hillier, & Hyland 1988). Ofpe/WN9 stars may link the Wolf-Rayet (WR) and Luminous Blue Variable (LBV) evolutionary stages (Maeder & Conti 1994); their spectra can resemble LBV spectra at minimum and, by definition, are similar to the late WN (WNL) stars (Bohannon & Walborn 1989). Blum, DePoy & Sellgren (1995b) have compared seven of the GC He I stars to a sample of the LMC Ofpe/WN9 stars and found similarities in their K ($2.2 \mu\text{m}$) band spectra. Libonate et al. (1995) present H and K band spectra of nine GC He I sources and conclude that several of them are similar to Ofpe/WN9 or LBV stars. If the GC stars are similar to the LMC Ofpe/WN9 stars, they must be young, massive stars.

If a recent burst of star formation has occurred at the GC, how long ago did it happen? What was the duration of the burst and what mix of massive stars might still be present? Are the GC He I stars only the most obvious component of recent star formation by virtue of their brightness and strong He I emission, or have the initially more massive stars evolved away? Tamblyn & Rieke (1993) and Schaerer (1994) have investigated these questions theoretically by exploring burst models for star formation in the GC. At least one red supergiant has been identified (IRS 7, Lebofsky, Rieke, & Tokunaga 1982; Sellgren et al. 1987), but no candidate main sequence O stars have been discovered and, until now, no hotter WR stars. An unknown component of hot stars has been suspected on the basis of the observed nebular excitation in the GC, since the He I stars may not provide significant amounts of ionizing photons

(Najarro et al. 1994). Clearly, identifying any components of a young, massive, stellar population in the GC will help establish the age and extent of recent star formation and its impact on the region.

In this Letter, we present a K band spectrum for a candidate WR star within the central parsec of the Galaxy. The object is located approximately at $\alpha(1950) = 17^h 42^m 28.62^s$, $\delta(1950) = -28^\circ 59' 24.1''$ which is $2.5''$ west and $1.5''$ north of the AF star. We give the source a preliminary classification of WC9 based on the identification and relative strengths of lines due to He I, C IV and C III between $2.06 \mu\text{m}$ and $2.12 \mu\text{m}$.

Libonate et al. (1995) discuss the spectrum of a source $2.4''$ west and $1''$ north of the AF star which they suggest has a featureless K spectrum similar to a hot dwarf (B) star. Based on the spatial position of this source it is likely the source we discuss here. Libonate et al. probably did not detect the line emission that we report due to low signal to noise and smaller spectral coverage. Their spectrum extends from $2.08 \mu\text{m}$ to $2.18 \mu\text{m}$. This would be insufficient to detect the He I $2.06 \mu\text{m}$, C IV $2.08 \mu\text{m}$, C IV $2.32 \mu\text{m}$, and C III $2.33 \mu\text{m}$ emission which we report here.

6.3 Observations and Data Reduction

The observations were taken on 1993 July 12 with the Ohio State Infrared Imager and Spectrometer (OSIRIS; DePoy et al. 1993) on the CTIO 4-m telescope. OSIRIS employs a 256×256 HgCdTe array and was used in low resolution mode ($R \approx 570$). This set-up results in a slit $\approx 115'' \times 1.3''$ with a spatial scale of $0.45'' \text{ pix}^{-1}$.

After flat-fielding and sky subtraction, spectra of the object were extracted from the two dimensional long slit images by tracing and synthesizing $1.8''$ wide apertures

along the spectral dimension. We also extracted a background aperture located $\approx 2''$ east of the source and subtracted it from the object spectrum. The extracted spectra from three 150 second exposures were co-added; the resultant spectrum was corrected for telluric absorption by dividing it by the spectrum of a hot star (BS6486, A3). The spectrum was put on a flux density scale by multiplying it by an 8500°K black body. OH airglow lines were used for wavelength calibration. The details of the data reduction are the same as given in Blum et al. (1995b) for observations of a number of the GC He I stars. The final spectrum is shown in Figure 16. The spectrum suffers from the same fringing problems discussed by Blum et al. (1995b). Narrow features at the 2-3 % level are not reliable.

