

## Letter to the Editor

# An X-ray binary model for the Galactic Center source IRS 13E

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Received 6 July 2000 / Accepted 14 August 2000

**Abstract.** We present several models for IRS 13E, an infrared, mm and X-ray source in the Galactic Center. Our favored interpretation is that of an early-type binary with strong colliding winds emission. This naturally explains the observed X-ray count rate and the strong infrared emission lines, and has a distinct advantage over competing hypotheses based upon a single star or black-hole system.

**Key words:** stars: individual: IRS 13E – stars: Wolf-Rayet – X-rays: stars

### 1. Introduction

It is probable that Sgr A\*, the compact, nonthermal radio source at the Galactic Center (GC) is a  $2\text{--}3 \times 10^6 M_{\odot}$  black-hole (see, e.g., Ghez et al. 1998). Deep in the potential well of Sgr A\* and pervading the central parsec of the Milky Way, there exists a cluster of HeI and late-type stars (see, e.g., Sellgren et al. 1990 and Genzel et al. 1996). In order to understand the evolution and dynamics of this unique stellar cluster, it is necessary to investigate individual stellar sources in detail. IRS 13, identified as a Pa- $\alpha$ , [FeIII], HeI, and HeII line source (Stolovy et al. 1999; Lutz, Krabbe, & Genzel 1993; Libonate et al. 1995; Krabbe et al. 1995), is a compact HII region, dominated by the source IRS 13E.

Motivated by the *Chandra* results we speculate on the nature of IRS 13 and conclude that it is most likely an early-type binary system. This interpretation also supports the other observations.

### 2. Source identification

Due to the  $\sim 30$  magnitudes of visual extinction towards the GC (Wade et al. 1987; Blum, Sellgren, & Depoy, 1996), the only observations of IRS 13 are at radio, infrared and X-ray wavelengths. At  $\lambda = 2$  cm, the IRS 13 complex is one of the brightest sources in the central  $10''$  of the Galaxy (Yusef-Zadeh, Roberts, & Biretta 1997). Observations at 7mm and 13mm, where interstellar scatter-broadening is less significant, resolve IRS 13 into two sources. Infrared K-band photometry also resolves IRS 13E into two sources (IRS 13E1 and IRS 13E2), the former being identified with a Wolf-Rayet star of type WN9-10 (Najarro

et al. 1997, hereafter N97). The two sources are separated by  $0.16'' \sim 1000$  AU in projection (assuming a GC distance of 8 kpc) with positional uncertainties of  $\sim 0.1''$  (Ott, Eckart & Genzel 1999). This compares to a separation of  $\sim 500$  AU for the mm sources although the positional uncertainties are consistent with these mm sources<sup>1</sup> being the same as the infrared sources identified by Ott, Eckart & Genzel (1999). Fig. 1 presents a schematic of the region, showing the mini-spiral and various wind sources in the central 10 arcseconds.

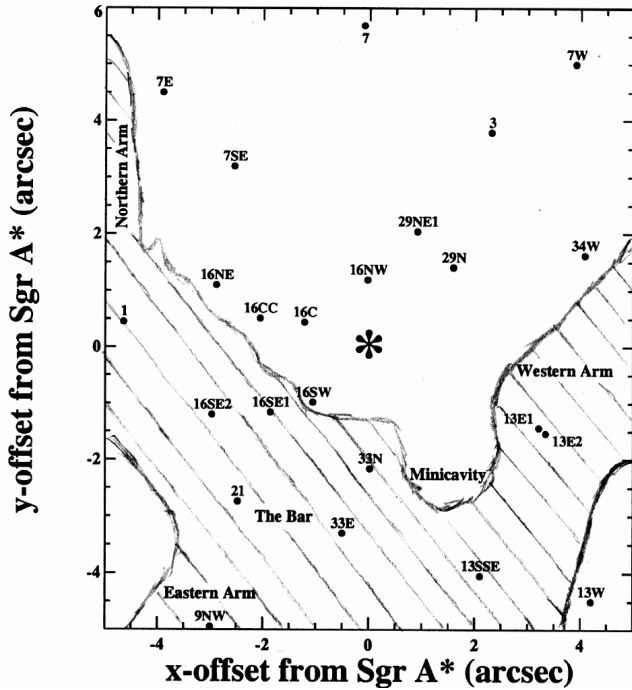
A recent *Chandra* observation of the GC (Baganoff et al. 1999) shows a compact spherical X-ray source apparently coincident with IRS 13, located  $\sim 3''$  ESE from Sgr A\*. With  $\sim 100$  counts after a 50 ksec observation, it is nearly as bright as Sgr A\*. The only other point source in the central  $\sim 10''$  is a more asymmetrical object, with no obvious radio or infrared counterpart, that is located  $\sim 9''$  NNE of Sgr A\*.

