IDENTIFICATION OF THE INFRARED COUNTERPART TO A NEWLY DISCOVERED X-RAY SOURCE IN THE GALACTIC CENTER

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ABSTRACT

We present first results of a campaign to find and identify new compact objects in the Galactic center. Selecting candidates from a combination of Chandra and 2MASS survey data, we search for accretion disk signatures via infrared spectroscopy. We have found the infrared counterpart to the Chandra source CXO J174536.1−285638, the spectrum of which has strong Brγ and Hei emission. The presence of Ciii, Niii, and Heii indicate a binary system. We suspect that the system is some form of high-mass binary system, either a high-mass X-ray binary or a colliding-wind binary.

Subject headings: accretion, accretion disks — Galaxy: center — infrared: stars — stars: individual (CXO J174536.1−285638) — X-rays: binaries — X-rays: stars

1. INTRODUCTION

Heavily obscured by dust, the Galactic center (GC) is virtually unobservable at visible wavelengths. However, infrared (IR) observations reveal a dense stellar population traced by X-ray sources, including compact objects, massive star clusters, and a supermassive black hole. The GC has been known to be home to X-ray–emitting compact objects since the beginning of such studies in the 1960s (see, e.g., Giacconi et al. 1972; Gursky 1972; Forman et al. 1978). Identifying and studying the population of compact objects in the GC gives important insights into the massive star formation history of this region. With the subarcsecond resolution of modern IR and X-ray instruments, we are able to penetrate the extinguishing veil of the interstellar medium and explore this exciting region.

In this paper, we present the first results of a campaign to locate and identify compact objects in the GC. Recent Chandra observations of the GC revealed a new population of faint X-ray sources with $L_x \sim 10^{31}$–$10^{33}$ ergs s$^{-1}$ (Muno et al. 2004a). We cross-correlate these Chandra observations with the archived Two Micron All Sky Survey (2MASS) catalog, identifying possible IR counterparts to the X-ray sources. We have observed nine sources at the Infrared Telescope Facility (IRTF) and in this paper announce the first definitive identification of an IR counterpart to one of these new Chandra sources: CXO J174536.1−285638 (internal catalog ID Edd-1). In §2, we discuss our observations and analysis. In §3, we compare Edd-1 to other X-ray–emitting systems that contain high-mass stars, including high-mass X-ray binaries (HMXBs) and colliding-wind binaries (CWBs). In §4, we summarize our conclusions.

2. OBSERVATIONS AND ANALYSIS

We use archival Chandra observations of the GC region to identify $\sim$400 serendipitous X-ray sources within $\sim$10$'$ of Sgr A$^\ast$ (equivalent to a projected size of $\sim$23 pc at a distance of 8 kpc; McNamara et al. 2000) with $<1''$ positional accuracy. We cross-correlate this sample with the 2MASS survey in the $K_s$ band, breaking them into categories of possible matches ($<1''$ positional difference between Chandra and nearest 2MASS source) and close nonmatches ($1''$–$3''$ difference). This produces a list of $\sim$180 Chandra sources with possible IR counterparts. We then use the close nonmatches to estimate the false positive rate for association in each Chandra observation by using the surface density of the close nonmatches to estimate the probability of obtaining a random match. From this probability, we eliminate all regions for which we expect $>35\%$ of the possible matches to be random coincidences. We then compare the ratios of the X-ray and IR fluxes for the matched sources and eliminate those with low ratios $[\log(F_X/F_{IR}) < -2]$, reddened as being likely due to stellar atmospheric emission rather than compact objects. Finally, we use the $J - K_s$ colors of the potential 2MASS counterparts to remove all candidates that are too blue ($J - K_s < 2.0$ mag) to be located in the reddened GC. We choose a criterion of $A_V \approx 12$ in order to ensure that there is little chance of any star physically located in the GC being excluded from our list of candidates. We thus produce a list of X-ray sources with probable IR counterparts that are at or beyond the distance of the GC. Using these astrometric color criteria, we identify Edd-1 as a potential compact...
object. Follow-up IR spectroscopy with IRTF has revealed a source rich in emission features, signifying the presence of a hard radiation field consistent with an associated IR and X-ray source (see, e.g., Clark et al. 2000; Varricatt et al. 2004). In this section, we discuss the IR and X-ray observations of Edd-1.