The absolute flux density scale was set by scaling the $2.2\ \mu\text{m}$ intensity to the object's K magnitude (10.57). This K magnitude was obtained from our own unpublished images of the GC which were taken to locate the long slit spectroscopy and were calibrated by the K band image of DePoy & Sharp (1991). We derived the object's J band magnitude similarly. The resulting $J - K = 5.40$ mag suggests the object lies near the GC.

6.4 Line Identification

The spectrum in Figure 16 shows striking similarities to spectra of the WC9 stars WR 69, WR 81, WR 88, WR 92, and WR 103 (Williams & Eenens 1989; Eenens, Williams, & Wade 1991; Eenens & Williams 1994). The most compelling evidence that the GC object is a WC9 star comes from the identification of He I, C IV, and C III lines in the $2.06\ \mu\text{m}$ to $2.12\ \mu\text{m}$ region. The transitions and wavelengths are

Fig. 16.— *K* band spectra of the proposed Galactic Center WC9 star showing the He I 2.06 μm - C IV 2.08 μm and C III - He I 2.11 μm emission. The resolution ($\lambda/\Delta\lambda$) is approximately 570 at 2.2 μm. This spectrum was extracted from an $\approx 1.8'' \times 1.4''$ aperture and includes background subtraction from a nearby ($\approx 2''$ away) aperture. He I 2.06 μm, the C IV multiplet near 2.08 μm, the C III - He I blend near 2.11 μm, and He I (7-4) 2.159 μm - 2.166 μm are detected. C IV 2.318 μm and the C III triplet at 2.325 μm are tentatively detected but suffer from poorer signal to noise. He II 2.1895 μm is indicated for reference but not clearly detected.

given in Table 8. The relative importance of He I 2.06 μm , the C IV multiplet, and the blend of C III and He I at 2.11 μm is similar to that for several of the WC9 stars given in the references above. Because all of the strong lines are blended, we can not accurately deduce individual line parameters. However, we estimate equivalent widths (W_λ) for He I 2.06 μm , C IV near 2.08 μm , and the C III – He I blend near 2.11 μm by fitting Gaussian profiles to the emission near these peaks (Table 8). The He I 2.06 μm line width (FWHM) is approximately 1200 km s^{-1} . We estimate that the equivalent widths are uncertain by approximately 2 $\text{\AA}$ from the rms deviation of the spectrum in regions away from the line emission.

Additional evidence comes from the possible identification of two lines, one due to C IV (2.318 μm) and the other to the C III triplet at 2.325 μm , which are present in the spectrum of WR 88 shown in Ekenens et al. (1991). See their Figure 4, and note that the C III triplet dominates in their spectrum. Our signal to noise is poor in this region and the C IV line is coincident with a telluric absorption feature which makes its identification less certain. Estimates for equivalent widths are given in Table 8.

The 2–2.25 μm spectrum of Ekenens et al. (1991) for WR 88 also shows emission near 2.165 μm which they attribute to a combination of He I (7–4) 2.159–2.165 μm and He II (14–8) 2.166 μm emission. Our spectrum of the GC source shows emission here, but it peaks at 2.162 μm , and is, therefore, probably due to He I (7–4). There is no evidence for any H (Br γ 2.1661 μm) emission in the GC object, which is consistent with the evolved status of WC9 stars. This is in contrast to the He I stars, many of which show a combination of He I and Br γ emission at 2.166 μm (e.g., Libonate et

