IRS 16SW - A NEW COMOVING GROUP OF YOUNG STARS IN THE CENTRAL PARSEC OF THE MILKY WAY

J. R. LU, A. M. GHEZ1, S. D. HORNSTEIN, M. MORRIS, E. E. BECKLIN
UCLA Department of Physics and Astronomy, Los Angeles, CA 90095-1562

ABSTRACT

One of the most perplexing problems associated with the supermassive black hole at the center of our Galaxy is the origin of the young stars in its close vicinity. Using proper motion measurements and stellar number density counts based on 9 years of diffraction-limited K(2.2 μm)-band speckle imaging at the W. M. Keck 10-meter telescopes, we have identified a new comoving group of stars, which we call the IRS 16SW comoving group, located 1′′9 (0.08 pc, in projection) from the central black hole. Four of the five members of this comoving group have been spectroscopically identified as massive young stars, specifically He I emission-line stars and OBN stars. This is the second young comoving group within the central parsec of the Milky Way to be recognized and is the closest, by a factor of 2, in projection to the central black hole. These comoving groups may be the surviving cores of massive infalling star clusters that are undergoing disruption in the strong tidal field of the central supermassive black hole.

Subject headings: black hole physics – Galaxy: center – infrared: stars – techniques: high angular resolution

1. INTRODUCTION

The central parsec of our Galaxy harbors not only a supermassive black hole (SBH) of mass ~3.7 × 10⁶ M⊙ (Ghez et al. 2003, 2005; Schödel et al. 2003), but also a cluster of young, massive stars within the sphere of influence of this black hole. The young stars include ~40 He I emission-line stars identified from spectra as blue supergiants (Of), luminous blue variables (LBVs), and Wolf-Rayet (WN/C) stars with masses ranging from 30 to 120 M⊙, ages of 2-7 Myr, and distances limited to 1-10″ from the SBH (e.g. Allen, Hyland, & Hillier 1990; Paumard et al. 2004). Dynamical studies of these He I emission-line stars used the three-dimensional velocities to show that several, including the brightest members of the IRS 16 complex such as 16C and 16SW, exhibit a coherent, clockwise rotation pattern (Genzel et al. 2000) and may all lie as part of a common orbital plane highly inclined to our line of sight (Levin & Beloborodov 2003). In addition to this clockwise plane, the counter-clockwise orbiting He I emission-line stars are consistent with a second plane oriented nearly face-on to our line of sight (Genzel et al. 2003). Within the counter-clockwise plane, IRS 13 has been identified as a comoving, compact cluster of massive young stars located ~4″ from the SBH (Maillard et al. 2004).

The origin of these young stars is puzzling given that the local gas densities are orders of magnitude too low to overcome the tidal shear of the SBH and collapse to form stars (Sanders 1992; Morris 1993). Several possible solutions have been proposed including scenarios that enhance the local gas densities such as a self-gravitating accretion disk (Levin & Beloborodov 2003) or infalling and colliding dense gas clouds (Genzel et al. 2003), both of which allow stars to form in situ. However, no such sufficiently dense gas clouds have been observed. Alternatively, stars might form at larger radii where the tidal forces are less extreme and migrate inwards through dynamical friction as part of a massive stellar cluster (Gerhard 2001; Kim & Morris 2003; Portegies Zwart, McMillan, & Gerhard 2003; McMillan, & Portegies Zwart 2003).

It has been suggested that for this cluster to migrate to within a few arcseconds of the SBH within the lifetime of the massive young stars observed, the stellar cluster would need to be so dense as to undergo core collapse and contain an intermediate mass black hole (IMBH; Hansen & Milosavljević 2003; Kim, Figer, & Morris 2004; Gürkan & Rasio 2005). Although no clear cut case for an IMBH has yet emerged, the IRS 13 cluster is coincident with a bright, discrete X-ray source (Baganoff et al. 2003; Muno et al. 2003) and may be the remaining core of an infalling cluster harboring such an IMBH (Maillard et al. 2004).

The orbital kinematics of the young stars provides important insight into their origins. In this paper we report the discovery of a new comoving group of stars within the clockwise plane which includes the bright young He I emission-line star, IRS 16SW. Diffraction-limited observations and data reduction are described in Section 2. Section 3 reports the discovery and quantitative significance of the IRS 16SW comoving group. Finally, Section 4 addresses the implications of this result for the proposed theories for the origins of young stars at the Galactic Center and discusses the possibility that this group is the remnant core of an infalling cluster.