### 3. Radio, sub-mm and IR observations

(Zhao & Goss 1999) determined a spectral index of  $0.9 \pm 0.2$  for IRS 13E1, similar to that expected from a fully ionized stellar wind (Wright & Barlow 1975; Nugis, Crowther, & Willis 1998). Conversely IRS 13E2 has a flat mm spectrum which may be consistent with a nebula (Whiteoak 1994). Such a mixture of compact and extended emission is similar to the Luminous Blue Variable (LBV)  $\eta$  Car (see, e.g., Cox et al. 1995), which may have a binary companion (Damineli et al. 2000).

A major feature of IRS 13 is the strength of some of its IR emission lines. IRS 13 has stronger  $2.19\mu\text{m}$  HeII (N97) and Pa- $\alpha$  (Stolovy et al. 1999) lines than its nearby IRS 16 brethren and is one of the strongest Br- $\gamma$  sources in the central parsec of the Galaxy (Libonate et al. 1995; Roberts, Yusef-Zadeh, & Goss 1996; Herbst et al. 1993). However, IRS 13 has a rather weak H92 $\alpha$  line; Roberts et al. (1996) thus suggest that the H92 $\alpha$  source is hotter, denser and more compact than the Br $\gamma$  source. Although its  $1.644\mu\text{m}$  [FeII] emission is weak (Stolovy et al. 1999), IRS 13 is located at the local peak of  $2.2178\mu\text{m}$  [FeIII] emission (Lutz, Krabbe, & Genzel 1993), suggesting a local ionizing source. It should be noted, however, that for some of the above observations, line blending (e.g. HeI(4-3) with Pa- $\alpha$

<sup>1</sup> Zhao & Goss (1999) label these source as IRS 13E and IRS 13W; here, we will identify them as IRS 13E1 and IRS 13E2, respectively.



**Fig. 1.** A schematic of the central half parsec of the Galaxy, showing the IRS sources which are discussed in this paper as well as other early-type stars in the region. Shown in crosshatch are some of the ionized gas components of the central mini-spiral. The location of Sgr A\* is shown by an asterisk. The locations of IRS 13E1 and IRS 13E2 are from Ott et al. (1999) and assume that IRS 7 is offset from Sgr A\* by  $-0.1$  and  $-5.69$  arcseconds in  $x$  and  $y$ , respectively.

and HI(12-4) with the  $1.644 \mu\text{m}$  [FeII] line) can be a significant problem.

From observations of the K-band HeI and Br $\gamma$  emission lines, N97 constructed non-LTE atmospheric models of IRS 13E1 and determined the parameters given in Table 1. At first glance this mass loss rate is substantially more than the canonical upper limit of  $\sim 1 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$  for WR stars (Nugis 1999). However, a number of arguments exist against such a high estimate. First N97 did not include wind clumping or line-blanketing and as a result probably over estimated the mass loss rate by at least a factor of 2 (Morris et al. 2000). Second, assuming the parameters in Table 1, the classical stellar wind theory of Wright & Barlow (1975) predicts a 13 mm flux of  $\sim 30$  mJy, considerably higher than the observed  $\sim 10$  mJy for the combined IRS 13E complex, again suggesting an overestimate of  $\dot{M}/v_{\infty}$  by at least a factor of 2. Third, if the other GC wind sources have similarly overestimated mass loss rates, hydrodynamical accretion simulations (e.g. Coker & Melia 1997), which predict a large mass accretion rate onto Sgr A\*, are brought more into agreement with other accretion models (Coker & Melia, 2000; Narayan et al. 1998), which require a much lower accretion rate. For completeness, we also note that if the metallicity of IRS 13E is more than twice solar (see, e.g., Shields & Ferland 1994; Simpson et al. 1995), the maximum possible WR mass loss rate could be higher (Maeder & Meynet 1987).