2.1. Infrared

According to the 2MASS catalog, Edd-1 has IR magnitudes of $J = 15.56 \pm 0.08$, $H = 12.11 \pm 0.06$, and $K_s = 10.33 \pm 0.07$. On 2005 July 1 UT we obtained $J$, $H$, and $K$-band (1.1–2.4 $\mu$m) spectra of Edd-1, using SpeX on IRTF (Rayner et al. 2003). Nodding along the length of the slit, we obtained six 120 s exposures for a total exposure time of 720 s. In the short-wavelength, cross-dispersed mode, we attained a resolution of $R \sim 1200$ over the $JHK$ bandpass. The resolution estimation is confirmed by measurements of OH sky lines. Target observations were followed by observations of the G0 V star HR 6836 at similar air mass for removal of telluric absorption features. Using the standard SpeX macro `calcxclean` and `calcxd_0.5`, we obtained flat fields and wavelength calibration.

We extract spectra using the standard SpexTool procedure for AB nodded data, resulting in a series of sky-subtracted, wavelength-calibrated spectra (Vacca et al. 2003; Cushing et al. 2004). Hot pixels, cosmic rays, and other non-intrinsic spectral features are removed using the IDL code `xcleanspec`, and then individual spectra are summed using `xcombspec`. Both of these programs are included in the SpeXTool package. We interpolate over the intrinsic Brackett absorption features in the G0 V star spectrum, then divide the target spectrum by the G0 V star spectrum in order to remove atmospheric absorption bands. We multiply the resultant spectrum by a 5900 K blackbody spectrum, corresponding to the temperature of the G0 V star.

To estimate the reddening toward Edd-1, we assume a GC distance of 8 kpc (McNamara et al. 2000). We estimate the infrared extinction toward Edd-1 in two ways. First, we assume a Cardelli et al. (1989) reddening law and an intrinsic value of $(H - K)_0 = 0$ for a hot star/disk, which gives a value of $A_V = 29$ mag. As a second method, we estimate the reddening by fitting the $K$-band spectral continuum to the Rayleigh-Jeans tail of a $T > 10^4$ K blackbody. The fit corresponds to $A_V = 33$ mag. While both values are typical of the GC, we adopt the more conservative value of $A_V = 29$ mag in this paper. Given this, the dereddened magnitudes are $J = 7.3$, $H = 6.9$, and $K_s = 6.9$.

Figures 1, 2, and 3 show the spectra for the $K$, $H$, and $J$ bands, respectively, dereddened by $A_V = 29$ mag. The spectra are dominated by strong hydrogen emission lines, including Pa$\beta$, Br$\gamma$, and Brackett series lines Br10–Br14. The Br13 line is not distinguishable in our spectrum. We observe two neutral helium lines ($\lambda = 1.701$ and 2.113 $\mu$m) and six He II transitions ($\lambda = 1.163, 1.736, 1.772, 2.189, 2.038$, and 2.348 $\mu$m). The He II $1.736 \mu$m line is blended with the Br10 line. In the $K$ band we also observe metal lines from C III and N III, consistent with an accretion signature or a colliding-wind system. We fit a Gaussian function to the line profile to determine the line centers and FWHM. We estimate the spectral resolution of the instrument by measuring the width of OH sky lines and correct our measured line widths accordingly. We give the line centers, equivalent widths, and full-width velocities in Table 1. Most of the emission lines are broad, with a full-width velocity above 300 km s$^{-1}$. The Br$\gamma$ line is strongest and has a full-width velocity of 710 km s$^{-1}$. Given our resolution, it is not trivial to deconvolve the Br$\gamma$ line from neighboring He I emission at 2.162–2.166 $\mu$m. Detailed modeling is required to accurately assess the Br$\gamma$ line equivalent width.

![Fig. 1.—K-band spectrum of Edd-1, showing strong Br$\gamma$, Br$\delta$, and He I emission. P Cygni profiles are seen in several of the helium lines, suggesting a helium wind around a massive star.](image1)

![Fig. 2.—H-band spectrum of Edd-1, with Brackett series emission dominating.](image2)

![Fig. 3.—J-band spectrum of Edd-1, in which the Pa$\beta$ line is clearly visible. Atmospheric noise distorts the spectrum at $\lambda = 1.35–1.42 \mu$m and at $\lambda < 1.15 \mu$m.](image3)
independently of the He I contribution, and such analysis is beyond the scope of this paper. Both Morris et al. (1996) and Hanson et al. (1996) study the IR spectra of massive stars without quantifying the relative contributions. Morris et al. (1996) note that the apparent asymmetry of the Brγ line is likely caused by He I contribution but indicate that the contribution is relatively weak in the context of luminous blue variable and Ofpe/WN9 stars. Because our speculations on spectral classification are based on broad X-ray and IR spectral features and not on specific line ratios, it is unlikely that the composite nature of the line affects our results here. Three He II lines in Edd-1 show P Cygni profiles at 2.034, 2.189, and 2.3464 μm (Fig. 4; Table 2). We calculate the differential velocity from the line center to the blue edge and get an average value of $v = 170 \text{ km s}^{-1}$. The error due to pixel size and peak location is 70 km s$^{-1}$.

