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Clarifying our View of Star Formation in Massive Young Clusters with Adaptive Optics

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Abstract. Observations of massive ($> 10^4$ M$_\odot$), young (<10 Myr) star clusters within our Galaxy allow us to fully sample the upper end of the initial mass function within a single star formation event. Such clusters also reside in a range of environments including the Galactic disk, the Galactic center region, and immediately surrounding the supermassive black hole in our Galactic nucleus. However, studies of these clusters are limited by crowding in the dense cores, strong and variable visible extinction, and confusion between cluster members and contaminating field stars. Using Keck laser-guided adaptive optics observations, we obtain high-resolution images and high-precision proper motions to both identify individual cluster members and investigate the kinematic properties of such clusters. As we build up complete proper motion data sets for several massive young clusters, our multi-color near-infrared photometry will yield precise mass functions that can be compared to search for environmental dependencies.

1. Introduction

Star formation occurs in a broad range of environments from low density regions, such as Taurus, to the densest molecular clouds and the centers of galactic nuclei. An open question, even at the end of the UP2010 conference, is whether these environments influence the star formation and cluster formation process. Although our knowledge of this process is extensive (but not complete) for nearby star forming regions such as Taurus and Orion, much less is known for the more extreme environments in the most massive ($\lesssim 10^4$ M$_\odot$), young (<10 Myr) "starburst" clusters due to their large distances, high stellar densities, high obscuration, and confusion with the dense field population in the Galactic plane.

A tremendous advance in the study of heavily embedded resolved stellar populations, such as massive young star clusters in the Galaxy, is underway aided by adaptive optics systems on large ground-based telescopes. Laser guide star adaptive optics (LGS AO) observations provide sufficiently high spatial resolution (<0.″2) at near-infrared wavelengths to both resolve individual stars and penetrate the dust and gas from intervening spiral arms and molecular clouds surrounding the clusters. The increased resolution also provides high astrometric precision and the resulting proper motions of individual stars can help distinguish cluster members from contaminating field stars. Using the identified cluster members, precise initial mass functions can be determined for the entire cluster, even at large radii where the surface density of cluster members is lower than the density of field stars. Additional cluster properties such as mass segregation, binary fractions, and, eventually, internal cluster kinematics can also be investigated. In this contribution, we show results from Keck LGS AO astrometric observations of massive young star clusters in the extreme environment at the Galactic center. We also discuss on-going programs to apply our precision astrometry techniques to massive young star clusters in the Galactic disk where peculiar motions are smaller. By studying these clusters in a range of Galactic environments in an identical fashion, we plan to make very precise relative comparisons of initial mass functions and other cluster properties in order to better understand the impact of environment on the formation process.

2. Galactic Center: Young Nuclear Star Cluster

The young (~6 Myr) nuclear star cluster in the Galactic center resides in one of the most extreme environments within our Galaxy. Strong tidal shear and ambient radiation fields, high temperature and pressure, and high stellar density all contribute to this hostile environment (Morris 1993; Krabbe et al. 1995). The presence of young stars in the immediate vicinity of the supermassive black hole is remarkable and, if the young stars did indeed form *in situ* (Levin & Beloborodov 2003), then the young nuclear star cluster is one of the most likely clusters to have an initial mass function that is altered by the environment. However, an alternative is that the young stars may have formed elsewhere in an Arches-like star cluster and migrated inward to their present day location (Gerhard 2001). Both *in situ* and cluster-infall scenarios were proposed to explain the observational signature of coherent rotation and aligned orbital planes for many of the young stars suggesting the possibilty of two disks of young stars (Genzel et al. 2000; Levin & Beloborodov 2003; Paumard et al. 2006). Distinguishing characteristics between these scenarios include the radial profile and eccentricity distribution of the young stars. *In situ* formation scenarios originally predicted steep radial profiles ($\Sigma \propto R^{-2}$, Lin & Pringle 1987; Levin 2007) and low eccentricities (Alexander et al. 2007; Cuadra et al. 2008) while cluster-infall scenarios give rise to flatter radial profiles ($\Sigma \propto R^{-0.75}$, Berukoff & Hansen 2006) and circular or eccentric orbits that reflect the initial eccentricity of the infalling cluster (Portegies Zwart et al. 2003; McMillan & Portegies Zwart 2003; Kim & Morris 2003; Kim et al. 2004; Gürkan & Rasio 2005; Berukoff & Hansen 2006).