2. OBSERVATIONS & DATA ANALYSIS

Speckle imaging observations of the Galaxy’s central stellar cluster were taken in the K-band (λc=2.2 μm, Δλ=0.4 μm) using the facility near-infrared camera, NIRC (Matthews et al. 1996), on the Keck I 10-meter telescope. Data sets taken between 1995 June and 2003 September, detailed in Ghez et al. (1998, 2000, 2005), and new data sets taken on 2004.34, 2004.56, and 2004.66, consist of ~10,000 short (τexp = 0.1 sec) exposures per observing run with a plate scale of 20.40 ± 0.04 mas/pixel and a 5″22 × 5″22 field of view. Frames are combined using a weighted shift-and-add technique (Hornstein et al. in prep) to form a final high resolution map for each data set (see Ghez et al. 2005 for details). The data from each run were also divided into three sub-sets to create “sub-maps” used to determine positional and brightness uncertainties.

Sources were identified using the IDL PSF fitting routine, StarFinder (Diolaiti et al. 2000). StarFinder generates a PSF...
from several bright stars in the field and cross-correlates the resulting PSF with the image. Candidate sources are those with correlation peaks above 0.7 in the main maps and above 0.5 in the sub-maps. Only sources detected in all 3 submaps are included in the final source list for each observation. The coordinate system for each list is transformed to a common local reference frame by minimizing the net offsets of all stars as described in Ghez et al. (1998, 2005). Centroiding uncertainties are \( \sim 1 \) mas, while alignment uncertainties range from \( \sim 1\text{-}5 \) mas. The final relative positional uncertainty is the quadrature sum of the centroiding and alignment uncertainties and is \( \sim 2 \) mas for the bright (K \( \lesssim 13.5 \)) stars near IRS 16SW. Proper motions are derived by fitting lines to the positions as a function of time, weighted by the positional uncertainties. We conservatively require that only sources detected in 9 or more epochs, out of 22 total epochs, are included in the final sample. This results in a final sample of 180 stars, which have an average total proper motion uncertainty of 0.53 mas/yr for all sources located beyond one arcsecond of the central SBH. All proper motions were converted to linear velocities using a distance of 8 kpc and the uncertainty in this distance is not included in the velocity uncertainties (Reid 1993).

3. RESULTS

A two-dimensional velocity dispersion map of the stars in the sample reveals a minimum located between IRS 16SW and IRS 16SW-E (Fig. 1, panels 1 and 2; grayscale). The velocity dispersion map is produced by calculating, at each position separated by 0\( \arcsec \)1, the following quantity for the nearest 6 stars: 

\[
\sigma_{\text{intrinsic}}^2 = \sigma_{\text{measured}}^2 - \sum_{i=1}^{N} [\text{error}^2 (v_{x,i}) + \text{error}^2 (v_{y,i})] / [2(N-1)],
\]

where the first term is the dispersion of the measured proper motions and the second term removes the bias introduced by the uncertainties in the proper motion measurements. The minimum in the velocity dispersion map is insensitive to the number of stars used in the calculation; using the nearest 5 to the nearest 8 stars produces a similar result. The significance of the velocity dispersion minimum is determined by comparing it to the velocity dispersion of stars in the sample that are at comparable radii (1\( \arcsec \) ≤ \( r_{2D} \) ≤ 2\( \arcsec \)). Because the young stars are known to show some level of dynamical anisotropy due to coherent rotation about the SBH (Genzel et al. 2003), we restrict the comparison sample to known late-type stars (Figer et al. 2003; Ott 2003). The minimum in the velocity dispersion is significantly lower (4.6\( \sigma \)) than the field velocity dispersion.

The velocity dispersion minimum arises from a comoving group of stars; to formally define the members of the comoving group, we must first eliminate those stars which appear near the group due to projection effects. Formal membership is determined by considering the difference between the velocity of each individual star and the group’s average velocity. Within the region of the velocity dispersion minimum, only 5 stars have velocity offsets that are consistently \( \lesssim 2\sigma \). Using only these 5 stars to re-define the values of group velocity and velocity dispersion, we find no additional stars with a total velocity offset less than 3.5\( \sigma \) within a 1\( \arcsec \)1 search radius. We therefore define these 5 stars, which include IRS 16SW, as the members of the comoving group (Table 1, Fig. 1, panels). The IRS 16SW comoving group has an average and RMS distance from Sgr A* of 1\( \arcsec \)92 and 0\( \arcsec \)43, respectively, and a velocity dispersion of 36 ± 13 km/s in RA and 38 ± 13 km/s in DEC.

There are two additional, independent lines of evidence supporting the existence of this comoving group. First, two of the group members, IRS 16SW and IRS 16SW-E, have identical radial velocities (Ott 2003); the other members, un-
fortunately, have no measured radial velocities. Second, the stellar number density counts show an enhancement at the position of the IRS 16SW comoving group (see Fig. 1h). Since the stellar number counts are strongly affected by the varying sensitivity across the field from the halos of bright stars, we consider only stars with K < 13.5, corresponding to 99% completeness, for this analysis. Using an aperture of 0".55, which is the minimum radius necessary to encompass the IRS 16SW comoving group, we generated a stellar number density map. Positions including the IRS 16SW comoving group members show the highest stellar number density, which corresponds to 6 sources per aperture. The probability of such an enhancement at this radius over the field’s average bright star density, 2 sources per aperture, is relatively small (0.03).