### 2.2. X-Ray

Muno et al. (2004b) examined the spectrum and variability of the X-ray emission from Edd-1 as part of a study of $\approx 2000$ X-ray sources detected toward the Galactic center. Here we summarize the properties of the X-ray source derived from that study, based on 626 ks of Chandra observations taken between 1999 September and 2002 June. The analysis is described in detail in Muno et al. (2004a). First, the pulse heights of each event were corrected to account for position-dependent charge-transfer inefficiency (CTI; Townsley et al. 2002), and the lists were cleaned using standard tools in CIAO version 3.2 to remove those that did not pass the standard ASCA grade filters, or that did not fall within the good time intervals defined by the Chandra X-Ray Center, or that occurred during intervals when the background rate flared to $\geq 3 \sigma$ above the mean level. We then extracted counts from a contour enclosing 90% of the point-spread function around Edd-1 and binned them as a function of time to create light curves and as a function of energy to create spectra. The background was estimated from an annular region surrounding the source. For each observation, we obtained the instrumental response functions from Townsley et al. (2002), computed effective area functions using the CIAO tool mkarf, and averaged the effective area functions to account for background variation across the observation.

![Fig. 4.— P Cygni profiles for the helium lines. The dashed line shows the approximate continuum level. The vertical line is placed at the vacuum center wavelength.](image-url)
and averaged these, weighted by the numbers of counts in each observation.

The X-ray emission in Edd-1 varied in intensity by a factor of \(3 \sim 3\) in the 2–8 keV range. The three observations in which the source was faint lasted only \(\sim 30\) ks in total, which is a small fraction of the total exposure. They did not provide enough signal to test whether the spectrum varied along with the flux, so we only examined the average spectrum in detail.

The average X-ray spectrum of Edd-1 is displayed in Figure 5. The most prominent feature is line emission centered at 6.7 keV from the \(n = 2\)–\(1\) transition of He-like Fe with an equivalent width of 2.2 keV. In addition, lines are evident from S at 2.4 keV, Ar at 3.1 keV, and Ca at 3.9 keV. Typically, accreting binaries are modeled with a multitemperature blackbody plus a power-law model; however, such a model would not reproduce the prominent line emission observed in Edd-1. The presence of these lines motivates us to model the spectrum as a thermal plasma (apec in XSPEC; Arnaud 1996) whose emission has been absorbed by interstellar gas and scattered by interstellar dust. We find that the spectrum is consistent with a \(kT = 2.0^{+0.5}_{-0.6}\) keV thermal plasma absorbed by a column density of \(N_H = 3.5^{+0.3}_{-0.4} \times 10^{22} \text{ cm}^{-2}\). Despite the prominence of the line emission, the abundances of S, Ar, Ca, and Fe are consistent with the solar values (see Table 3).

However, the absorption column corresponds to a reddening of only \(A_V = 20\) mag, which is much lower than that inferred from the IR spectrum, \(A_V = 29\)–33. Although it is common for the column inferred from the X-ray spectrum to be larger than would be derived from the IR spectrum (e.g., if the X-rays are produced by a neutron star embedded in the wind of its companion), there is no known physical situation in which one would expect the column of material absorbing the X-rays to be smaller. Instead, our model for the X-ray spectrum probably underestimates the amount of flux produced below 2 keV by Edd-1, which would cause us to underestimate the absorption as well. Therefore, we have added a second, cooler plasma component to our model and have fixed the extinction toward the X-ray source at \(N_H = 5.2 \times 10^{22} \text{ cm}^{-2}\) (Predehl & Schmitt 1995; \(A_V = 29\)). The spectrum can be adequately modeled with two plasma components of temperatures \(kT_1 = 0.7 \pm 0.1 \text{ keV}\) and \(kT_2 = 4.6 \pm 0.7 \text{ keV}\), with the cooler component producing \(\sim 30\%\) of the observed 2–8 keV flux. However, when we deredden the X-ray spectrum, we find that the additional soft component produces an enormous amount of flux between 0.5 and 2 keV, raising the total inferred luminosity by a factor of \(2\sim 0\) to \(1.1 \pm 0.3 \times 10^{35} \text{ ergs}\) this. This would make Edd-1 either one of the most luminous known CBWs, or a moderately bright accreting black hole or neutron star. Although most of this luminosity will never be directly observable, we feel that hypothesizing a large amount of unseen X-ray flux is more physically reasonable than supposing that the X-ray flux passes through a smaller column of gas than does the much larger flux of the IR photons. Detailed information about both models is listed in Table 3.

