Proceedings of the Fall 2006 Astronomy 233 Symposium on

STAR FORMATION AT THE GALACTIC CENTER: THE PARADOX OF YOUTH

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Astronomy 233 *"Star Formation: From the Early Universe to the Solar Neighborhood"* was taught during the fall semester of 2006 by Professor Martha Haynes with the always willing and able assistance of Astronomy graduate student Melissa Rice. This course is intended to provide students interested in majoring or concentrating in astronomy with an introduction to current forefront topics in the field and also to expose them to pratical aspects of a professional research career such as the circumstance of the current "symposium".

Astronomy 233 this semester revolved around the discussion of how the process of star formation has varied in different locations within the Milky Way and other galaxies and over cosmic time. One of the most fascinating regions of the Milky Way is the Galactic Center. Obscured at optical wavelengths, modern infrared, radio and X-ray telescopes have allowed us to peer into the heart of the Milky Way. The compact, unresolved radio continuum source known as SgrA* has been shown to be a supermassive black hole with a mass 3 million times that of the Sun. The stellar density around the black hole is 300,000 times that of the Solar Neighborhood. Such a region is so dense that molecular clouds, the stuff from which stars are formed, are subjected to tremendous tidal forces. Our conventional ideas of how stars might form do not work there, yet there are lots of hot, blue, massive young stars. How could they have formed?

As part of our discussion of star formation, students were placed in the role of summarizing papers selected from the profesional literature pertaining to "Star Formation at the Galactic Center: The Paradox of Youth." The papers contained herein represent their original work, with minor editting mainly to conform to the style used in producing this volume. The students are asked to forgive us for modifications made in the editorial process.

All of us wish to compliment the authors on their contributions, on their diligence and enthusiasm, and on their patience.

Martha P. Haynes

Melissa S. Rice

Ithaca, New York
30 November 2006

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1. Star Formation In A Dense Gaseous Disk Around Sgr A*

Anand Bhaskar[1]

ABSTRACT

Levin & Beloborodov (2003) put forth a new hypothesis to explain the formation of stars near the center of the Milky Way galaxy. Even though molecular cloud formation within the vicinity of Sgr A* would not have been possible due to intense tidal forces exerted by the black hole, the coplanar orbital velocities of the closest stars to Sgr A* indicate that they formed in a dense gaseous disk around the supermassive black hole, which has since then been accreted. In particular, they analyze the orbital velocity data of 13 young stars in Genzel *et al.* (2000) to support their theory of a massive accretion disk that either gave birth to new stars or trapped older ones, thus providing an explanation for the "paradox of youth" (Ghez *et al.* 2003).

1.1 Introduction

It is widely believed that the center of the Milky Way Galaxy, Sgr A*, is a supermassive black hole. The formation of stars from molecular clouds in the vicinity of Sgr A* should be almost impossible due to extreme tidal forces exerted by the massive black hole. Contrary to expectation, many young stars have been observed to orbit around Sgr A*; this apparent contradiction is what Ghez *et al.* (2003) have termed the "paradox of youth". Using data that Genzel *et al.* (2000) have collected, Levin & Beloborodov (2003) propose an alternate model of in situ stellar formation that hinges on the presence of a dense gaseous disk around Sgr A* that could have supported stellar birth in the recent past.

1.2 The Young Stellar Disk

Genzel *et al.* (2000) have collected the orbital velocities of 13 stars close to Sgr A* (see Figure 1.1), of which 11 have been found to move in a clockwise direction in the sky. Levin & Belborodov have fitted a plane for 10 of these stars and have found that they orbit within 1.6 sample standard deviations from it.

The authors have employed the stochastic technique of Monte Carlo simulations to generate 10 random velocity vectors and then measure their dispersion about the mean velocity. Through these simulations, the probability for 10 random velocity vectors to lie within 1.6 standard deviations from the mean was found to be very small (only about 10^{-2}). This deviates from the belief that the orbital velocities of stars in the Milky Way is random and gives strength to the authors' hypothesis that these stars were formed from a dense gaseous disk surrounding Sgr A*.

The authors have divided the stars into two groups: the first group with 10 stars which move clockwise in the sky and whose three dimensional velocities lie very close to a plane; and a second group with three stars whose velocities deviate quite greatly from the aforementioned plane, two of which move counter-clockwise in the sky. The authors have computed a best-fit plane to model the orbital velocities of the first 10 stars and

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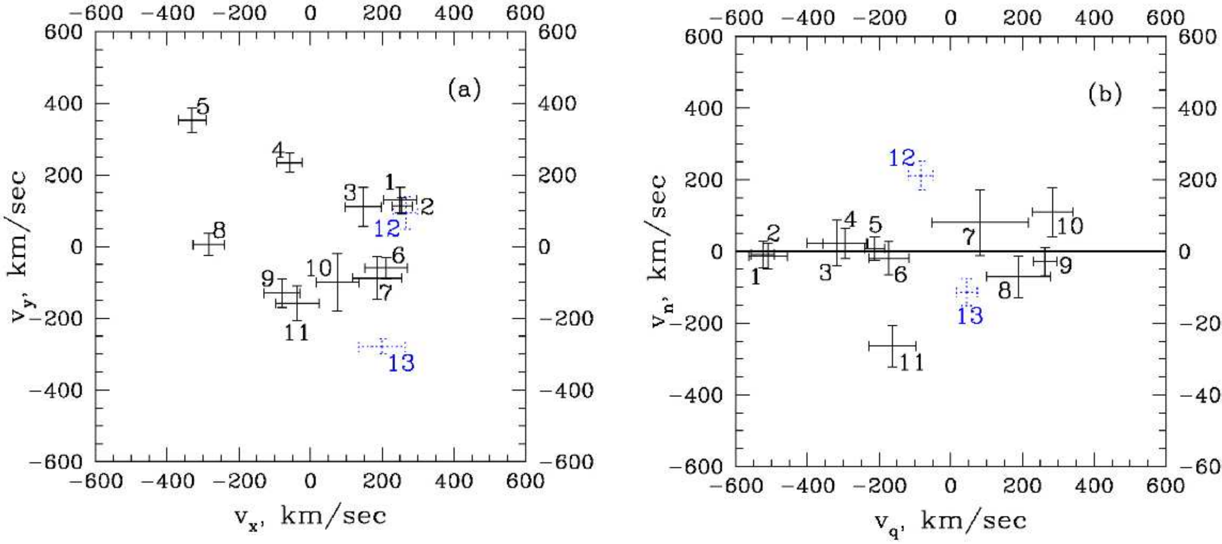