**Table 1.** Computed model for IRS 13E1 (from N97)

$\dot{M}$ ( $10^{-4} M_{\odot} \text{ yr}^{-1}$ )	7.9
$v_{\infty}$ ( $10^3 \text{ km s}^{-1}$ )	1.0
$L_*$ ( $10^6 L_{\odot}$ )	2.3
$T_{\text{eff}}$ ( $10^4 \text{ K}$ )	2.9
He/H	$> 500$

If we assume the metallicity of the GC is twice solar then based on the estimated bolometric luminosity of IRS 13E1 the present mass and zero-age main-sequence (ZAMS) mass of IRS 13E1 are  $\sim 60 M_{\odot}$  and more than  $120 M_{\odot}$ , respectively (Schaller et al. 1992). However, updated evolutionary models (e.g., Mowlavi et al. 1998) show that a high metallicity star with ZAMS mass of  $\gtrsim 60 M_{\odot}$  will shed so much mass while on the main sequence that it would never reach the WR stage. The canonical assumption that the metallicity of the GC is twice solar, however, is based on gas phase abundances. Carr, Sellgren, & Balachandran (2000) further argue that GC stellar abundances may in turn be overestimated due to higher stellar rotation rates. For example, high-resolution near-infrared spectra of IRS 7, a red supergiant located in the central parsec, show solar metallicity.

#### 4. What is IRS 13E?

It is certain that IRS 13E is a luminous object embedded in a hot, dense medium, but more than this is not clear. However, it is possible to explore a few options which best fit the observations. First, the estimated luminosity and mass loss rate of IRS 13E1 are too large for a single evolved WR star; they are more like that of an LBV. In addition Libonate et al. (1995) noted that the K-band spectrum of IRS 13 resembles that of the LBV, P Cyg. Similarly, the FWHM of the Br- $\gamma$  line ( $\sim 350 \text{ km sec}^{-1}$ ) as well as the extent of the emission region ( $\lesssim 0.12 \text{ pc}$ ) (Herbst et al. 1993) is consistent with the idea that IRS 13E has recently undergone an LBV-like mass ejection, and also ties in well with the radio and sub-mm observations. However, in spite of this agreement its temperature and wind velocity are larger than a typical LBV. As has been suggested for IRS 16NE, IRS 16C, and IRS 16SW (N97), it could therefore be a transition object just coming out of the LBV phase. This would be consistent with the  $v$  and  $\dot{M}$  profiles of García-Segura, Mac Low & Langer (1996). Humphreys & Davidson (1994) point out that a WN9/Ofpe star appears very much like an LBV at minimum brightness and thus the distinction between the two types is often blurred. However, the large He/H of IRS 13E1, compared to a He/H of  $\sim 1$  for the IRS 16 sources (N97), makes an LBV/WNL determination problematic. Observational and theoretical counterarguments include the fact that the identity of WR 122, the calibrating WNL source used by N97, has been called into doubt (Crowther & Smith 1999) and recent work (e.g., Langer et al. 1999) suggests mixing in massive stars is more efficient than previously thought, resulting in a larger He/H at the start of the WNL phase. Hence an LBV/WNL classification is certainly within reason (although see below).