Using high-precision proper motions obtained with Keck and radial velocities from the literature, we constrained the orbital properties of individual young stars. We confirmed one clearly defined clockwise-rotating (CW) disk containing ~50% of all the young stars (Lu et al. 2009) and assigned disk membership probabilities to each star (Figure 1, top). For those young stars that reside on the disk and are almost certainly

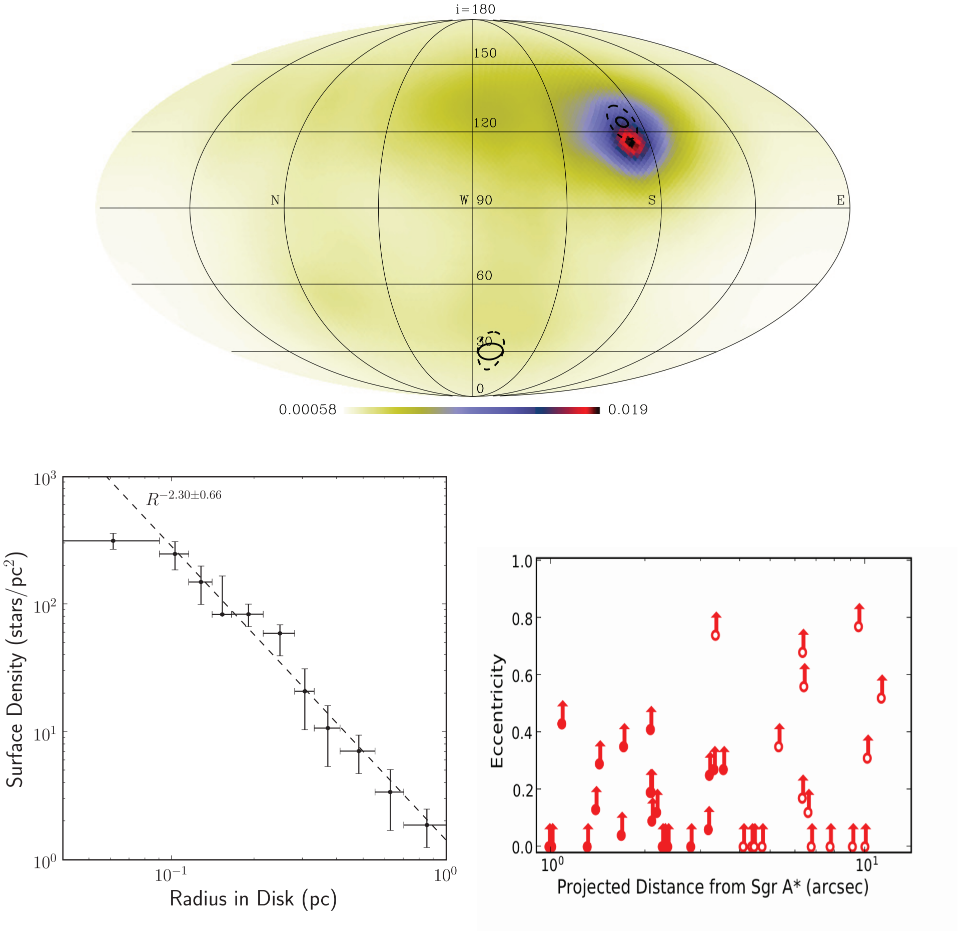

Figure 1. Properties of the young stars within 1 pc of the supermassive black hole at the Galactic center. The *top* panel shows the projected sky as seen from the black hole. Overlaid colors represent the density of orbital-plane normal vectors (stars/deg^2), calculated from precise proper motion and radial velocity studies (Lu et al. 2009). The peak indicates an over-density of stars with similar orbital planes and 50% of the young stars reside within this disk. The *bottom left* panel shows that the young stars in the disk have a steep radial profile, falling off as R$^{-2.3}$, which is consistent with *in situ* star formation theories that fall off as R^{-2}. The *bottom right* panel shows the 3σ eccentricity lower limits for stars on the disk. The high eccentricities are inconsistent with *in situ* formation in a circular gas disk. All of these properties may be explained by *in situ* formation in gas clouds that have fallen inwards on near-radial orbits following a collision.