FIGURE 1.1. Velocities of 13 stars around Sgr A* (left) projected on the plane of the sky and, (right) as viewed by an observer located on the best-fit plane, shown as the bold horizontal line. Stars 1 to 10 are within 1.6 standard deviations from the best-fit plane, stars 12 and 13 move counter-clockwise in the sky while the remaining stars move clockwise in the sky. From Levin & Beloborodov (2003).

have performed the χ^2 goodness-of-fit test for this plane. The χ^2 test is used to determine the certainty with which one can claim that a random variable follows a certain probability distribution. The lower the value of the computed χ^2 statistic, the closer the agreement between observations of the random variable and the hypothesized probability distribution, and vice versa. The authors have found that the χ^2 test applied to the 10 velocity vectors and the best-fit plane produces a very low χ^2 value of 0.67 (a random sample of 10 velocity vectors could achieve this with probability less than 10^{-3}). On the other hand, if the 11^{th} star is fitted to this best-fit plane, the χ^2 value would increase significantly to 3.2, thus indicating that it is very unlikely that this 11^{th} star has a coplanar orbital velocity with that of the first 10 stars.

The quantity called the half-opening angle of the best-fit plane is a yardstick of the measurement error in the measured orbits of the stars. The authors determine an upper bound for the half-opening angle for this best-fit plane by randomly choosing the orbital planes for the first 10 stars within some $\Delta\theta$ degree of dispersion from the best-fit plane. They then determine a new best-fit plane for this dispersed system, and perform the above steps in a Monte-Carlo simulation to determine the probability that the χ^2 value for the new best-fit plane falls below 0.67 (that is, the new-best fit plane is at least as good as the old best-fit plane in describing the orbits of the 10 stars). The simulations (Figure 1.2) show that this probability drops sharply as $\Delta\theta$ increases and is only about 0.1 for $\Delta\theta = 10°$. This leads them to conclude that the half-opening angle is bounded by about 100°.

1.3 The Interpretation: Disrupted Young Cluster Versus Remnant Of An Accretion Disk

The authors refute the theory that the stars around Sgr A* belong to a cluster that has spiraled towards it due to gravity. Gerhard (2001) has proposed that a stellar cluster of roughly 2×10^4 $M_\odot$ had formed relatively

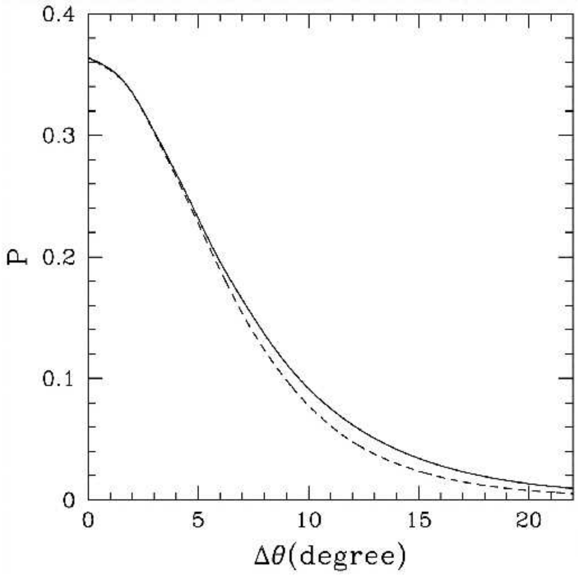

FIGURE 1.2. The graph of the probability of a best-fit plane for a $\Delta\theta$ dispersion of the orbits of stars 1 to 10 in Figure 1.1 being as good a fit (ie. $\chi^2 \leq 0.67$) as the best-fit plane in Figure 1.1. The solid line indicates that the $\Delta\theta$ dispersions were chosen from a Gaussian distribution, while the dashed line indicates they were chosen from a homogenous distribution. The plots were made based on Monte-Carlo simulations. From Levin & Beloborodov (2003).

distant from Sgr A* (about 10 pc away) but had spiraled into its vicinity due to gravitational interaction with other stars. The stars in the cluster have had their matter accreted by the black hole until all that remains of them is their presently observed cores orbiting around it. Such a theory would not permit any star to get closer than 0.4 pc from Sgr A*, while many of the stars that have been observed are closer than 0.1 pc. Their hypothesis to explain the "paradox of youth" is that the stars around Sgr A* have formed from a dense disk-shaped molecular cloud that once orbited it. This disk had accumulated gas from neighboring regions and became dense in its plane of rotation leading to some of its fragments clumping together to form stars. Work done by Kolykhalov & Sunyaev (1980), Shlosman & Begelman (1987), and Collin & Zahn (1999) has noted that this process also occurs in the centers of other galaxies. The dense gas in the disk could have influenced the orbit of other old stars that were initially inclined to the plane of the disk and the accretion of matter from the disk could cause these stars to grow in size and appear as young stars, as also expressed by Artymowicz *et al.* (1993).