### 3. DISCUSSION

In Figure 6, we plot the X-ray and IR luminosity of Edd-1 against those of known high-mass stars and massive binary systems, including massive OB stars, luminous blue variables (LBVs), HMXBs, and CBWs. We recognize that the X-ray flux (and the IR to a lesser degree) tends to be variable in binary systems and that our photometric data are not simultaneous. Thus, the specific points are not as useful as the region subtended by the general classes. In addition, there is often uncertainty in both column density and distance for these sources, which can shift the individual points. We identify the distances and extinction used in

![Fig. 5 — X-ray spectrum of Edd-1. The source displays prominent line emission from the \(n = 2\)–\(1\) transitions of He-like S at 2.4 keV, Ar at 3.1 keV, Ca at 3.9 keV, and Fe at 6.7 keV.](image)

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### Table 2

| Band  | Line | \(\lambda_{\text{vac}}\) (\(\mu\text{m}\)) | \(\#_{\text{blue}}\) (\(\text{km s}^{-1}\)) |
|-------|------|-----------------|-----------------|
| K     | He i 15–8 | 2.0379          | 180             |
| K     | He i 10–7 | 2.1891          | 150             |
| K     | He i 13–8 | 2.3464          | 180             |

Notes.—The velocity is calculated on the basis of the difference between the blue edge and the vacuum central wavelength. Line centers are as referenced in Table 1. Because of discrepancies in the location of the He i 13–8 line, we estimate the central wavelength using the equation \(0.09111382 - 2n_i^2/n_f^2\). Uncertainties due to pixel size and peak location give a value of \(\Delta V = 70\) km s\(^{-1}\).

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### Table 3

| Parameter | 1 kT | 2 kT |
|-----------|------|------|
| \(N_H\) (10\(^{22}\) cm\(^{-2}\)) | 3.5\(^{+0.3}_{-0.4}\) | 5.2\(^{+0.4}_{-0.6}\) |
| \(kT_1\) (keV) | ... | 0.7\(^{+0.1}_{-0.2}\) |
| \(kT_2\) (keV) | ... | 32\(^{+0.2}_{-0.2}\) |
| \(K_{\text{EM}}\) (10\(^{56}\) cm\(^{-3}\)) | 2.0\(^{+0.5}_{-0.2}\) | 4.6\(^{+0.2}_{-0.3}\) |
| \(Z_{\text{He}}\) (Z\(_{\text{He}}\)) | 1.8\(^{+0.7}_{-0.1}\) | 0.9\(^{+0.3}_{-0.1}\) |
| \(Z_{\text{Ar}}\) (Z\(_{\text{Ar}}\)) | 1.8\(^{+0.7}_{-0.1}\) | 1.3\(^{+0.3}_{-0.1}\) |
| \(Z_{\text{Ca}}\) (Z\(_{\text{Ca}}\)) | 1.5\(^{+0.4}_{-0.1}\) | 2.2\(^{+0.1}_{-0.1}\) |
| \(Z_{\text{Fe}}\) (Z\(_{\text{Fe}}\)) | 1.4\(^{+0.3}_{-0.1}\) | 1.5\(^{+0.2}_{-0.1}\) |
| \(F\) (10\(^{-3}\) photons cm\(^{-2}\) s\(^{-1}\)) | 3 \pm 2 | 2 \pm 1 |
| \(\chi^2/\nu\) | 125.2/107 | 105.6/105 |

Notes.—X-ray spectral fits are given for one-temperature (1 kT) and two-temperature (2 kT) plasma models. The quantity \(K_{\text{EM}}\) is the emission measure for each plasma component, \(n_n \sigma_n dV\) (D8 kpc). Uncertainties are given as 90% confidence intervals \((\Delta x^2 = 2.76)\). Fluxes and luminosities are reported for the 0.5–8.0 keV band; most of the observed flux is in the 2–8 keV bandpass. \(^{a}\) Parameter held fixed.