associated with a single star formation event, we find a steep radial profile, consistent with earlier results (Paumard et al. 2006), and stars with high eccentricities (Figure 1, bottom). The steep radial profile ($\Sigma \propto R^{-2.3\pm0.66}$) supports the *in situ* formation scenario; however, the gas disk most likely did not build up slowly over time as it would circularize and would not yield the observed high eccentricities. A more likely scenario is the infall of an eccentric massive cloud or a cloud-cloud collision event that leads to rapidly triggered star formation within the central parsec of the Galaxy (Sanders 1998; Vollmer & Duschl 2001; Alexander et al. 2008; Cuadra et al. 2008). The cloud-cloud collision scenario may result in both a thin gas disk as well as gas distributed with a range of angular momenta as a result of the complex interactions and shocks during the collision. Thus, this scenario may also explain the other 50% of young stars that do not currently reside on the disk since such collisions (however, see Paumard et al. 2006; Bartko et al. 2009). All the early-type stars in the central parsec of the Galaxy may have formed in a single *in situ* starburst event ~6 Myr ago.

The initial mass function of the young stars in the Galactic center appears to be top-heavy for at least a sub-sample of the young stars (Nayakshin & Sunyaev 2005; Nayakshin et al. 2006; Paumard et al. 2006; Bartko et al. 2010). The young nuclear star cluster has three kinematically distinct populations (1) young stars on the CW disk, (2) young stars off the disk at r>0.04 pc and (3) young stars within only 0.04 pc of the SMBH with isotropically distributed orbits. Previous claims of top-heavy IMFs typically include only a subset of the young stars, predominantly the disk stars, and show that the rest of the young stars are consistent with a normal IMF (Bartko et al. 2010). This is puzzling given that the young stars at large radii both on and off the disk appear to have a similar age of 6 Myr. Understanding the relationship between the different young star populations as well as increasing the depth of spectroscopic studies to identify the young stars is essential before claims of a top-heavy IMF can be solidified.

3. Galactic Center: Arches Cluster

Beyond the young nuclear star cluster in the central parsec of the Galaxy, the Galactic central molecular zone (r<200 pc, see Morris & Serabyn 1996) still represents a very different star formation environment than throughout the disk of the Milky Way. The Arches star cluster is located in this region, only 30 pc in projection from the SMBH (Figer et al. 1999). This cluster is comparable in mass (10^4 $M_\odot$) to NGC 3603, located in the Milky Way disk, but the Arches cluster may have formed in the high pressure, high density region of the Galactic center where the formation of high mass stars may be favored. High-resolution infrared observations of the Arches cluster have resulted in conflicting claims of both a normal IMF (Kim et al. 2006; Espinoza et al. 2009) and a top-heavy IMF (Figer et al. 1999; Stolte et al. 2005). These discrepant results reveal the inherent difficulty in studying such distant, dense, and heavily extincted clusters. The high contamination by field stars is not easily corrected with photometry alone due to the varying extinction across both the cluster and any control fields that might be used for statistical removal of field stars from luminosity or mass functions.

Proper motions of the individual stars can distinguish between members of the Arches cluster and field stars and provide valuable kinematic information about the cluster. Early proper motion measurements using 1 epoch of Keck LGS AO data and 1 epoch of VLT AO data resulted in proper motion uncertainties of <1 mas/yr, or 38 km/s at 8 kpc (Stolte et al. 2008), and provided the absolute velocity of the cluster and constrained its orbit about the Galaxy. Multi-epoch observations using only a single camera and AO system minimize the impact of camera distortions, which can contribute >1 mas of astrometric error, even after distortion correction (S. Yelda et al., in preparation, see also Yelda et al. (2010)). In an upcoming paper (W. Clarkson et al., in preparation, see also Clarkson et al. (2010)), we use just such a data set obtained with the Keck LGS AO system and achieve astrometric precisions of ~0.2 mas per epoch and proper motion errors of 0.1 mas/yr (4 km/s) over 3 years. Figure 2 (*left*) shows the resulting velocity point diagram for the Arches cluster. Not only are cluster members easily distinguished from the field, but the internal velocity dispersion of the cluster is measured to be ~7 km/s. This yields an enclosed mass estimate of $1-4\times10^4$ $M_\odot$, which is consistent with photometric mass estimates assuming a Salpeter IMF ($2\pm0.6\times10^4$ $M_\odot$ Espinoza et al. 2009). Figure 2 (*right*) also shows the effect of field-decontamination using proper motions on a preliminary color-magnitude diagram. In an upcoming paper (N. McCrady et al., in preparation, see also McCrady et al. (2010)), this membership selection will be combined with AO near-infrared photometry to derive a precise, extinction-corrected luminosity function and initial mass function. The information provided by proper motions is greatest below 10 $M_\odot$, a critical mass range for measuring the slope of the mass function with a sufficiently high number of stars to reduce Poisson errors.