TABLE 8
WC9 STAR LINE IDENTIFICATIONS

Transition	λ (μm)	W_λ ($\text{\AA}$)
He I $2s\ ^1S-2p\ ^1P^o$	2.0587	16
C IV $3p\ ^2P^o_{1/2}-3d\ ^2D_{3/2}$	2.0705	12
C IV $3p\ ^2P^o_{3/2}-3d\ ^2D_{5/2}$	2.0796	
C IV $3p\ ^2P^o_{3/2}-3d\ ^2D_{3/2}$	2.0842	
C III $5s\ ^1S-5p\ ^1P^o$	2.1081	14
He I $3p\ ^3P^o-4s\ ^3S$	2.1126	
He I $3p\ ^1P^o-4s\ ^1S$	2.1137	
C III 8-7	2.117	
He I 7-4	2.1586 – 2.1655	7
He II 10-7	2.189	...
C IV 17-13	2.318	2
C III $5s\ ^3S_1-5p\ ^3P^o_2$	2.3234	6
C III $5s\ ^3S_1-5p\ ^3P^o_0$	2.3247	
C III $5s\ ^3S_1-5p\ ^3P^o_1$	2.3265	

NOTE.—Line identifications taken from Moore (1993), except C III (2.318 μm) taken from Eenens & Williams (1991) and He I (7-4) taken from Najarro et al. (1994). W_λ 's are for blends near strong emission peaks; see text. He II (2.1895 μm) not clearly detected. The line equivalent widths are uncertain by $\sim 2\ \text{\AA}$, see text.

al. 1995, Najarro et al. 1994, Blum et al. 1995b). The equivalent width of He I (7-4) is given in Table 8.

Eenens et al. (1991) also clearly detect He II at $2.189 \mu\text{m}$; there is a small feature near this wavelength in our spectrum, but it is of the same level as spurious features due to fringing mentioned above, and we do not claim to have detected it.

While the lines due to C IV and C III provide strong evidence that the GC object is a WC9 star, there are several potential problems with our preliminary identification. First, the equivalent widths of the GC object emission lines are considerably smaller than those for WC9 stars cited above (we estimate a factor of 3–10 difference). This difference may be explained by a contamination of the GC object with another nearby source, a distinct possibility in the dense GC region. The K magnitude of the source is somewhat brighter than predicted for a WC9 star (see below). The difference between the observed and predicted K brightness could result in the observed dilution of the equivalent widths. Another possibility is that the emission features are weakened by continuum emission from a circumstellar dust shell. This is the case for WR 69, the WC9 star with the smallest equivalent widths of the stars listed above (Williams et al. 1987).

A second problem may be the absence of emission lines at shorter wavelengths in the GC object. Eenens et al. (1991) present an H band ($1.65 \mu\text{m}$) spectrum of WR 88. This spectrum shows relatively strong emission at 1.70 and $1.74 \mu\text{m}$ (about 0.6 the equivalent width of the strong K band lines) from He I and C IV, respectively. We have recently obtained low resolution H band spectra of the GC region using

the same set-up described for these observations. We find no strong emission at 1.70 and 1.74 μm for the GC object (W_λ 's $\lesssim 5 \text{ \AA}$). If we scale our observed K band line equivalent widths to predict the H band line equivalent widths, as suggested by the spectrum of WR 88, then we would expect W_λ 's $\approx 6\text{--}10 \text{ \AA}$ at 1.70 μm and 1.74 μm in the GC object. Additional spectra of other WC9 stars at H are required to see if emission at these wavelengths is consistent with our non-detection.

6.5 Discussion

The discovery of a WR star in the GC may help constrain the character and extent of the region's recent star formation. Evolutionary models for massive stars depend heavily on the adopted mass loss rates and metallicity, among other things (Meynet et al. 1993), so they are not yet reliable indicators of absolute stellar age. While the GC He I stars suggest a burst of recent star formation, perhaps 10^7 years ago, the presence of at least one WC star at the GC suggests that part of the burst may have occurred even more recently (see, e.g., the burst models in Schaerer 1994 and Tamblyn & Rieke, 1993).