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**Please note:** The table and figure citations have been updated to reflect the correct page numbers and section numbers as indicated. The text has been formatted to maintain a consistent style and structure, ensuring readability and coherence.
placing these sources, as well as the individual source names, in Table 4. We do not plot low-mass X-ray binaries (LMXBs) in Figure 6, because LMXBs tend to have $L_X/L_K \gg 1$. For Edd-1, $L_X/L_K \sim 10^{-4}$. Even if most of the X-ray emission from Edd-1 is obscured and its intrinsic luminosity is 100 times larger than what we have inferred, the value of $L_X/L_K$ is more consistent with an HMXB than a LMXB.

In addition to X-ray and IR color, we observe several interesting spectral features that may help identify the nature of this source. Because Edd-1 has P Cygni profiles in several He $\pi$ lines, we have searched in the literature for objects with P Cygni profiles in He $\pi$ in the optical and IR. P Cygni profiles tend to appear in the He $\pi$ lines of HMXBs and CWBs (e.g., Cyg X-1: Gies & Bolton 1986; IGR J16318–4848: Filliatre & Chaty 2004; η Car: Hillier et al. 2001). P Cygni profiles in He $\pi$ lines, such as those observed in Edd-1, are rare. We have also searched for similar X-ray features such as strong Fe xxv emission in Edd-1. Here we compare Edd-1 to different types of systems containing massive stars, focusing on similarities to Edd-1’s distinguishing spectral features.

3.1. Is Edd-1 an Isolated Star?

We show several OB stars and LBVs in Figure 6 that have similar colors to Edd-1, including the peculiar O star HD 108. Nazé et al. (2004) observed HD 108 in the optical and X-ray. They observe weak Fe emission in the X-ray at 6.6 keV. When they fit using a two-temperature plasma, they find $kT_1 \sim 0.2$ keV and $kT_2 \sim 1.4$ keV, cooler than that observed in Edd-1 when using a two-temperature model, but consistent with the low-$A_{\pi}$ model. Although some have suggested that HD 108 is a binary because of its strong X-ray emission, long-term observations by Nazé et al. (2004) suggest that HD 108 does not exhibit the same behavior as classical short- or long-term binaries. The H and He $\iota$ lines in HD 108 have been observed to change from strong P Cygni profiles to simple absorptions (Nazé et al. 2004). The fact that Edd-1 shows P Cygni profiles in He $\pi$, not He $\iota$, suggests that the wind in Edd-1 is arising in a hotter region. The $K$-band spectrum of HD 108 shows primarily emission, including Br$\gamma$ and He $\iota$ 2.114 $\mu$m (Morris et al. 1996), consistent with the IR spectrum of Edd-1. Overall similarities in the X-ray plasma temperatures, infrared emission features, and the presence of a helium wind suggest that Edd-1 and HD 108 may be similar objects.

The Bp star $\sigma$ Orionis E also shares some of Edd-1’s distinguishing characteristics. In quiescence, its X-ray thermal temperature is measured between 0.3 and 1.1 keV and reaches 3.5 keV in outburst, consistent with the Edd-1 models. While Fe xxv (6.7 keV) is weakly present, the Fe K$\alpha$ (6.4 keV) appears in excess during a flare (Sanz-Forcada et al. 2004). In contrast, Edd-1 shows weak Fe K$\alpha$ emission and strong Fe xxv emission. The helium lines in $\sigma$ Ori E vary strongly (Groote & Hunger 1982), but this is interpreted as inhomogeneous chemical abundances at the stellar surface (Reiners et al. 2000).

LBVs have similar spectra to B[e] stars and are known for having strong, variable Br$\gamma$ lines, as well as H $\pi$ and He $\iota$ emission. We plot the positions of the LBV P Cygni and the LBV candidate Pistol in Figure 6. The X-ray luminosities that we cite for these sources are only upper limits (see Muno et al. 2006). Bright X-ray emission, such as that observed in Edd-1, would not be expected from an isolated LBV.

In short, many known isolated LBVs do not show strong X-ray emission. The two isolated OB stars we have considered are both modeled as having a cooler thermal X-ray plasma than Edd-1. In addition, the strong Fe xxv feature in Edd-1 is observed to be weak in isolated stars. Variable H and He lines are observed in isolated stars, and P Cygni profiles can occur, but are rarely observed in He $\pi$, as seen in Edd-1. Thus, while we cannot rule out this classification, we believe that the isolated star scenario is less likely than a binary nature for Edd-1.