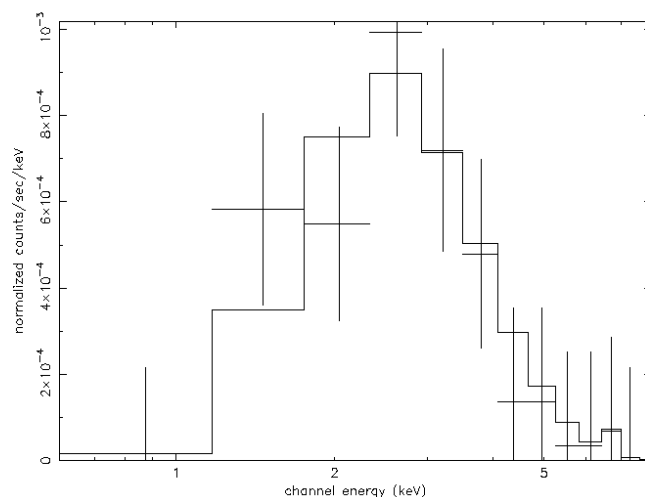
Second, we note that there are  $\gtrsim 27$  massive HeI stars in the GC (Blum, Ramírez, & Sellgren 1999). Given the observed frequency,  $f$ , of WR binary systems ( $12\% \lesssim f \lesssim 50\%$ ; van der Hucht et al. 1981), it is likely that some of the GC HeI stars are binaries as well. In fact, IRS 16SW is thought to be an eclipsing binary with a period of  $\sim 10$  days (Ott, Eckart & Genzel 1999). Thus it is possible that IRS 13E is also a binary system, containing for example a WN10 primary with a ZAMS mass of  $\sim 100 M_{\odot}$  and a somewhat less massive companion that is either an O star or another WR star, or, possibly, a massive compact object.

## 5. Consequences

Of the single and binary scenarios, the latter is preferred. As previously mentioned, the model of N97 underpredicts the K-band HeII emission for IRS 13E1 by a factor of  $\sim 3$ ; the colliding winds of a binary will produce more  $\text{He}^+$  (Marchenko et al. 1997), potentially explaining this deficiency. Also, the ionizing flux from a massive O star would explain why IRS 13E stands out in Pa- $\alpha$  and [FeIII].

An early-type binary system will also have strong shocks as a result of colliding stellar winds. The X-ray luminosity of a binary system will be brighter than that from a solitary star so that in order of increasing X-ray luminosity one qualitatively has (with everything else equal) WR, O, O/O, WR/O, WR/WR. However, this is modified by the binary separation: if the binaries are too close, absorption will suppress the observed X-ray emission but if they are too far apart the shocks are largely adiabatic and do not produce significant additional X-ray luminosity (Pittard & Stevens 1997).

The various WR sources of IRS 16 (including IRS 16SW) do not appear as point sources in the Chandra observations. A solitary WR or even a WR with a B or later companion may not be visible with Chandra due to the large column density between here and the GC. Using XSPEC<sup>2</sup> and a Raymond-Smith thermal plasma model (which assumes optically thin X-ray line and continuum emission; Raymond & Smith 1977) in ionization equilibrium one can simulate the *Chandra* spectrum of a solitary O-star placed at the GC. Assuming an ISM-corrected X-ray luminosity (0.5–10.0 keV)  $L_x \sim 0.25 L_{\odot}$  (from  $L_x/L_{\text{bol}} \sim 10^{-7}$ , see e.g. Waldron, et al. 1998), a characteristic temperature  $kT \sim 0.5$  keV (representative of typical solitary O-stars, see Chlebowski, et al. 1989), an intervening column density  $N_{\text{H}} \sim 5 \times 10^{22} \text{ cm}^{-2}$  (typical for the GC, see e.g., Zylka et al. 1995), and solar abundances throughout, a 50 ksec *Chandra* observation, spanning the 0.5–10 keV band, would detect  $\lesssim 3$  photons, and the O-star would not stand out above the background. Thus the IRS 16 sources blend into the diffuse background seen in the central  $\sim 5''$  of the image in Baganoff et al. (1999). Note that this hints that either the unseen IRS 16SW companion does not have a significant stellar wind and thus is of type B or later (and therefore implies a lower system mass than estimated by Ott et al. 1999), or that the circumstellar absorption and/or binary separation were unfavorable.



**Fig. 2.** Plot of a model WR/O spectrum detected by Chandra with a 50 ksec observation, assuming an intrinsic (0.5–10.0 keV) X-ray luminosity of  $0.5 L_{\odot}$  and a characteristic temperature of 1.5 keV (both of which are typical for colliding wind binaries, see, e.g., Maeda, et al. 1999, Stevens, et al. 1996), and a column density of  $5.0 \times 10^{22} \text{ cm}^{-2}$ . Chandra would see a total of  $\sim 100$  photons from this hypothetical binary system.