The presence of one or more WR stars at the GC may also be an important source of UV ionizing radiation. Analysis of the emission from diffuse gas in the central region of the Galaxy suggests that $\gtrsim 10^{50} \text{ s}^{-1}$ Lyman continuum photons are required from a source, or sources, with effective temperature about 35,000°K (Serabyn & Lacy 1985; Shields & Ferland 1994). The ionizing flux distribution produced by WR stars is complicated by the radiative transfer effects in their optically thick winds. Varying wind parameters such as the velocity structure and mass loss rate can dramatically

affect the emergent ionizing flux distribution compared to a black body distribution (Schmutz et al. 1992).

Schmutz et al. (1989) have modeled the atmospheres of a number of WR stars including WC(5–9) stars. The WC stars have stellar temperatures (see Schmutz et al. 1989 for a definition of temperature; here we are quoting their T_*) of approximately 30,000°K to 35,000°K. The emergent ionizing flux ($Q(H)$ and $Q(He)$) has been calculated from these models (Schmutz 1994, private communication). For the temperature range noted above and appropriate core radii of about $10 R_\odot$ (Schmutz et al. 1989), the models predict $Q(H) \approx 5 \times 10^{48}$ to 1×10^{49} photons s^{-1} and $Q(He) / Q(H) \approx 0$ to 0.2. The larger values are for a WR star as hot as 35,000°K, and we note that $Q(He)$ is quite sensitive to temperature. These results suggest that it is possible for one or more WC stars to contribute significantly to the ionizing flux in the GC.

More WR stars may exist in the GC. As the WR stars evolve, they become less luminous bolometrically and hotter. This would tend to make their K magnitudes fainter because the energy distribution shifts to shorter wavelengths and the total luminosity is lower. This provides a natural explanation of why the He I stars have been found but not more evolved WR stars. The He I stars are brighter (they are presumably related to the WNL stars, $M_{bol} \approx -10$, Blum et al. 1995b) and their lower temperatures result in strong He I emission. The WC stars have $M_{bol} \approx -8.0$ (Schmutz et al. 1989), corresponding to $K \gtrsim 12$ assuming $R_o = 8$ kpc, $A_K = 3.0$, and a $BC_K = -2.5$ to -3.0 . The BC_K is derived from the same atmosphere models

described by Schmutz et al. (1989, flux distributions are from Schmutz 1994, private communication) and agrees well with the result from the empirical relation derived for other massive evolved stars of similar temperature by Blum et al. (1995b).

The GC object we have observed has $K = 10.57$. If this is due to a combination of light from a WR star with $K \gtrsim 12$ and another contaminating star, then the lower observed equivalent widths would be explained. The crowded GC field and weaker He I emission would effectively hide WR stars from discovery in all previous surveys.

6.6 Summary

We find a preliminary classification of WC9 for an object located at 0.5 pc projected radius from the center of the Galaxy based on the strong similarity of its K band spectrum to the spectra of known WC9 stars. The relative strengths of emission lines of He I, C IV, and C III between $2.06 \mu\text{m}$ and $2.12 \mu\text{m}$ in the GC object agree well with published spectra of WC9 stars. We note that the equivalent widths are approximately a factor of 3–10 lower in the GC object than in the comparison stars; this could result from contamination by other nearby stars or circumstellar emission from dust. We also point out that for at least one WC9 star (WR 88), there is strong He I and C IV emission in the H band near $1.70 \mu\text{m}$ and $1.74 \mu\text{m}$ which we do not see in a preliminary spectrum of the GC object.

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Werner Schmutz for generously supplying the results of his WR star model atmospheres and an anonymous referee for a helpful and careful reading of the manuscript.

CHAPTER VII

Summary

The stellar population and mass distribution in the inner Galaxy ($R \lesssim 300\text{pc}$) have been investigated through near infrared spectroscopy and imaging. Spectra obtained near the $2.3\ \mu\text{m}$ CO bandhead in a sample of M giants have yielded radial velocities for approximately 150 stars in four fields toward the inner Galaxy. In addition, H and K band spectra have been used to make quantitative comparisons between the emission-line spectra of a group of massive evolved stars in the central parsec of the Galaxy and the spectra of their counterparts in the Large Magellanic Cloud (LMC).