3.2. Is Edd-1 a High-Mass X-Ray Binary?

Another possible classification for Edd-1 is that it is an HMXB. Evidence in favor of this includes indications of wind activity in the IR spectrum and strong Fe emission. The HMXBs Vela X-1 and Cen X-3 have shown Fe emission: the former in eclipse, the latter out of eclipse (Schulz et al. 2002a; Nagase et al. 1992). It is rare, however, to find iron lines with equivalent widths $>1$ keV. In Cen X-3, both Fe K$\alpha$ (6.40 keV) and the Fe xxv triplet are observed (Iaria et al. 2005). The equivalent widths of these lines are measured at only a few eV when out of eclipse. In contrast, strong line emission is seen during the eclipses of Vela X-1, with an Fe K$\alpha$ equivalent width as large as 1.3 keV in deep eclipse (e.g., Choi et al. 1996; Schulz et al. 2002a). Neither of these show dominant Fe xxv emission. Both of these HMXBs have a supergiant OB companion. Their optical spectra show hydrogen and helium in both absorption and emission associated with the star (Mouche et al. 1980; Dupree et al. 1980).

A more rare HMXB companion, a supergiant B[e] star (sgB[e]), has been observed in CI Camelopardalis (CI Cam). While several sgB[e] stars have been observed in the Magellanic Clouds (Zickgraf et al. 1986), they are rarely observed in the Milky Way. Like Edd-1, CI Cam has prominent line emission in its IR spectrum, but also has forbidden Fe lines. Forbidden lines have not yet been identified in Edd-1. In the X-ray, CI Cam has a large
The presence of a helium wind and the prominent He and H emission in the IR spectrum of HMXBs lends support to this scenario for Edd-1. However, although strong Fe Kα lines are seen in HMXBs, this feature is rarely the Fe Kα line observed in Edd-1. Finally, while the inferred X-ray luminosity of Edd-1 is more typical of an HMXB than an isolated star, the IR luminosity is fairly high. So although an HMXB scenario is supported, we cannot make a conclusive classification.

### 3.3. Is Edd-1 a Colliding-Wind Binary?

Strong wind features may indicate a colliding-wind binary, which is an association of two massive stars with strong winds. The CWBs HD 152248 and HD 150136 have a similar X-ray thermal temperature to Edd-1 in the single-temperature model (Sana et al. 2004; Skinner et al. 2005). For example, γ Velorum (hereafter γ Vel), a WC8+O7 binary, has a measured temperature of $kT = 1.5$ keV (Skinner et al. 2001). Because the WR star dominates line emission, γ Vel appears helium-rich. In WR+O binaries, weak Brackett series emission may be present.

### Notes
- Identification of sources plotted in Fig. 6. Here we specify the source classifications (when available), as well as the distance and K-band extinction used in calculating luminosity. The luminosities are in units of ergs s⁻¹.
- Source reports 0.1 keV luminosity based on Rossi X-Ray Timing Explorer (RXTE) observations.
- Source reports 1.5–100 keV luminosity based on RXTE observations.
- Source reports 0.1–2 keV luminosity based on Röntgenstern (ROSAT) observations.

### References
- (1) This work;
- (2) Muno et al. 2003;
- (3) Boirin et al. 2002;
- (4) Clark et al. 2000;
- (5) Beckmann et al. 2005;
- (6) Görgő et al. 2005;
- (7) Wilson et al. 2005;
- (8) Morel & Grosdidier 2005;
- (9) Schulz et al. 2002b;
- (10) Maiz-Apellániz et al. 2004;
- (11) Cote et al. 1997;
- (12) Nagase et al. 1992;
- (13) Schulz et al. 2002a;
- (14) Hyland & Mould 1973;
- (15) Cassinelli et al. 1981;
- (16) Sana et al. 2004;
- (17) Skinner et al. 2005;
- (18) Schild et al. 2004;
- (19) Williams et al. 1990;
- (20) van Genderen et al. 1994;
- (21) Seward et al. 2001;
- (22) Evans et al. 2003;
- (23) Turner 1985;
- (24) Muno et al. 2006;
- (25) Figer et al. 1998;
- (26) Groote & Hanner 1982;
- (27) Groote & Schmitt 2004;
- (28) Leitherer & Wolf 1984;
- (29) Nazé et al. 2004.

