The nature of IRS 13N: YSOs in the central parsec of the Galaxy?

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Abstract. IRS 13N is a small (∼0.25″ projected diameter), compact group of sources located ∼3.5″ from Sgr A* and ∼0.5″ north from the well known IRS 13E cluster. The sources exhibit strong infrared excess due to warm dust, with colors that are consistent with colors of extremely young objects. We present proper motion measurements for the IRS 13N cluster based on multi-epoch 3.8 μm observations of the Galactic Center with NACO/VLT. Our measurements reveal a new co-moving group of stars, whose dynamical youth speaks in favor of the YSO hypothesis. The confirmation of the existence of such young stars in the Galactic Center would have profound implications on our understanding of star formation close to Sgr A* and to massive black holes in general.

1. Introduction

The central parsec of the Galaxy harbors a population of massive young stars (see e.g. Paumard et al. 2006; Ghez et al. 2005), organized in at least one disk-like structure of clockwise rotating stars (CWS; Genzel et al. 2003; Levin & Beloborodov 2003; Paumard et al. 2006). There are also indications for the existence of a second, less populated and thicker disk containing the counter-clockwise rotating stars (CCWS; Paumard et al. 2006). It is not yet clear how the young stars have been formed at the Galactic Center (GC), since the strong tidal field of the super-massive black hole (SMBH) Sgr A* should prevent any star formation in its vicinity. The two most prominent scenarios include star formation “in-situ” (in an accretion disk; see e.g. Nayakshin et al. 2007), and the in-spiral of a massive stellar cluster formed at a distance of 5-30 pc from the GC (Gerhard 2001; McMillan & Portegies Zwart 2003; Kim et al. 2004; Portegies Zwart et al. 2006). The former scenario seems to be favored by number of authors (Nayakshin & Sunyaev 2005; Nayakshin et al. 2007; Paumard et al. 2006). Also, the results by Stolte et al. (2008) definitively rule out the possibility that the Arches cluster could migrate inwards and fuel the young stellar population at the GC.

Both of the above mentioned star formation scenarios are additionally tested by the existence of the IRS 13 group of sources. IRS 13E (located ∼3″ west and ∼1.5″ south of Sgr A*) is the densest stellar association after the stellar cusp in the immediate vicinity of Sgr A* and contains several massive Wolf-Rayet (WR) and O-type stars (Maillard et al. 2004; Paumard et al. 2006; Moultaka et al. 2005). It is generally considered to be associated with the mini-spiral (Moultaka
et al. 2005; Paumard et al. 2004) and is probably bound, since four out of seven identified stars show highly correlated velocities (Maillard et al. 2004; Schödel et al. 2005). For both of the above mentioned star formation scenarios there are several issues when dealing with IRS 13E. In principle, such a cluster could have been formed in an accretion disk (Milosavljević & Loeb 2004; Nayakshin & Cuadra 2005). However, in numerical simulations of star forming disks, fragmentation of a disk cannot produce such a dominant feature (Nayakshin et al. 2007). In light of the cluster in-fall scenario, an intermediate-mass black hole (IMBH) was proposed to reside in the center of the cluster (Maillard et al. 2004) in order to ensure that stars in the core of the cluster actually reach the central parsec. However, the presence of an IMBH in IRS 13E is disputed (see e.g. Schödel et al. 2005). Paumard et al. (2006) suggest that, in the case that IRS 13E is associated with the Bar of the mini-spiral, the mass of the stellar content would be high enough to protect the cluster from tidal disruption in the gravitational field of Sgr A*.

Approximately 0.5° north of IRS 13E, a small cluster of unusually red compact sources has been reported (IRS 13N; Eckart et al. 2004). Eight sources have been resolved and labeled α through η as shown in Figs. 1 and 2 of Eckart et al. (2004). The spectrum is flat and well fitted by a blackbody of T ~1000 K, indicating that the strong infrared excess is due to the emission of warm dust (Moultaka et al. 2005). Based on photometry in H, Ks and L'-bands, Eckart et al. (2004) propose two possible explanations for the nature of IRS 13N: (1) objects older than a few Myr and similar to bow-shock sources reported by Tanner et al. (2005) or (2) young stars (0.1 - 1 Myr old). The latter scenario implies more recent star formation than what has been assumed so far for the GC environment.