Members of the IRS 16SW comoving group appear to be young, massive stars. The two brightest members have spectra that classify them as He I emission-line stars identified by Krabbe et al. (1995). An additional two stars, S2-6 and S2-4, have recently been proposed, from spectroscopic observations, as OBN stars, which are more luminous, nitrogen-rich OB stars (Paumard et al. 2004). The identification of four of the five members as young, massive stars further supports the existence of this comoving group. The remaining member, S2-5, lacks any spectral measurements to definitively classify it; however, its absolute K-magnitude, assuming A_k = 30, is consistent with either a late-type giant (M3 or M4 III) or a young massive star (WR or OB). The latter possibility is favored by narrow-band photometry through a CO feature, which shows no evidence of the CO absorption characteristic of late-type giants (Ott 2003). Furthermore, S2-5’s dynamical association with other young stars suggests that it is also a young star.

A model-dependent estimate of the IRS 16SW comoving group’s three-dimensional distance from the SBH suggests that the line-of-sight component is negligible. Specifically, IRS 16SW and IRS 16SW-E are supposed members of the clockwise plane identified by Levin & Beloborodov (2003) and Genzel et al. (2003). If we assume that all the members of the comoving group lie on this plane, then their line-of-sight offsets from Sgr A* range from -1.7" to +0.5", with an average value of -0.4'" ± 0.016 pc. This is small compared to their plane-of-the-sky offsets from Sgr A* and places the group along the line of nodes where the plane of the sky intersects the orbital plane. Therefore, in this model, the physical distance between the IRS 16SW comoving group and the SBH is ∼0.08 pc.

It is highly unlikely that an inclined plane of stars orbiting the SBH could give rise to apparent comoving groups at the line of nodes. To quantify the likelihood that observational biases might lead to apparent coherence, Monte Carlo simulations were performed of 1000 stars with the following assumptions: 1) stars are distributed with uniform surface density in the plane out to a radius of 7"′, which is the outer edge imposed by Genzel et al. (2003), and 2) the stars are in circular orbits. Results from the simulation show that the line of nodes, where the IRS 16SW comoving group lies, is a point of high velocity dispersion, not low velocity dispersion as is observed. Given the above assumptions, the probability of finding an apparent comoving group by random chance projected along the line of nodes within 4"′ of the SBH is less than 1 in 10⁴. This suggests that the observed IRS 16SW comoving group members are dynamically associated with each other beyond simply belonging to the clockwise orbital plane.

4. DISCUSSION & CONCLUSIONS

The IRS 16SW comoving group is now the second such grouping found within the central parsec of the SBH. The first, IRS 13, has been proposed as a compact, massive star cluster located 3"′6 in projection from Sgr A* and possibly harboring an IMBH (Maillard et al. 2004; Eckart et al. 2004). Although the IRS 16SW comoving group is assigned to the clockwise plane and the IRS 13 cluster is assigned to the counter-clockwise plane, both contain young, massive stars, indicating that the two groups have comparable ages, strongly suggesting a similar formation mechanism. However, there are distinct differences between the two comoving groups. Unlike the IRS 13 cluster, which has a high stellar number density of ∼40-80 objects/arcsec² (Eckart et al. 2004), the IRS 16SW comoving group shows only a slight stellar number density enhancement (∼7 objects/arcsec² to a similar limiting magnitude of ∼16.5). Likewise, while the IRS 13 complex sits on a bright complex of dust, ionized gas, and possibly an unresolved population of stars, the IRS 16SW comoving group shows no equivalently bright halo in the K-band. Any formation scenario for the young, massive stars in the galactic center must explain the presence of both groups.

One proposed in situ formation mechanism invokes self-gravitating accretion disks present a few million years ago but since consumed by star formation, accreted onto the SBH, or dissipated via winds from the young, massive stars (Morris 1993; Levin & Beloborodov 2003). The disk would produce stars in circular orbits in a common orbital plane. The low velocity dispersion of the IRS 16SW comoving group along the line of nodes suggests either a non-uniform distribution within the plane, which would indicate that star formation was clumpy, or non-circular orbits, which would argue against ac-