4. Galactic Disk: Proper Motion Studies of Clusters

Several massive young star clusters have also been identified throughout the Milky Way disk. While these clusters are closer and often less extincted, they are still heavily contaminated by field stars. Peculiar motions of these clusters are substantially smaller than for clusters in the Galactic center, thus high-precision proper motions are essential. Figure 3 shows absolute proper motions for a sample of massive (>10^4 $M_\odot$) young (<10 Myr) clusters within the Milky Way disk. Each panel shows the proper motions from stars at a range of distances following a model Galactic rotation curve along the line of sight toward a cluster. All the field stars not at the distance of the cluster have large proper motion offsets from the expected proper motion of the cluster itself, making the field stars easy to remove from further analysis. This includes not only foreground stars, which may be removed by rejecting blue-colored stars, but also background stars which are redder than the cluster and can easily be confused with intrinsically reddened young stars. We note that not all massive young clusters are equally well suited for proper motion membership selection (Wd2 and NGC 3603). Those clusters that reside on or near the solar circle have very small differential proper motions over a large range of distances. However, for most massive young stars clusters, only 2-3 years of observations are needed, assuming astrometric precisions of 0.2 mas that are already achieved with LGS AO, to reach proper motion uncertainties of 0.1 mas/yr (3 km/s at 6 kpc). Such precise proper motions can be used to distinguish field stars even at the distance of the cluster itself and internal velocity dispersions of clusters can be measured, yielding dynamical mass estimates.

