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DISCOVERY OF A POSSIBLE WOLF-RAYET STAR AT THE GALACTIC CENTER

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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 μm) 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 μm, the C IV $3d\,^2D$–$3p\,^2P^o$ multiplet with components between 2.071 and 2.084 μm, and a blend of two C III lines and He I near 2.11 μm.
Subject headings: Galaxy: center — stars: formation — stars: Wolf-Rayet

1. 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 Brα source by Forrest et al. (1987) and as a strong source of He I 2.06 μm 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 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 (Bohannan & Walborn 1989). Blum, DePoy, & Sellgren (1995) 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 μm) 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 (1995) 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 $\alpha(1950) = 17^h42^m28^s.62$, $\delta(1950) = -28°59'24''.1$ 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 and 2.12 μm.

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 to 2.18 μm. This would be insufficient to detect the He I 2.06 μm, C IV 2.08 μm, C IV 2.32 μm, and C III 2.33 μm emission which we report here.

2. 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 ≈115'' × 1''.3 with a spatial scale of 0''.45 pixel^{-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 ≈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 (BS 6486, A3). The spectrum was put on a flux density scale by multiplying it by an 8500 K blackbody. OH airglow lines were used for wavelength calibration. The details of the data reduction are the same as given in Blum et al. (1995) for observations of a number of the GC He I stars. The final spectrum is shown in Figure 1. The spectrum suffers from the same fringing problems discussed by Blum et al. (1995). Narrow features at the 2%–3% level are not reliable.

The absolute flux density scale was set by scaling the 2.2 μm intensity to the object's *K*-magnitude (10.57). This *K*-

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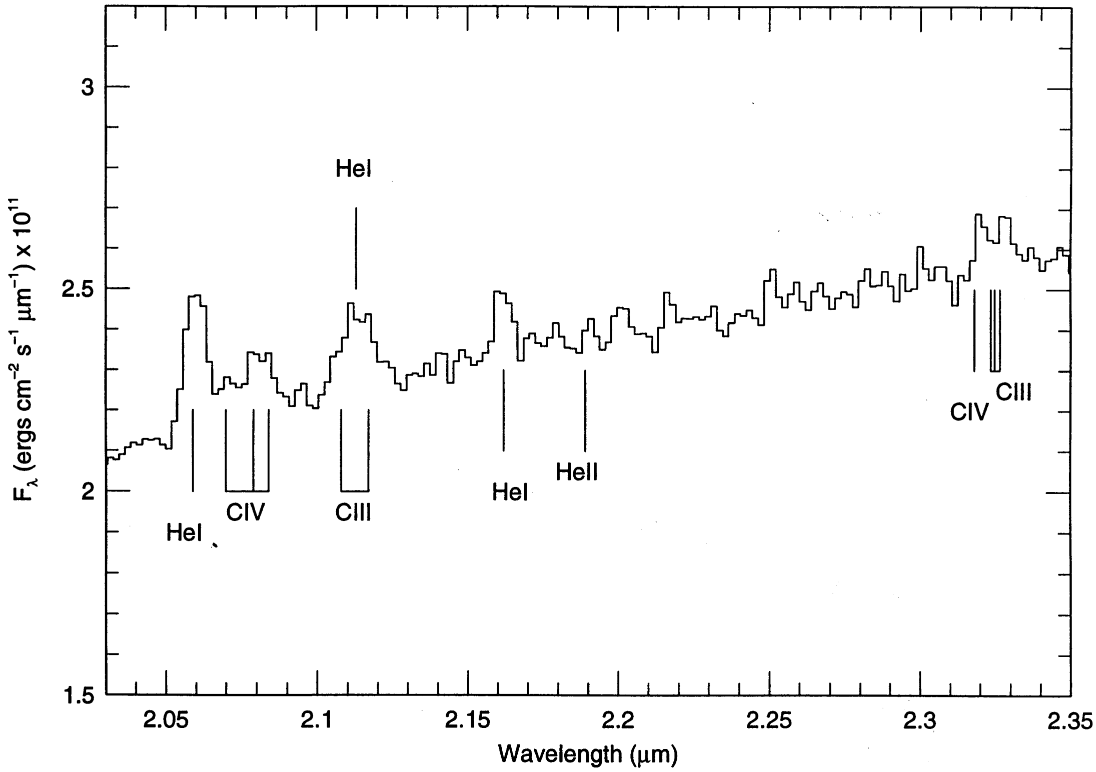

FIG. 1.—*K*-band spectra of the proposed Galactic center WC9 star showing the He I 2.06 μm–C IV 2.08 μm and C III–He I 2.11 μm emission. The resolution ($\lambda/\Delta\lambda$) is approximately 570 at 2.2 μm. This spectrum was extracted from an $\approx 1''.8 \times 1''.4$ aperture and includes background 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) 2.159–2.166 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.

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.

3. LINE IDENTIFICATION

The spectrum in Figure 1 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 to 2.12 μm region. The transitions and wavelengths are given in Table 1. 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 cannot 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 1). 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 Å 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 Eenens et al. (1991). See their Figure 4, and note that the C III triplet dominates in their spectrum. Our signal-to-noise ratio 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 1.

The 2–2.25 μm spectrum of Eenens 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 (Brγ 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 Brγ emission at 2.166 μm (e.g., Libonate et al. 1995; Najarro et al. 1994; Blum et al. 1995). The equivalent width of He I (7–4) is given in Table 1.

Eenens et al. (1991) also clearly detect He II at 2.189 μm; 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, 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

TABLE 1
LINE IDENTIFICATIONS

Transition	λ (μm)	Integrated W_λ (Å)
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 $5s\,^3S_1$–$5p\,^3P^o_1$	2.3247	
C III $5s\,^3S_1$–$5p\,^3P^o_0$	2.3265	

NOTES.—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 ~ 2 Å, see text.

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, van der Hucht, & Thé 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 μm) spectrum of WR 88. This spectrum shows relatively strong emission at 1.70 and 1.74 μm (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 $\lesssim 5$ Å). 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 ≈ 6–10 Å 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 nondetection.

4. 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 1995 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 $\gtrsim 10^{50}$ 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 blackbody ditribution (Schmutz, Leitherer, & Gruenwald 1992).

Schmutz, Hamman, & Wessalowski (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 (W. 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 $Q(\mathrm{H}) \approx 5 \times 10^{48}$ to 1×10^{49} photons s^{-1} and $Q(\mathrm{He})/Q(\mathrm{H}) \approx 0$ 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, $M_{\mathrm{bol}} \approx -10$, Blum et al. 1995) and their lower temperatures result in strong He I emission. The WC stars have $M_{\mathrm{bol}} \approx -8.0$ (Schmutz et al. 1989), corresponding to $K \gtrsim 12$ assuming $R_0 = 8$ kpc, $A_K = 3.0$, and a $\mathrm{BC}_K = -2.5$ 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. (1995).

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 H I emission would effectively hide WR stars from discovery in all previous surveys.

5. 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 and 2.12 μm 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 and 1.74 μm which we do not see in a preliminary spectrum of the GC object.

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