2. Observations and Data Reduction
We have observed the Galactic Center in the L'-band (3.8 μm) using the NAOS/CONICA adaptive optics assisted imager/spectrometer (Lenzen et al. 1998; Rouset et al. 1998; Brandner et al. 2002) at the ESO VLT/UT4. The data set includes images from 6 epochs (2002.66, 2003.36, 2004.32, 2005.36, 2006.41 and 2007.39) with a resolution of ~100 mas and a pixel scale of 27 mas/pixel. Data reduction and formation of final mosaics was performed using the DPUSER software for astronomical image analysis (T. Ott; see also Eckart & Duhoux 1990). The images were deconvolved using the linear Wiener filter technique. The absolute positions of sources in our AO images were derived by comparison to the VLA positions of IRS 10E, 28, 9, 12N, 17, 7 and 15NE as given by Reid et al. (2003). Stellar positions were extracted with StarFinder (Dilouit et al. 2000). Proper motions were derived by linear fitting of positions as a function of time, weighted by the positional uncertainties. Both the error of the transformation to the reference frame and the error of the stellar position fitting contribute to the uncertainties. We assume the distance to the GC to be 7.6 kpc (Eisenhauer et al. 2005).

3. Results
3.1. Proper motions
In table 1 we list the proper motions of the IRS 13N sources identified in the L'-band. In Fig. 1 we show the proper motions of all stars superposed on the L'-band image. Stars β through η show similar proper motions, revealing a new comoving group of sources at the GC. As shown in Eckart et al. (2004), only η is bright also in the K-band. Paumard et al. (2005) give the full velocity information for this star: $v_{R.A.}$ = (-52 ± 28) km s$^{-1}$, $v_{Dec.}$ = (257 ± 28) km s$^{-1}$ and $v_{r.}$ = (40 ± 40) km s$^{-1}$. The authors identify it as a member of a possibly existing second stellar disk (CCWS).

3.2. Keplerian orbit fitting
The next step in our analysis was to fit the positional and velocity data of the IRS 13N stars that show similar proper motions (stars β to η) with Keplerian orbits, assuming that the gravitational
Figure 1. Identification and L’-band proper motions of the stars in the IRS 13 complex. Stars named $\alpha - \eta$ are IRS 13N sources as identified by Eckart et al. (2004). E1, E2, E3 and E5 are members of the IRS 13E group. Four arrows are shown for each star, indicating the $\pm 3\sigma$ uncertainty of the value and direction of its proper motion.

Table 1. Proper motions of IRS 13N sources observed in L’-band.

| name | $\Delta \alpha$ | $\Delta \delta$ | $\nu_{\text{R.A.}}$ | $\nu_{\text{Dec.}}$ |
|------|-----------------|-----------------|-------------------|-----------------|
| $\alpha$ | -2.70 | -1.48 | 44 $\pm$ 8 | 147 $\pm$ 13 |
| $\beta$ | -2.89 | -1.25 | -6 $\pm$ 20 | 228 $\pm$ 15 |
| $\gamma$ | -3.10 | -0.99 | -114 $\pm$ 14 | 298 $\pm$ 7 |
| $\delta$ | -2.92 | -0.85 | -33 $\pm$ 13 | 248 $\pm$ 9 |
| $\epsilon$ | -2.88 | -1.02 | -58 $\pm$ 15 | 306 $\pm$ 13 |
| $\zeta$ | -3.16 | -0.82 | -134 $\pm$ 9 | 333 $\pm$ 6 |
| $\eta$ | -3.11 | -0.66 | -91 $\pm$ 22 | 323 $\pm$ 39 |
| 13N$\xi$ | -3.01 | -0.93 | -73 $\pm$ 7 | 289 $\pm$ 8 |

†relative to Sgr A*, in arcseconds
†all velocities are in km s$^{-1}$; the uncertainties represent the 1$\sigma$ uncertainty of the linear fit
§average proper motion of six comoving sources $\beta-\eta$

potential is dominated by Sgr A*. For details of the fitting procedure and definition of parameters see e.g. Eisenhauer et al. (2003). We assumed the distance and the mass of Sgr A* to be 7.6 kpc and $3.6 \times 10^6$ M$_\odot$, respectively. The velocity of Sgr A* was assumed to be zero (Reid & Brunthaler 2004). It is clear that our data cover only a small part of each star’s orbit around Sgr A*. Therefore it is crucial to fix as many parameters as possible, in order to achieve reasonable uncertainties. First we fix all the parameters concerning Sgr A*: its mass, distance, position and velocity. Paumard et al. (2006) give the radial velocity for $\eta$ which we adopt for all of the IRS 13N stars. We created a grid over which the three angles defining the orientation of the orbit were varied: inclination angle $i$ between 0$^\circ$ and 90$^\circ$ in steps of 1$^\circ$, position angle of the
Figure 2. (a) the best fit orbital solutions for IRS 13N stars ($\beta - \eta$); (b) the best fit orbital solutions for five IRS 13N stars ($\gamma - \eta$); (c) orbital solutions for a single plane ($i=24^\circ, \Omega=180^\circ$), for stars $\gamma - \eta$; (d) chosen $1\sigma$ orbits for $\eta$, with the best fit orbit colored black; NOTES: part of the orbit in front of the plane of the sky is colored red; crosses mark present positions of the stars; coordinate axes show the offset from Sgr A$^*$.  