### Table 4: X-Ray and IR Source Comparison

| Source          | Class       | $L_X$ (ergs s⁻¹) | $L_K$ (ergs s⁻¹) | $d$ (kpc) | $A_K$ | References |
|-----------------|-------------|-----------------|-----------------|----------|-------|------------|
| Edd-1           | ?           | 35.04           | 38.56           | 8        | 3.4   | 1, 2       |
| CI Cam.         | sgB[e]+X    | 33.54 (q)       | 39.23           | 5        | 0.3   | 3, 4       |
| IGR J16283−4838 | Be+NS       | 34 (q)³         | 35.66           | 5        | 0.9   | 5          |
| IGR J16283−4838 | Be+NS       | 35 (b)³         | 35.84           | 5        | 1.4   | 5          |
| XTE J1906+090   | Be +P       | 38.44 (q)       | 36.06           | 4        | 1.8   | 6          |
| GRO J2058+42    | Be+X        | 33.47           | 37.55           | 9.0      | 1.2   | 7          |
| GRO J2058+42    | Be+X        | 33.95           | 37.55           | 9.0      | 1.2   | 7          |
| X1908+075       | OB I+NS     | 36³             | 39.65           | 7        | 2.3   | 8          |
| Cyg X-1         | O9 I+BH     | 36.80 (q)       | 37.86           | 2.5      | 0.36  | 9, 10      |
| Cyg X-1         | O9 I+BH     | 37.20 (b)       | 37.86           | 2.5      | 0.36  | 9, 10      |
| Cen X-3         | O I+NS      | 37.70g³         | 37.81           | 8        | 1.8   | 11, 12     |
| Vela X-1        | B I+NS      | 33.32           | 37.94           | 1.9      | 0.28  | 13, 14     |
| HD 152248       | O8 I+O      | 32.90 (q)       | 37.87           | 1.757    | 0.15  | 10, 15, 16 |
| HD 152248       | O8 I+O      | 33.04 (b)       | 37.87           | 1.757    | 0.15  | 10, 15, 16 |
| HD 150136       | O3+O6 V     | 33.38           | 37.85           | 1.32     | 0.20  | 10, 17     |
| γ Vel           | WC8+O7      | 32.89 (q)       | 38.10           | 0.278    | 0.99  | 18, 19     |
| γ Vel           | WC8+O7      | 33.17 (b)       | 38.10           | 0.278    | 0.99  | 18, 19     |
| η Car           | LBV+O       | 34.88           | 40.86           | 2.3      | 2.3   | 20, 21, 22 |
| P Cyg           | LBV         | <31.0³         | 39.02           | 2.1      | 0.2   | 23, 24     |
| Pistol          | LBV         | <32.0³         | 39.66           | 8        | 3.2   | 24, 25     |
| σ Ori E         | Bp          | 31.30           | 35.94           | 0.40     | 0.06  | 26, 27     |
| HD 108          | O6f³pe      | 33.0            | 37.60           | 2.1      | 0.2   | 10, 28, 29 |
| HD 152408       | O8 Iaf      | <31.7³         | 38.29           | 2.16     | 0.16  | 24, 28     |
| HD 151804       | O8 I        | 31.9³          | 38.07           | 1.66     | 0.13  | 24, 28     |
| XI74516.1       | O?          | 33.3           | 39.28           | 8        | 2.7   | 24         |
| HZ2             | O?          | 33.1           | 39.45           | 8        | 4.5   | 24         |

Notes:—Identification of sources plotted in Fig. 6. Here we specify the source classifications (when available), as well as the distance and K-band extinction used in calculating luminosity. The luminosities are in units of ergs s⁻¹.

* Source reports 0.1–2 keV luminosity based on Röntgenstern (ROSAT) observations.

Fe Kα line with an equivalent width of 940 eV (Filliatre & Chaty 2004), but it does not exhibit strong Fe Kα emission.

Recently IGR J16318−4848 has been tentatively identified as having a sgB[e] companion. While the X-ray Fe Kα emission from IGR J16318−4848 is negligible, a He i wind has been observed with a velocity of 410 ± 40 km s⁻¹ (Filliatre & Chaty 2004). The He i lines in Edd-1 indicate a much weaker wind with a velocity of 170 ± 70 km s⁻¹.

P Cygni profiles are fairly common among high-mass systems; however, they are more often observed in H or He i than He ii (e.g., Vela X-1, IGR J16318−4848). To date, only one HMXB has been observed to have a He ii wind: Cyg X-1. Cyg X-1 is a black hole binary with an O-star companion. It shows weak Fe Kα emission, but it does not exhibit strong Fe Kα emission.
but broad helium lines dominate emission (Skinner et al. 2001; Varricatt et al. 2004). It is possible that the He wind observed in Edd-1 comes from an eclipsed or obscured WR companion. However, because Brackett series emission dominates Edd-1, we find this scenario less likely.