The critical mass beyond which clumps of gas stabilize and hold together to form protostellar clouds, the Jeans mass, is quickly reached in this dense molecular disk, and very high-mass stars are easily able to form here. The accretion of mass by the newborn stars also causes gaps to open up in the disk, and coupled with the fact that the gas can be blown away by stellar wind, this explains the absence of any observable gaseous disk around Sgr A* at present.

1.4 The Lense-Thirring Precession Of Close Stars

Levin & Beloborodov attribute the inclination of the orbit of S2, the closest known star to Sgr A*, with respect to the plane of best-fit, to the general relativistic effect known as Lense-Thirring precession. A star orbiting very close to a supermassive black hole can change orbital orientation over time, where the rate of change is dependent on the spin of the black hole and the age of the star. Thus, the highly inclined orbit of

S2 is not a contradiction to their theory of a dense gaseous disk that has led to star formation around Sgr A*. They also deduce a lower bound on the spin of the black hole, a measure of its angular momentum, in terms of the age of S2 and the mass of the black hole, and conclude that if more stellar orbital orientations are determined in the vicinity of Sgr A*, their precession argument could either be strengthened or rejected.

1.5 Conclusion

The authors explain the "paradox of youth" by noting that the stars around Sgr A* either are very young massive stars or are older stars whose orbits have been shifted. If they are young massive stars, they have formed very recently (3-9 million years ago) in a dense gaseous disk that once orbited the black hole. On the other hand, if they are older stars, their orbits have been shifted due to gravitational interaction with the gaseous disk, and the accretion of the disk's matter has caused them to appear as young massive stars even though they have older cores.

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2. IRS 16 SW: Evidence of the Remnant Core of the Disrupted Cluster in the Galactic Center

Piyanat "Boom" Kittiwisit[1]

ABSTRACT Lu *et al.* have used the near-infrared camera (NIRC) of the 10 m Keck I telescope with the K band filter to observe the star cluster in the central parsec of the Galactic Center. From star mapping and orbital analysis, they have discovered the new comoving group of young, massive stars named IRS 16 SW. The comoving group may be the surviving core of the disrupted star cluster that formed at larger radii and migrated toward the Galactic Center a few thousand years ago. This discovery provides the new explanation for the paradox of star formation at the Galactic Center that involves the star cluster.

2.1 Introduction

As is being discovered by many astronomers, the center of our Milky Way galaxy, contains a super-massive black hole (SMBH) of mass $\sim 3.7 \times 10^6\ M_\odot$. The most interesting thing about this SMBH is the stellar environment around it. Due to its extremely high mass, the SMBH generates large tidal forces on the local gas around it. In order to collapse and form the star, the local gas must be dense enough to overcome the SMBH's tidal shear, but this dense gas has never been observed. Nevertheless, astronomers have discovered a cluster of young, massive stars within the central parsec of the SMBH. The discovery of this young, massive star cluster is a new mystery in astronomy because the current star formation model is not applicable to the high tidal force environment around the SMBH. Astronomers have proposed several new models in the last decade. These include a self-gravitating accretion disk or infalling and colliding of dense gas clouds, but no such dense gas cloud has been observed to support the model. Alternatively, stars might form at larger radii, where the tidal shear is small, and then migrate into the SMBH. In order to migrate a few arcseconds toward the SMBH, the star cluster must be dense enough to undergo core collapse and contain an intermediate-mass black hole (IMBH). Although this model is still not fully confirmed, it might be one of the correct models. Recently, astronomers have discovered an X-ray source from the IRS 13 star cluster, which is also located in the central parsec of the SMBH. This discovery indicates the possibility of an IMBH in the cluster.

Lu *et al.* (2005; hereafter L05) published a report on the discovery of the new comoving group of young, massive star, IRS 16 SW in the central parsec of the SMBH. The report includes the mapping of the stars in the cluster and their orbital kinematics analysis. Based on the result, they propose a new formation mechanism suggesting that the discovered group is the remnant core of the infalling cluster. This model has great implications on star formation models around the SMBH, and provides evidence for the formation scenarios that involve star clusters which may be a key concept of star formation around the SMBH. In this paper, we will discuss the observation made by Lu *et al.*, their results and the implication of this discovery on star formation model.