ascending node $\Omega$ between $0^\circ$ and $180^\circ$ in steps of $20^\circ$ and longitude of periastron $\omega$ between $0^\circ$ and $360^\circ$ with a step size of $20^\circ$. We look for all the orbits that result in $\chi^2<\chi^2_{\min}+1$, separately for each of the stars. The results are given in Table 2. We list the best fit parameters $i$ and $\Omega$, and give the $1\sigma$ range for the inclination. We also list the range in eccentricities ($e$) and semi-major axes ($a$) resulting from the fits better than $1\sigma$. For all the stars except $\zeta$, the best fit reduced $\chi^2$ value ranges between 0.6 and 1.5. For $\zeta$ the best fit is obtained with $\chi^2=3.9$, probably implying that either positional uncertainties are underestimated, or that assuming the radial velocity of $\eta$ is a poor assumption. In the last line of Table 2 we give the parameters for the best-fit Keplerian orbit for the average position and velocity of all stars within the IRS13N co-moving group.

For all IRS 13N stars, with the exception of $\beta$, the range in eccentricities of $1\sigma$ orbits is restricted to relatively low values ($<0.4$), in agreement with the Paumard et al. (2006) value listed for $\eta$. Note that the corresponding semi-major axes also fall within a restricted range of values. In contrast, both parameters ($e$ and $a$) are poorly constrained for the star $\beta$ (see Fig 2a). An attempt to fit all of the stars onto an orbit with the same combination of $i$, $\Omega$ and $\omega$ failed completely. Therefore we fix $i$ and $\Omega$ and let $\omega$ vary. This confines the stars to the same plane, within which they can still have different orbits. Interestingly, the most likely common

$\dagger$ a fit with $\chi^2<\chi^2_{\min}+1$, for a corresponding star. For a convenience, we refer to all orbits that satisfy this condition as $1\sigma$ orbits.
Table 2. Results of the Keplerian orbit fitting

| name | $i(°)\dagger$ | $Ω(°)\dagger$ | $e\ddagger$ | $a(°)/\dagger$ |
|------|--------------|-------------|----------|-------------|
| β    | 79           | 180         | 53 - 80  | 0 - 0.9     |
| γ    | 19           | 180         | 4 - 67   | 0.17 - 0.21 |
| δ    | 48           | 180         | 39 - 71  | 0.15 - 0.4  |
| ε    | 33           | 180         | 17 - 56  | 0.1 - 0.3   |
| ζ    | 18           | 180         | 0 - 30   | 0.1 - 0.3   |
| η    | 24           | 180         | 1 - 45   | 0.1 - 0.3   |
| IRS 13N * | 28       | 180         | 14 - 49  | 0.1 - 0.2   |

†best fit parameters ($\chi^2 = \chi^2_{\text{min}}$)
‡all inclination values for which $\chi^2 < \chi^2_{\text{min}} + 1$
§calculated for ($i, Ω, ω$) combinations for which $\chi^2 < \chi^2_{\text{min}} + 1$
*average orbit

plane coincides with the plane of the counter-clockwise moving stars (CCWS). Four stars ($γ, ε, ζ, η$) are fitted with the $\chi^2$ better than 1σ, the star $δ$ can be reasonably (but still not within 1σ) fitted, and $β$ cannot to be fitted onto this plane (Fig. 2e).

According to Paumard et al. (2006), this CCWS disk is sparsely populated (12 stars), with $η$ belonging to it. The assumption that all IRS 13N stars belong to the CCWS significantly increases the population of the disk, and at the same time weakens the claim that the CCWS is essentially in non-circular motion, since five of the IRS 13N stars appear to be on low-eccentricity orbits. To get a feeling about the uncertainties of our analysis, we plot several 1σ orbits for the same star ($η$) in Fig. 2d.

The implications of these results are further discussed in the following section.

4. Discussion

The Keplerian orbital analysis from the previous section was performed in order to try to predict the kinematical behavior of the system at some point in the future. As we have seen, the best fit orbits for the IRS 13N stars have rather different orbital parameters. This would mean that we observe them exactly at the moment when they appear to be very close in projection, having similar proper motions, which is not very likely. There is no single orbit onto which all of the stars would fit with a good $\chi^2$, but at least four of the stars can be confined to the same plane. However, in this case the stars must still be on different orbits and consequently have different orbital periods, spanning a range from 1000 to 3000 years. This again implies that the present arrangement is temporary. Also, it is curious that the moment at which we observe them coincides exactly with the presence of dense gas at their position (see discussion on the spatial position of the cluster in Mužić et al. 2008).