| Name   | K (mag) | r_{90%} (arcsec) | ΔRA (1999.56) (arcsec) | ΔDEC (1999.56) (arcsec) | V_{rot} (km/s) | V_{vel} (km/s) | V_{radial} (km/s) |
|--------|---------|------------------|------------------------|------------------------|----------------|---------------|------------------|
| 16SW   | 10.0    | 1.406            | 1.035 ± 0.008          | -0.951 ± 0.009         | 228 ± 11       | 61 ± 11       | 400 ± 40         |
| 16SW-E | 11.0    | 2.153            | 1.836 ± 0.009          | -1.126 ± 0.015         | 144 ± 12       | 76 ± 13       | 450 ± 70         |
| S2-6   | 12.1    | 2.063            | 1.581 ± 0.011          | -1.325 ± 0.013         | 213 ± 12       | 27 ± 13       | -                |
| S2-4   | 12.3    | 2.047            | 1.438 ± 0.012          | -1.457 ± 0.012         | 207 ± 12       | 60 ± 12       | -                |
| S2-5   | 13.3    | 2.051            | 1.883 ± 0.007          | -0.813 ± 0.015         | 153 ± 12       | 137 ± 13      | -                |

* a Positions are with respect to Sgr A* using the absolute astrometry described in Ghez et al. (2005). All uncertainties include absolute astrometric errors.

* b Radial velocities obtained from Ott Thesis (2003).
cretion disk formation scenarios. It remains to be determined whether two accretion disks can assemble, form massive clusters of stars, and dissipate within only a few million years of each other. Another in situ formation scenario, colliding gas clouds, cannot be supported or disputed observationally as no detailed simulations of star formation during such interactions have been performed.

Alternative scenarios invoke the formation of massive star clusters at larger radii which spiral in via dynamical friction. As a result of mass segregation and possible core collapse, the surviving core would contain primarily massive stars. If the IRS 16SW comoving group is a bound cluster, then the virial, Bahcall-Tremaine (Bahcall & Tremaine 1981), and Leonard-Merritt (Leonard & Merritt 1989) projected mass estimators yield a cluster mass of $M \sim 10^4 M_\odot$, which is an upper limit if the cluster is not bound. Similarly, for the simple assumption that the cluster acts as a point mass, observations of the reflex motion of Sgr A* rule out clusters of $> 10^4 M_\odot$ at the projected distance of the IRS 16SW comoving group, assuming circular orbits (Reid & Brunthaler 2004). In order for the IRS 16SW comoving group to remain bound, the required mass density to overcome the tidal forces at 0.08 pc from Sgr A* is $\sim 4 \times 10^4 M_\odot/pc^3$ yielding a cluster mass lower limit of $M_{\text{lower}} \sim 10^5 M_\odot$ assuming a uniform density cluster for an order of magnitude calculation. Therefore, if the comoving group is indeed situated only 0.08 pc from Sgr A*, then it is most likely unbound.

If the IRS 16SW comoving group is not a bound cluster, then it is difficult to understand how such a comoving group can have survived in the extreme tidal field of the supermassive black hole. One possibility is that the group is the dissipating remnant core of a tidally disrupted cluster. Gerhard (2001) shows that, for the remaining unbound core of a cluster with extent $\alpha r_t$, where $r_t$ is the tidal radius, the timescale for orbital phases to spread by $\sim \pi$ is of order $t_{\text{spread}} \sim \frac{\alpha}{r_t}$. The circular orbital period at the group’s distance from Sgr A* is $< 1000$ years, suggesting that any clustering should be disrupted within a few thousand years. If the IRS 16SW comoving group is the remaining core of a massive star cluster, then the disruption may have begun at larger radii ($\sim 0.4$ pc), where the furthest young He I emission-line stars are observed, while the core continued to migrate in via dynamical friction (Gerhard 2001). Given the range of orbital timescales, $\sim 10^3$-$10^4$ yrs for 0.04-0.4 pc, and the present existence of a comoving group, disruption would have occurred only a few tens of thousands of years ago. The other young, massive stars that seem to lie on the same orbital plane as the IRS 16SW comoving group may be other members of the disrupted cluster core which are spreading in phase. IRS 13 and the associated stars in the second orbital plane would then be a second infalling cluster in an earlier stage of disruption. Increasing the number of known young stars and measuring the spread in phases would provide a better estimate of the time since disruption. Simulations of the final disruption of an infalling cluster are needed to fully test this possibility, and to determine if such a disruption can also give rise to the cusp of OB stars within 0.5 $r$ Sgr A* (e.g. Ghez et al. 2003, Eisenhauer et al. 2005). The short duration of the final cluster disruption, our observations at such a unique epoch, and the presence of two young comoving groups on different orbital planes suggest that either the frequency of formation and infall of massive clusters is high (Portegies Zwart et al. 2002) or, more likely, there was an epoch of triggered star formation several million years ago (Figer et al. 2004) which produced two massive clusters at similar distances from the central supermassive black hole. In conclusion, the IRS 16SW comoving group provides further evidence for formation scenarios that involve clustering whether from infalling massive star clusters or in situ formation.

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