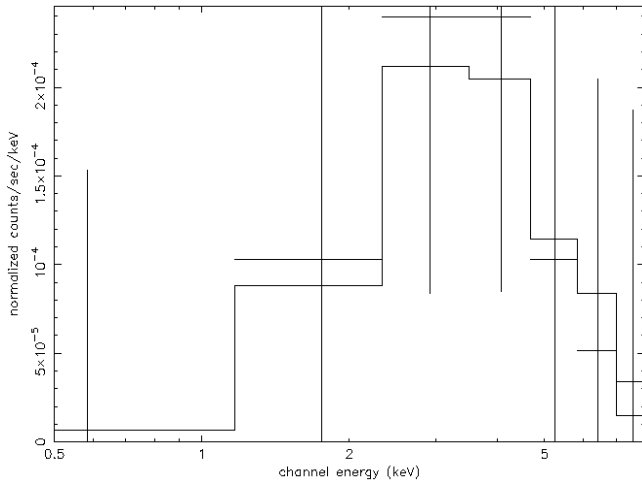
In contrast, Fig. 2 shows a theoretical *Chandra* spectrum for a hypothetical  $0.5 L_{\odot}$  GC X-ray source similar to the WR/O binary  $\gamma^2$  Vel, which has a 78.5 day period. The number of photons detected by a 50 ksec observation of such a source is  $\sim 100$ , consistent with the supposed IRS 13 source seen by Baganoff (1999). Note that the mm observations of IRS 13E2 probably do not correspond to the WR’s companion but rather to the extended emission due to the ejected nebula from the WR’s LBV phase. Thus the binary separation is not constrained to match that of the resolved mm sources.

Another possible interpretation of IRS 13 which would explain the *Chandra* observation follows from the suggestion by Gerhard (2000) that the GC HeI cluster is the remains of a disrupted cluster that formed tens of parsecs from Sgr A\*. If true, a massive binary system may not have survived the infall. This raises the possibility that IRS 13E2 hides a compact object, such as a  $\sim 10 M_{\odot}$  black-hole, which is accreting the wind from IRS 13E1. That is, IRS 13E may be an extended X-ray system. This is particularly applicable in the GC since dynamical friction over the lifetime of the Galaxy is likely to result in a high density of  $\sim 10 M_{\odot}$  black-holes in the central parsec (see, e.g., Morris 1993). One can estimate the X-ray luminosity of such a system using

$$L_x = \epsilon \dot{M} c^2 \left( \frac{GM}{2Dv^2} \right)^2, \quad (1)$$

where  $\epsilon$  is the accretion efficiency (taken as 0.1),  $M$  is the mass of the black-hole,  $v$  is the relative velocity of the black-hole to the wind, and  $D$  is the distance between the WR star and the black-hole. If  $M = 10 M_{\odot}$ ,  $v = 1000 \text{ km s}^{-1}$ , and  $D = 500 \text{ AU}$ , then  $L_x \sim 0.1 L_{\odot}$ . The spectrum, as shown in Fig. 3, would be shifted to slightly higher energy, the flux would be less at-

<sup>2</sup> Distributed and maintained by HEASARC



**Fig. 3.** Plot of a model WR/BH spectrum detected by Chandra with a 50 ksec observation, assuming an intrinsic luminosity of  $0.1 L_{\odot}$ , a characteristic temperature of 5.0 keV, and a column of  $5.0 \times 10^{22} \text{ cm}^{-2}$ . Chandra would see a total of about 45 photons from this hypothetical source.

tenuated by the high column and thus the  $\sim 45$  detected photons would be consistent with the IRS 13 detection of Baganoff (1999). Note that, if the  $\sim 10 \text{ mas yr}^{-1}$  relative mm proper motions (Zhao & Goss 1999) are any indication, the system may be unbound, making IRS 13E a unique transient X-ray source.

In summary, whilst a single massive star of unusually high X-ray luminosity cannot be discounted, we believe a colliding winds binary system best fits the various observations. A BH system also has some difficulties with reconciling the resolved mm sources (unless the second source is unassociated). Long term monitoring at mm wavelengths as well as a long-integration *Chandra* observation would help determine precisely what type of object lurks in IRS 13E.

*Acknowledgements.* This work was supported by PPARC and has made use of NASA's Astrophysics Data System Abstract Service. We thank Fred Baganoff for early discussions of his work and Angela Cotera for an inciteful review of the manuscript.

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