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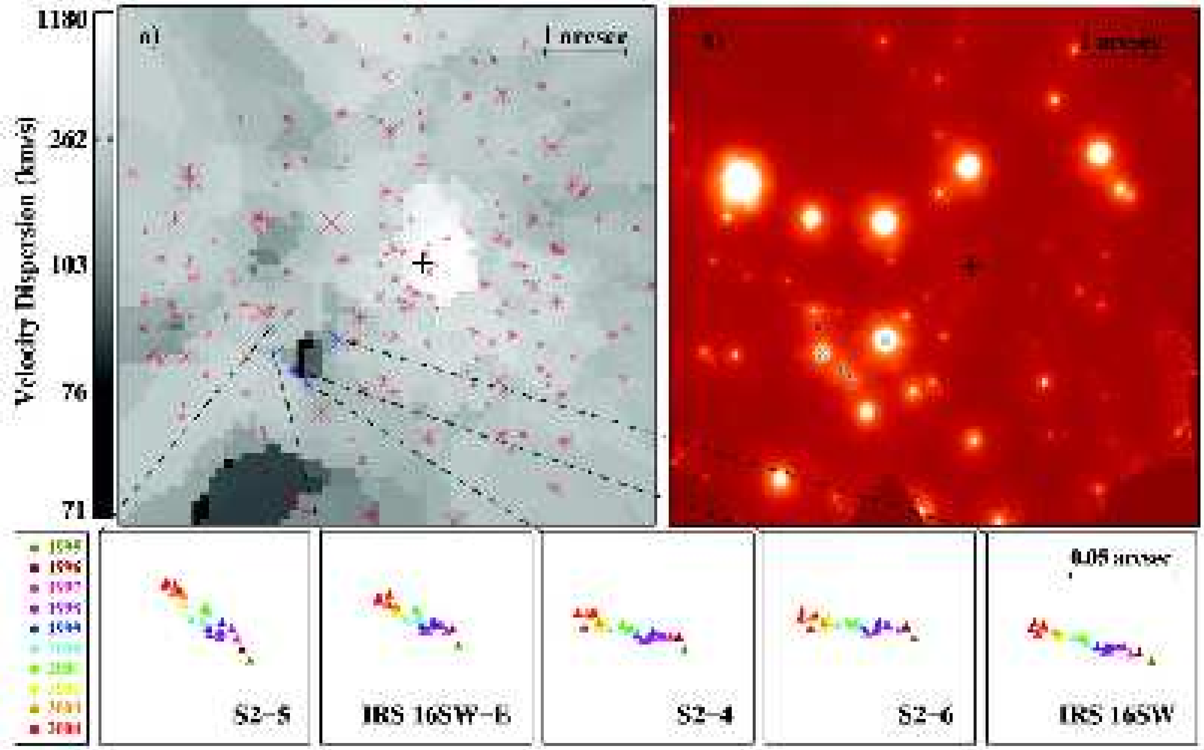

FIGURE 2.1. (a) Positions of all stars in the sample (asterisks) overlaid on a map of the two-dimensional velocity dispersion (gray scale). The sizes of the asterisks represent the stars' 2.2 μm brightness. The black region is a minimum in the velocity dispersion, located $\sim 2''$ from Sgr A* (black plus sign), and is caused by five comoving stars (blue), which define the newly identified IRS 16 SW comoving group. (b) A K-band (2.2 μm) speckle image showing the clustering of bright sources at the position of the IRS 16 SW comoving group. Group members are marked with blue crosses. Bottom: Proper motions of the IRS 16 SW comoving group members. In each $0.1'' \times 0.1''$ panel, the stellar positions are plotted with different years' data labeled with different colors. From L05.

2.2 Observation and Results

L05 have observed the star clusters at the central parsec of the Galactic Center in the K band ($\lambda_o = 2.2\mu m, \Delta\lambda = 0.4\mu m$) with the facility near-infrared camera, NIRC, on the 10 m Keck I Telescope from June 1995 until September 2003. The data consists of ~10000 short exposures, each with 0.1 s exposure time. The data are combined using a technique called weighted shift–and–add to form the final high resolution image for each data set. The stars in the sample are then eliminated, taking the error into account, leaving only 180 stars. Then, proper motions of the stars are derived and converted into linear velocities using a distance of 8 kpc. The velocity dispersion map of the sample is then created as shown in Figure 2.1. The dispersion map shows the minimum dispersion between seven stars with respect to IRS 16 SW, implying that this group is a comoving group. The member of the group is then eliminated to remove the stars that appear in the group as a result of projection, leaving only 5 members in the group. These 5 comoving groups are IRS 16 SW, IRS 16 SW-E, S2-6, S2-4 and S2-5. The proper motion data of the group is shown in Table 2.1. They all appear to be young, massive stars. The spectroscopic observations of the members have been conducted later to confirm their presence. The result suggests that the group is located ~0.08 pc from the SMBH and orbits clockwise on the orbital plane.

Name	K (mag)	r_{2D} (arcsec)	ΔRA (1999.56) (arcsec)	ΔDEC (1999.56) (arcsec)	V_{ra} (km/s)	V_{dec} (km/s)	V^b_{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	-

TABLE 2.1. Proper Motions for IRS 1 SW Co-Moving Group. From L05.

[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).

2.3 Discussion

The IRS 16 SW is the second comoving group observed within the central parsec of the SMBH based on the time of Lu *et al.*.'s publication. The first group discovered is IRS 13 which may contain an IMBH (Schödel *et al.* 2005; see paper by K-Y, Nguyen in this volume). Although IRS 13 orbits counterclockwise on the orbital plane while IRS 16 SW orbits clockwise, both of groups contain young, massive stars, indicating that they have similar ages, and suggesting similar formation mechanism. However, there are some distinct differences between the two groups. First, IRS 13 is high in stellar density number, $\sim 40 - 80$ objects per square arcsecond, while IRS 16 SW contains only 5 stars making the density to be ~16.5. Second, IRS 13 is located on a bright complex of dust, ionized gas while IRS 16 SW does not. Therefore, the formation mechanism for the two groups must be applicable to both distinctive situations. The most probable mechanism is that the IRS 16 SW formed at larger radii and migrated toward the SMBH. However, calculations yield that the group is an unbound cluster, meaning that all stars in the group are not gravitationally bound to each other. Hence, the group will not be able to survive the extreme tidal force of the SMBH while it migrates. L05 propose that the group might be a remnant core of the tidally disrupted cluster that migrates toward the SMBH. In this model, the outer part of the cluster is disrupted from the tidal shear while it is migrating toward the SMBH, but the core of the cluster is not disrupted. IRS 16 SW is, therefore, comparable to this surviving core. If this is the case, calculations show that the disruption would occur within only tens of thousand years, associated with the fact that the comoving group contains young stars. Simulations need to be done to test these assumptions.