The analysis of the 1σ orbits of the individual stars (Fig. 2d) shows that the uncertainties of the semi-major axes, $a$, as well as that of the orbital periods, $P$, are of the same order as the scatter of the best fit values of $a$ and $P$ for all stars. Therefore, at this point we still cannot exclude that the IRS 13N stars are indeed orbiting together, and should consider the possibility that the cluster is bound.

The virial mass estimate from the cluster velocity dispersion gives a mass of $\sim 3300 M_\odot$. The Hill radius for this mass, with $a = (2.8 - 5.7)''$ and $e = (0.1 - 0.3)$ is $r_{\text{Hill}} \approx 0.17'' - 0.34''$, with the average value remarkably close to the observed cluster radius of $\sim 0.25''$. Setting $r_{\text{Hill}} \approx 0.25''$, $a$ to its maximum and $e$ to its minimum value, we calculate the minimum mass needed to keep the cluster from disruption to be $1250 M_\odot$. This estimate seems to be unrealistically high for
the observed object. Now, let us consider the following equation:

\[
\frac{N}{\ln N} = \frac{8t_{relax}}{t_{cross}}
\]

where \( t_{cross} = R/v \) is the crossing time and \( t_{relax} \) the relaxation time (Binney & Tremaine 1987). Setting \( t_{relax} \approx P \) (few thousand yr), for a cluster with a velocity dispersion similar to that of IRS 13N, we see that the number of stars in such a cluster should be of the order 500 - 1000. 500 - 1000 main sequence stars of a total mass \( \sim 3300 M_{\odot} \) would be as bright as \( m_K = 17 - 18 \) (assuming the extinction \( A_K \approx 3 \), Schödel et al. 2007). These stars would be observed. For a lower mass limit of 1250\( M_{\odot} \), we get \( m_K = 19 - 21 \), exactly at the limit of NACO K-band data. To summarize, an object similar to IRS 13N could survive in the orbit around Sgr A* for a significant time only in two cases. First, we could invoke a presence of some dark mass in the center of the cluster, possibly an IMBH, as in the case of IRS 13E (Maillard et al. 2004). Otherwise, there should be a significantly higher number of observable stars than is actually the case. Therefore we conclude that it is not very likely that the entire system is bound and orbiting around Sgr A*.

If the IRS 13N stars are not bound, then the observed velocity dispersion probably indicates that the cluster is in the process of dissolution. The velocity dispersion will subsequently diminish the stellar surface number density of the cluster, which would then reach the background value given by Schödel et al. (2007) within only a few hundred years.

A detailed discussion about the nature of the IRS 13N sources is presented in Eckart et al. (2004). The colors and luminosities of the sources are consistent with YSOs and Herbig Ae/Be stars. Dusty envelopes that usually surround these objects would then give rise to the observed strong infrared excess. We find that the sources are also co-moving (in projection) and argue that they could hardly survive in the present arrangement for a significant amount of time. The indication of a dynamically young stellar system concurs with the hypothesis of the IRS 13N stars being extremely young. However, we should not forget that the timescales we have discussed are much shorter than any timescales within which stars normally form. But on the other hand, the Galactic center is an extremely complex environment and star formation there is far from being understood. The timescales for star formation in the Galactic center could be significantly shorter and we actually have some indications for this. The free-fall time in a collapsing cloud at the distance of the young stars in the central half parsec around Sgr A* is of the order of 100-1500 yr. Also, simulations of star formation in a gaseous disk around Sgr A* by Nayakshin et al. (2007) indicate that the timescales for star formation are fairly short, of the order of several thousand years. This is comparable to the orbital timescale of IRS 13N.

A serious obstacle for forming stars at the GC is that the gas densities in the central parsec are way too low for the gas to be able to form stars. However, with the aid of shocks and collisions, a small clump of gas in-falling to the center could be highly compressed and star formation within it triggered. The material of the mini-spiral is highly susceptible to shocks, as discussed by e.g. Mužić et al. (2007) and is in-falling right now, characterized by a dynamical timescale of only \( \sim 10^4 \) yr.

5. Conclusions
We have presented the proper motion measurements of IRS 13N, a new co-moving group of sources at the GC. We discuss whether the cluster can remain bound in the tidal field of Sgr A*. There exists the possibility that these stars are the youngest stellar objects ever observed in this environment, possibly formed within the mini-spiral itself. A confirmation of this hypothesis would be very exciting since it would prove that star formation in the immediate vicinity of SMBHs is possible and would also put constraints on star formation scenarios at the GC.

However, we should still be cautious when claiming that IRS 13N is very young: more imaging and especially high resolution spectroscopic data that could reveal features attributed to YSOs
will be necessary to confirm our hypothesis.

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