7.1 The Mass Distribution in the Inner Galaxy

The M giant sample was used to investigate the mass distribution in the inner Galaxy at projected radii between 150 pc and 300 pc where the large extinction due to dust had precluded studies at optical wavelengths. The mean radial velocity and radial velocity dispersion were computed in each of four fields where M giant spectra were obtained. These kinematics were compared to the axisymmetric dynamical model of Kent (1992) and the non-axisymmetric bar model of Zhao (1994). Both models are generally consistent with the observations; the bar model may provide a marginally better match. The results of Binney et al. 1991 then suggest it is the gas, and not

the stars, in the inner Galaxy that is most sensitive to non-axisymmetries in the mass potential.

The velocity dispersion in the innermost field is $153 \text{ km s}^{-1} \pm 17 \text{ km s}^{-1}$, 1 to 2 σ ($\sim 15 - 30 \text{ km s}^{-1}$) higher than either Kent's or Zhao's model prediction and higher than observed anywhere else in the inner Galaxy. This means that we have yet to observe a decrease in the velocity dispersion toward smaller radii as we might expect if the bulge and GC populations are to join smoothly together.

A simple mass model of the bulge was developed using the tensor virial theorem and a new spatial density distribution based on the near infrared surface brightness distribution of the stellar population within $\sim 10^\circ$ of the Galactic center (GC) as observed by the Cosmic Background Explorer (Dwek et al. 1995). The new density distribution is highly triaxial (bar shaped) and taken to rotate with a pattern speed of $81 \text{ km s}^{-1} \text{ kpc}^{-1}$ (Binney et al. 1991). The model predicts a bulge mass of $2.8 \times 10^{10} M_\odot$, significantly larger than previous estimates. This value is most dependent on the adopted pattern speed and the angle which the bar major axis makes with our line of sight ($\sim 20^\circ$, Dwek et al. 1995). Smaller pattern speeds and/or angles would lead to similar mass estimates as previous bar models.

7.2 The Population of Massive Stars at the Galactic Center

H and *K* band spectra of the GC He I emission-line stars were compared to similar spectra of early type mass losing stars in the LMC (Ofpe/ WN9 type) to which they had previously been associated. This comparison confirmed that the GC stars had spectra with morphological similarities to the LMC stars, but also that there are

characteristics unique to the GC. In particular, several of the GC stars exhibit He I emission-line velocity widths and equivalent widths which are significantly higher than any of the comparison stars. The velocity width difference may be due to differences in the GC and LMC environments in which the otherwise similar stars formed, e.g. the metallicity may be significantly higher at the GC. The He I equivalent width difference may be due to differences in evolutionary states between the stars.

The He I star spectra and broad-band colors were used to place the stars in a region of the Hertzsprung–Russell diagram, and their effect on the GC environment through ionizing radiation and mass loss were estimated. These estimates suggest that the He I stars could provide much of the bolometric radiation observed through re-radiation by dust in the far infrared and the ionizing radiation implied by the observed nebular excitation in the GC. The mass loss, as estimated from these spectra, appears insufficient to supply the excitation by shock heating of molecular material observed previously in the GC.

The He I stars probably represent recent ($\lesssim 10^7$ yr) star formation at the GC. One possibility is that a burst of star formation occurred within this time, of which the He I stars are the most luminous tracers. The discovery of a Wolf-Rayet star at the GC, presented in chapter 6, strongly enhances this possibility. For the first time, we now begin to see a wide range of evolutionary states of massive stars in the GC including the He I stars and an M2 supergiant (e.g. Sellgren et al. 1987). This would be expected for a burst of star formation involving a range of masses. The

Wolf-Rayet star was classified as a WC9 star based on its K band spectrum and its existence points to star formation at epochs even earlier than 10^7 yr ago.

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