2.4 Conclusion

The discoveries of two comoving groups near the SMBH, and the fact that the disruption periods of the clusters are short near the SMBH, suggest that the stars forming and infalling rates at the Galactic Center are high. This might be the reason why the stellar population density at the Galactic Center is high. The discovery of IRS 16 SW provides more evidence for the formation scenarios, whether the group is the remnant core of the disrupted cluster of not. If we can discover the disrupted clusters that are migrating toward the SMBH, the assumption might be confirmed, and it may help to solve the mystery of star formation at the Galactic Center.

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3. Potential IRS 13E Black Hole

Kim-Yen Nguyen[1]

ABSTRACT Schödel *et al.* (2005) explore the implications of the age and motions of the IRS 13E complex which contains massive young stars that are unexpected near the Milky Way's central supermassive black hole Sagittarius A* (Sgr A*). They examine the hypothesis that the complex is a remnant of a massive stellar cluster with a central intermediate-mass black hole (IMBH) that would balance the gravitational effects of Sgr A*. By analyzing the proper motions in IRS 13E, they conclude that the IMBH must have a mass of at least 10^4 $M_\odot$ to bind the complex gravitationally. They conclude that this high mass estimate, in conjunction with lack of evidence of a variable X-ray emission source in the complex, makes the existence of an IMBH in IRS 13E unlikely.

3.1 Introduction

At the center of the Milky Way galaxy, a supermassive black hole Sagittarius A* (Sgr A*) exists that should impose tidal forces too strong to allow for typical star formation (Ghez *et al.* 2003). Stars typically form from clouds of gas that condense until they become gravitationally bound and begin to collapse, commencing free-fall of gaseous material that will increase the protostar's density until angular momentum halts further collapse. However, in the galactic center, a burgeoning star would have to compete with the Sgr A*'s strong tidal forces, making it much more difficult for new stars to gather enough mass to become dense enough to survive there. And yet almost exclusively seemingly young massive stars surround Sgr A*. If the stars are actually young, they could have formed in situ, which requires much higher gas densities for the stars to survive in the tidal field. The stars could also only appear young but actually be old, or they could have formed further out from the effects of the black hole and then migrated inwards (Gerhard 2001; Kim & Morris 2003; Hansen & Milosavljevic 2003).

Schödel *et al.* (2005) attempt to explain the "paradox of youth" (Ghez *et al.* 2003) of the IRS 13E complex, one of the groups of unusual young stars near Sgr A*. The complex contains six fairly young massive stars of similar age that are within $0.25''$ of each other. These stars exhibit very similar proper motions, which, in addition to their young age, may suggest that IRS 13E is the core of a massive star cluster that has collapsed in upon itself. To explain the lack of disruption that Sgr A* is expected to be causing the complex, it has been proposed that an intermediate-mass black hole (IMBH) is at the center of IRS 13E. Schödel *et al.* analyze the proper motions of the stars in the IRS 13E complex using data from 10 years of near-infrared adaptive optics observations.

3.2 Observations and Data Reduction

Schödel *et al.* have gathered high-resolution data of the cluster using the near-infrared adaptive optics system at the ESO VLT telescope in Chile in primarily the K- and H-bands beginning in 2002. They have also used data from the Gemini North Galactic Center Demonstration Science Data Set from 2000 and SHARP data from 1995, 1996, and 2001. Standard data reduction procedures have been used for all sets of data.

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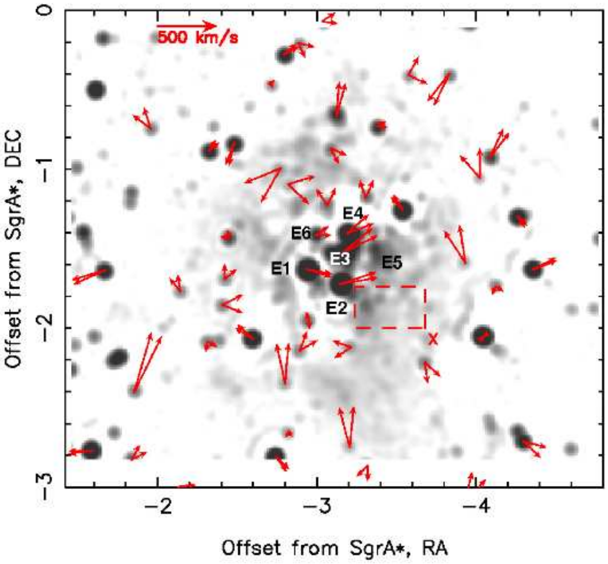

FIGURE 3.1. Proper motions of stars in IRS 13E. The image is a 2004 NACO K-band image. Sources discussed are labeled E1 through E6. Arrows represent proper motion; the lengths reflect the magnitude of velocity and the two arrows for each star show uncertainty in direction. The dashed–line box indicates the postulated position of the IMBH from X-ray data (Baganoff *et al.* 2003). From Schödel *et al.* (2005).