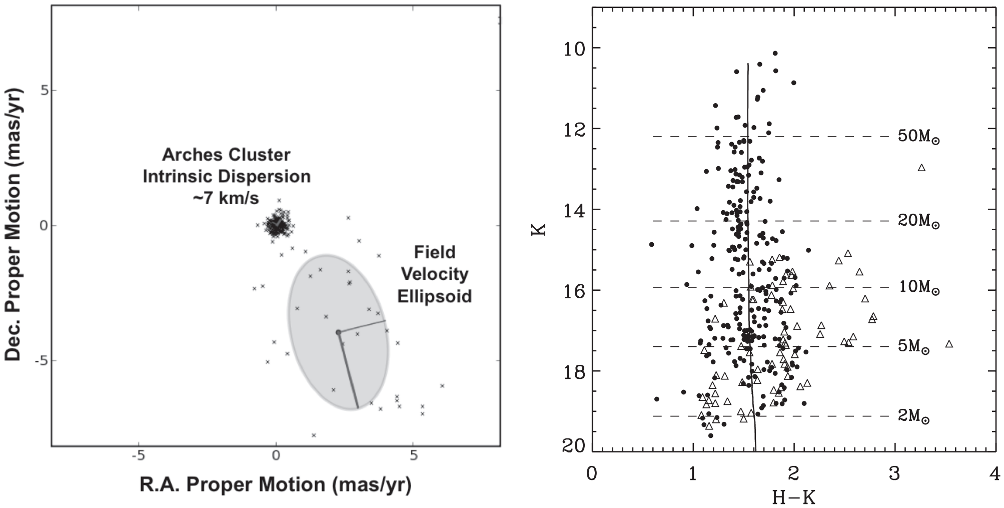

Figure 2. Astrometric membership selection (*left*) and color-magnitude diagram (*right*) for the Arches, a young massive cluster located in the Galactic center region. Observations were conducted with the Keck laser guide star adaptive optics system and will be presented fully in two upcoming papers on the Arches cluster internal velocity dispersion (W. Clarkson et al., in preparation, see also Clarkson et al. (2010)) and proper motion selected initial mass function (N. McCrady et al., in preparation, see also McCrady et al. (2010)). Cluster members concentrate together in the velocity point diagram (*left*) and can be separated from the field population. Proper motion precisions of <0.1 mas/yr yield a measure of the internal velocity dispersion of the Arches cluster of ~7 km/s and a dynamical mass estimate of $\sim 1 \times 10^4$ $M_\odot$, consistent with photometric mass estimates and a normal IMF. The contaminating field stars are highlighted in a preliminary color-magnitude diagram (*right*) with *triangle* symbols and cluster members are plotted as *points*. The vertical track is a Geneva model for a 2 Myr old population at 8 kpc with an average Arches extinction value. Differential extinction across the Arches has not yet been corrected for in this diagram. With proper motion selection, the resulting mass function derived from the color-magnitude diagram is substantially different below 15 $M_\odot$.

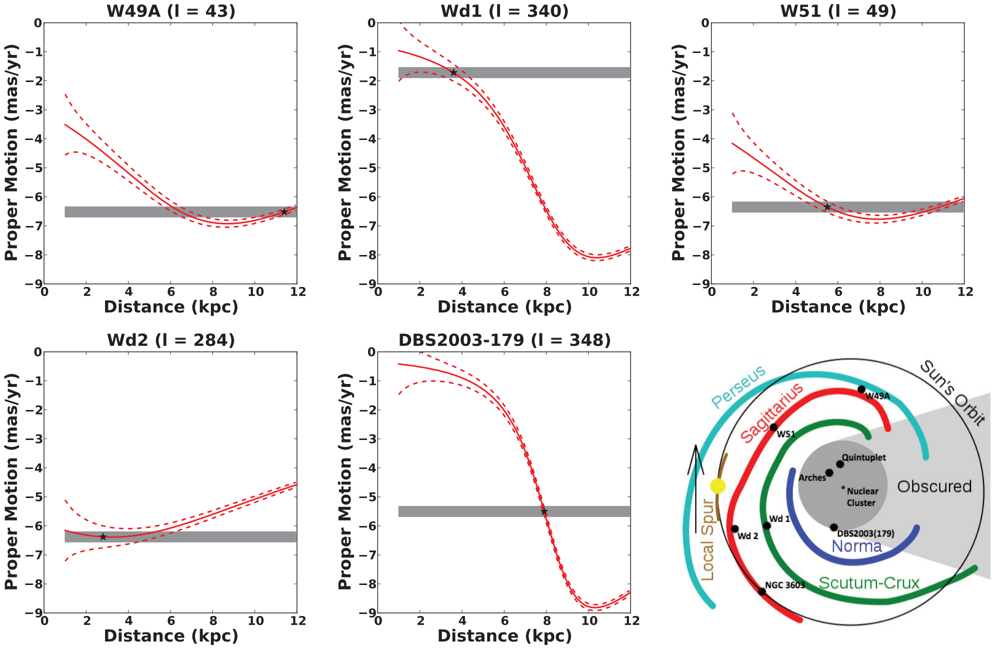

Figure 3. Proper motions predicted from a model Galaxy rotation curve at different distances along sight lines towards several massive (10^4 $M_\odot$) star clusters (*solid*). Dispersions of ±5 km/s are also shown (*dashed*). Each cluster is plotted with a black star at the average velocity of the disk at the cluster's published distance. The vertical height of the *grey filled* region shows proper motion uncertainties of 0.35 mas/yr, which can be measured in 1 year with Keck adaptive optics observations. The narrow intersection between the grey filled regions and lines shows that proper motions can be used to throw out contaminating field stars in the foreground and background. The final panel shows the approximate cluster locations overlaid on a schematic Galactic plane (http://commons.wikimedia.org/wiki/File:Milky_Way_Spiral_Arm.svg).

5. Conclusion

High spatial resolution astrometric observations of massive young star clusters within the Milky Way are a valuable tool for measuring not only precise initial mass functions of clusters but also dynamical masses, mass segregation, kinematic evolution, and more. With the advent of LGS AO and the refinement of our precision-astrometry observational and analysis techniques, we can achieve astrometric precisions of <0.2 mas in a single epoch. Over a two year time span this amounts to proper motion precisions of <0.14 mas/yr or 2, 4, and 5.3 km/s at distances of 3, 6, and 8 kpc, respectively. Similar proper motion precisions should also be possible with WFC3-IR on HST with longer time baselines of ~5 years.