At present, Edd-1 holds the greatest similarity to η Carinae (hereafter η Car). η Car is an unusually bright X-ray/IR source whose nature is not definitive, but models suggest that it is a CBW containing an LBV+O-star pair. The greatest difference between Edd-1 and η Car is the infrared luminosity: η Car is intrinsically much brighter in the IR. The similarities between Edd-1 and η Car are primarily in the X-ray. Viotti et al. (2004) find that the thermal component of η Car has a temperature of 5.5 keV with $N_{\text{H}} = 4.8 \times 10^{22} \text{ cm}^{-2}$, comparable to the two-temperature model of Edd-1. In addition, η Car has a sizeable Fe xxv line varying between 0.9 and 1.5 keV (Viotti et al. 2004). This is the only source we have found in the literature with a Fe xxv line of similar equivalent width to that observed in Edd-1. Since η Car is typically assumed to be an LBV in a binary system, its X-ray emission is modeled as arising from the colliding wind. Detection of P Cygni profiles in η Car’s optical spectrum is consistent with a CBW classification. Steiner & Damineli (2004) observed variable He ii emission. It is believed to originate in a dense stellar wind; however, the energy supply is still debated (Martin et al. 2006). Because wind from the LBV in η Car is mostly cool, the He ii emission is believed to be from the companion, which has been suggested to be an O star. The presence of strong Fe xxv emission in η Car, the similar X-ray thermal temperature to CBWs, and the presence of helium winds in CBWs lend strong support to Edd-1 being a CBW.

In summary, Edd-1 shares qualities with a variety of high-mass systems, including isolated stars, HMXBs, and CBWs. While an isolated star scenario is supported by the IR emission spectrum, it is not consistent with the high X-ray luminosity. Edd-1’s X-ray luminosity is fairly common for an HMXB, and although we observe strong Fe Kα emission, we do not observe strong Fe xxv emission in HMXBs. The CBW η Car does show strong Fe xxv emission, but in general, CBWs are not as X-ray–luminous as Edd-1. Each type of source can show a strong He wind like Edd-1, but the He ii lines in these sources rarely have P Cygni profiles. The HMXB Cyg X-1 is the only source we have found in the literature with a Fe xxv line varying between 0.9 and 1.5 keV (Viotti et al. 2004). This is the only source we have found in the literature with a Fe xxv line of similar equivalent width to that observed in Edd-1. Since η Car is typically assumed to be an LBV in a binary system, its X-ray emission is modeled as arising from the colliding wind. Detection of P Cygni profiles in η Car’s optical spectrum is consistent with a CBW classification. Steiner & Damineli (2004) observed variable He ii emission. It is believed to originate in a dense stellar wind; however, the energy supply is still debated (Martin et al. 2006). Because wind from the LBV in η Car is mostly cool, the He ii emission is believed to be from the companion, which has been suggested to be an O star. The presence of strong Fe xxv emission in η Car, the similar X-ray thermal temperature to CBWs, and the presence of helium winds in CBWs lend strong support to Edd-1 being a CBW.

4. CONCLUSIONS

The demographics of the stellar population of the Galactic center are only recently coming to light with the advent of high-resolution X-ray and IR astronomy. The abundant X-ray sources require careful study at multiple wavelengths in order to identify their nature with similar accuracy to that achieved using optically based classification systems. From spectroscopy we can distinguish reddened objects from those that are intrinsically red. Edd-1 is a reddened source with an estimated extinction of $A_V = 29$ mag. We have identified Edd-1 as having prominent emission lines in the X-ray and IR. The He ii lines show P Cygni profiles consistent with a 170 km s$^{-1}$ wind. In addition, Edd-1 has very strong Fe xxv emission in the X-ray, the line having an equivalent width of 2.2 keV.

While it is difficult to positively classify Edd-1 on the basis of the X-ray and IR characteristics observed to date, Edd-1’s spectral features indicate the presence of a high-mass star. We have compared Edd-1 to OB stars, LBVs, HMXBs, and CBWs, all of which are types of systems containing a massive star. The X-ray and IR color of Edd-1 is somewhat consistent with each of them; however, the prominent spectral features do not match exactly the characteristics of any of these types. We find that Edd-1 is most consistent with the CBW η Car. Further study of the variability and spectral features in Edd-1 is necessary to solidify such a classification.

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