3.3 Dynamics in the IRS 13E Complex

IRS 13E has six primary sources: E1, E2, E3, E4, E5, and E6 (see Figure 3.1). Although E3 appears to be a multiple source (Maillard *et al.* 2004), its single brightest component is labeled E3 in the figure. Schödel *et al.* have determined the proper motions of the sources, which are superposed in Figure 3.1, by finding the best-fit position graph based on gathered data. Although their existence is possible, more sources could not be distinguished and thus are not included in the analysis. E5 appears too highly confused with other sources to determine its proper motion, and E6 is anomalous because of its smaller velocity and extinction, so both have also been excluded from Schödel *et al.*'s analysis.

Schödel *et al.* have used proper motions to find the minimum mass necessary to bind IRS 13E cluster members in three possible cases: (1) using the average proper motion of the whole, (2) using the proper motion of E1, and (3) using the proper motion of E4. Case 1 yields the greatest range of possible masses, so Schödel *et al.* have omitted analysis of the other two cases from their paper.

They have determined the average proper motion of sources E1, E2, E3, and E4 using the unweighted average of the velocities. To first obtain a very rough estimate of the mass necessary to bind IRS 13E, they have used the residual velocities and the equation $M =< v^2 > R/G$ where R is the size of the system and G the gravitational constant to get $M \sim 5600\ M_\odot$.

For more precise estimates, they have used two more methods: (1) the Leonard-Merritt mass estimator (eq. [19] in Leonard & Merritt 1989), where the IMBH mass is directly proportional to the star's distance and its velocity components squared, and (2) the relation $Rv_{proj}^2/2G \leq rv_{esc}^2/2G = M$, where R is the projected distance between a star and the IMBH, v_{proj} is the star's velocity projected onto the plane of the sky, r the real distance from the IMBH, v_{esc} the escape velocity, G the gravitational constant, and M the mass of the IMBH. Both methods find distance and velocities of surrounding stars to be most important in determining the mass of the IMBH.

With the Leonard-Merritt mass estimator, the mass is $\sim 50000 \pm 15000\ M_\odot$. In using the second relation, Schödel *et al.* have obtained four maps of possible IMBH locations based on the four sources (E1, E2, E3, E4) to account for uncertainty in the location of the IMBH. They have combined the four maps by taking the maximum of the mass at each location, which yields a most conservative mass estimate of $\geq 7000\ M_\odot$ if the black hole is close to E1. If the IMBH is between E2 and E4, then $M > 15000\ M_\odot$.

If other sources, like E6, are taken into account, the black hole mass would increase due to the increased velocity gradient. Therefore, Schödel *et al.* have chosen the mass required to bind the IRS 13E complex to be at least $10^4\ M_\odot$ as an order of magnitude estimate.

3.4 Discussion

IRS 13E is approximately 130 mpc from the black hole Sgr A*. Schödel *et al.* find that the complex's small radius of $\sim 0.25''$ would make 1000 $M_\odot$ sufficient to protect against disruption from Sgr A*. After taking into account the proper motions of the sources, they have found that the minimum mass to bind the system increases to $7000 \pm 1800\ M_\odot$, which is in the expected mass range of an IMBH.

However, IRS 13E has none of the nonthermal radio and X-ray emissions expected of an accreting black hole. The interstellar medium and warm dust are both located very close to the complex, which – in addition to the stars in the complex that could be gas and dust sources – would supply enough accretion material to yield detectable emissions.

The complex does exhibit radio emissions, but these are most likely thermal emissions from a source (E3) in the complex (Eckart *et al.* 2004). Baganoff *et al.* (2003) also reported an X-ray source, but the source is nonvariable and offset from the complex. These X-rays are much closer to the confused E5 source, so they are more likely from colliding stellar winds of a massive star rapidly losing mass than from a black hole. It is unlikely that an accreting IMBH exists in IRS 13E because the complex does not exhibit characteristic black hole behavior.

The infall and dissolution (evaporation of mass due to strong tidal fields) of a massive cluster seems like a reasonable explanation for the "paradox of youth" (Ghez *et al.* 2003), but this hypothesis would also require high core densities and large cluster masses. An IMBH would lower the necessary total mass and core density, but would also need to comprise $\sim 10\%$ of the total cluster mass. This would increase the estimated mass of the original cluster to an unrealistic $> 10^6\ M_\odot$. An IMBH of $< 10^4\ M_\odot$ could still exist in the center of the complex, but IRS 13E would have to be in the process of dissolution. Levin *et al.* (2005) have even concluded that an IMBH at the center of the complex still does not explain the current positions of all the stars.

IRS 13E could be gravitationally bound by a not unusually massive IMBH, but the consequent expectance of an unusually massive progenitor cluster and the lack of nonthermal variable X-ray emissions make this hypothesis very unlikely. However, the complex could still be a cluster in the process of dissolution. To better understand IRS 13E and similar complexes, Schödel *et al.* propose more studies of proper motions, velocities, distribution, and types of stars within one parsec of the Galactic Center.

3.5 References

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4. The Truncated Mass Function of the Arches Cluster

Lamarr Parsons[1]

ABSTRACT Stolte *et al.* (2005) have established the center of the starburst Arches Cluster using high resolution adaptive optics obtained from the Nasmyth Adaptive Optics System Near Infrared Imager and Spectrograph (NAOS-CONICA) in the H–K band. In addition, the mass function of the cluster has been determined, indicating that its composition is deficient of intermediate– and low–mass stars in its core. This review summarizes the ideas and results expressed in their paper.