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References

Alexander, R. D., Armitage, P. J., Cuadra, J., & Begelman, M. C. 2008, ApJ, 674, 927
Alexander, R. D., Begelman, M. C., & Armitage, P. J. 2007, ApJ, 654, 907
Bartko, H., Martins, F., Fritz, T. K., Genzel, R., Levin, Y., Perets, H. B., Paumard, T., et al. 2009, ApJ, 697, 1741
Bartko, H., Martins, F., Trippe, S., Fritz, T. K., Genzel, R., Ott, T., Eisenhauer, F., et al. 2010, ApJ, 708, 834
Berukoff, S. J., & Hansen, B. M. S. 2006, ApJ, 650, 901
Clarkson, W., Lu, J. R., Ghez, A., Morris, M., McCrady, N., Stolte, A., & Yelda, S. 2010, in The Galactic Center: A Window to the Nuclear Environment of Disk Galaxies, edited by D. Q. M. R. Morris, D. Q Wang, & F. Yuan, Astronomical Society of the Pacific Conference Series
Cuadra, J., Armitage, P. J., & Alexander, R. D. 2008, MNRAS, 388, L64
Espinoza, P., Selman, F. J., & Melnick, J. 2009, A&A, 501, 563
Figer, D. F., McLean, I. S., & Morris, M. 1999, ApJ, 514, 202
Genzel, R., Pichon, C., Eckart, A., Gerhard, O. E., & Ott, T. 2000, MNRAS, 317, 348
Gerhard, O. 2001, ApJ, 546, L39
Gürkan, M. A., & Rasio, F. A. 2005, ApJ, 628, 236
Kim, S. S., Figer, D. F., Kudritzki, R. P., & Najarro, F. 2006, ApJ, 653, L113
Kim, S. S., Figer, D. F., & Morris, M. 2004, ApJ, 607, L123
Kim, S. S., & Morris, M. 2003, ApJ, 597, 312
Krabbe, A., Genzel, R., Eckart, A., Najarro, F., Lutz, D., Cameron, M., Kroker, H., et al. 1995, ApJ, 447, L95
Levin, Y. 2007, MNRAS, 374, 515
Levin, Y., & Beloborodov, A. M. 2003, ApJ, 590, L33
Lin, D. N. C., & Pringle, J. E. 1987, MNRAS, 225, 607
Lu, J. R., Ghez, A. M., Hornstein, S. D., Morris, M. R., Becklin, E. E., & Matthews, K. 2009, ApJ, 690, 1463

McCrady, N., Lu, J. R., Clarkson, W., Ghez, A. M., Morris, M., Stolte, A., & Yelda, S. 2010, in The Galactic Center: A Window to the Nuclear Environment of Disk Galaxies, edited by D. Q. M. R. Morris, D. Q Wang, & F. Yuan, Astronomical Society of the Pacific Conference Series

McMillan, S. L. W., & Portegies Zwart, S. F. 2003, ApJ, 596, 314

Morris, M. 1993, ApJ, 408, 496

Morris, M., & Serabyn, E. 1996, ARA&A, 34, 645

Nayakshin, S., Dehnen, W., Cuadra, J., & Genzel, R. 2006, MNRAS, 366, 1410

Nayakshin, S., & Sunyaev, R. 2005, MNRAS, 364, L23

Paumard, T., Genzel, R., Martins, F., Nayakshin, S., Beloborodov, A. M., Levin, Y., Trippe, S., et al. 2006, ApJ, 643, 1011

Portegies Zwart, S. F., McMillan, S. L. W., & Gerhard, O. 2003, ApJ, 593, 352

Sanders, R. H. 1998, MNRAS, 294, 35

Stolte, A., Brandner, W., Grebel, E. K., Lenzen, R., & Lagrange, A.-M. 2005, ApJ, 628, L113

Stolte, A., Ghez, A. M., Morris, M., Lu, J. R., Brandner, W., & Matthews, K. 2008, ApJ, 675, 1278

Vollmer, B., & Duschl, W. J. 2001, A&A, 377, 1016

Yelda, S., Ghez, A. M., Lu, J. R., Do, T., Clarkson, W., & Matthews, K. 2010, in The Galactic Center: A Window to the Nuclear Environment of Disk Galaxies, edited by D. Q. M. R. Morris, D. Q Wang, & F. Yuan, Astronomical Society of the Pacific Conference Series