4.1 Introduction

The elongated shape of Arches, shown in Figure 4.1, and its relatively short distance of 25 pc to the Galactic center makes it an interesting star cluster. These traits provide evidence of the tidal forces that stretch it, thus compromising its density. These tidal forces lead to a disproportionate number of high mass stars concentrated in the cluster's core. Consequently, the slope Γ of the integrated Mass function (MF) is found to be approximately between $\Gamma = -0.9$ and $\Gamma = -1.1$, depending on the distance from the core. Stolte *et al.* (2005) have utilized adaptive optics to gather their data in order to construct the present-day MF in the Arches Core.

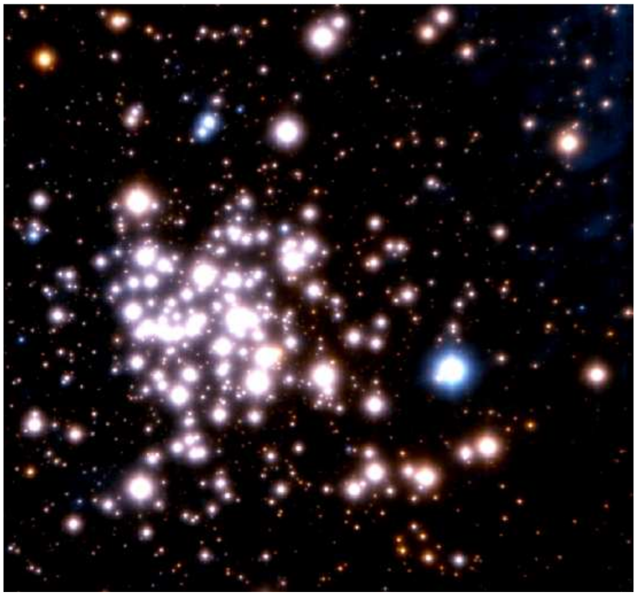

FIGURE 4.1. K image of the Arches cluster. North is up and east is to the left. The image shows the high density of the cluster that increases the difficulty in gathering data. From Stolte *et al.* 2005.

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The results of this study directly address the “paradox of youth”, as the circumstance of finding very young, massive blue stars near the Galactic center has been dubbed by Ghez *et al.* (2003). Stolte *et al.* (2005) have indicated that some process may have allowed only high mass stars to form in the center of the cluster, prohibiting the formation of intermediate and low mass stars there. However, this is in direct contrast with our current understanding that young stars are formed in the center and move towards the halo as they evolve. But given the number of low and intermediate stars that aren’t being allowed to form in the center, the authors suggest that these stars were not formed in the center but in the halo, thus opposing the idea that only older stars are located in the halo.

4.2 Observations and Data Reduction

The Arches cluster, has been observed by the Stolte *et al.* (2005) team using the Nasmyth Adaptive Optics System Near-Infrared Imager and Spectrograph (NAOS-CONICA) by means of visual and near-infrared spectra. The H and K bands were especially useful for this study, because the lie in the infrared portion of the spectrum, centered at 1.65 and 2.2 μm respectively.

Methods of over-sampling in conjunction with standard data reduction have been applied to improve detection of the data sources. Sampling refers to how many pixels have been used by the data-collecting instruments to produce details. In general, when more pixels have been used, the resulting data is more precise. Point-spread function (PSF) fitting photometry has been implemented and has proved very useful in determining the magnitudes of these stars given their crowded fields.

4.2.1 ARTIFICIAL-STAR SIMULATIONS

As seen in the combined HK image of the Arches Cluster (Figure 4.1), the cluster is extremely dense. As a result, artificial-star simulations had to be used. This simulation recovered the stars that were muddled, but as with real stars, only certain simulated stars were selected for use, based on their uncertainty and color. In addition, only stars that were identified in both the H and K bands were utilized.

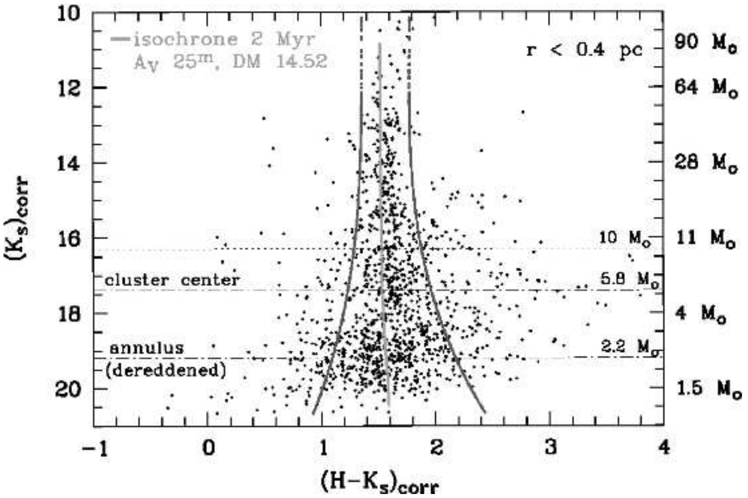

FIGURE 4.2. Corrected color magnitude diagram of the Arches Cluster. The gray vertical line corresponds to the 2 Myr Geneva isochrone fitted to the distribution and the two curved lines on either side represent the color cut applied to remove field stars. From Stolte *et al.* 2005.

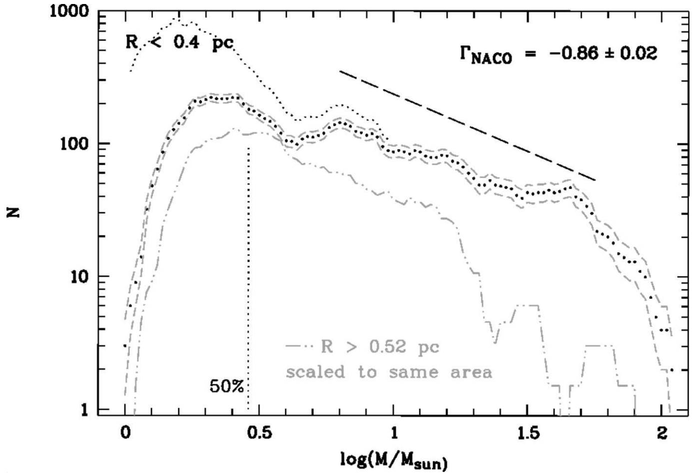

FIGURE 4.3. Present day mass function of the Arches star cluster. The turn-off point is seen at approximately M = 6 $M_\odot$. At high masses, the MF is flattened, indicating a bias towards high mass stars. From Stolte *et al.* 2005.

4.3 The Arches Cluster Present-Day Mass Function

The authors have fitted a 2 Myr Geneva isochrone to the color-magnitude diagram of the Arches Cluster as illustrated by a light vertical solid line in Figure 4.2. Foreground and background sources were then excluded from the graph using a color cut which excluded the stars of fainter magnitude that are redder and bluer than the majority of stars in that magnitude range. In Figure 4.2, the curve on the left of the main distribution is the cut off point for red stars and the curve on the right is the cut off point for blue stars.

After resolving the K bands of the focus stars, the 2 Myr Geneva main-sequence isochrone has enabled the team to convert the K-band magnitude of each star into masses. These calculated masses were then scaled alongside the y-axis of Figure 4.2. However, stellar evolution has been unaccounted for in this study (with their use of present-day masses). Fortunately, only stars with masses greater than $50M_\odot$ were affected by this factor. These data points, shown in Figure 4.3, compromise the right tail of the present-day MF and have been disregarded.

Figure 4.3 depicts the mass function found from the isochronal fitting of Figure 4.2. The scale of the y-axis represents the number of stars having the quantity Δ log(M/$M_\odot$) equal. The slopes in Figure 4.3 have been obtained by means of linear least-square fitting. From this graph we see a peak in the MF called the Turn Off Point (TO), where the slope changes from positive to negative. The general slope after the TO is $\Gamma = -0.86$, indicated by the broken line.

This TO occurs at approximately M $\sim$ 6 $M_\odot$, fitting the mass range of the MF to 6 $M_\odot <$ M $<$ 60 $M_\odot$. The problem of field contamination then surfaces, causing an increase in the apparent MF and a function decrease towards lower masses.

In explanation of the flattening of the mass function in Figure 4.3, the team has come up with two possible solutions. Firstly, the MF may be truncated at the lower mass end, which means that there is essentially a cut off limit as to how massive stars can be in the cluster core. Secondly, tidal forces may have caused rapid dynamical segregation in times as short as 2 Myr. This dynamical segregation is literally the physical separation of high mass and low mass stars. The tidal forces move high mass stars towards the clustural center and low mass stars towards the outer halo of the cluster.

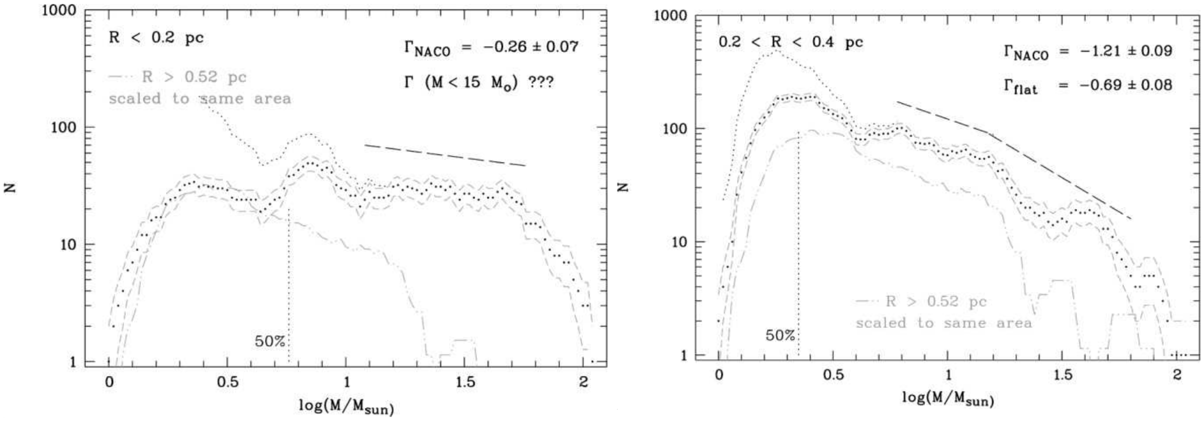

FIGURE 4.4. Mass function of the Arches star cluster. The left panel shows the mass function derived at radii less than 0.2 pc from the center of the cluster while the right graph shows the same for stars at radii between 0.2 and 0.4 pc from the core. These are denoted as annulus 1 and annulus 2 respectively. From Stolte *et al.* 2005.

4.4 The Mass Function Turnover in Two Annuli

Figure 4.4 presents the mass functions derived separately for stars lying in inner (left panel) and outer (right panel) annuli, in contrast to the global MF shown in Figure 4.3. These two figures separate the stars by their distances with respect to the core of the cluster. The first annulus (left) is at R < 0.2 pc and the second annulus (right) is at 0.2 < R < 0.4 pc. We see from the graph of the second annulus the shift in the TO towards the left. This suggests that there is a truncation in the lack of low-mass stars in Arches.

These two annuli are very different, especially at masses greater than 6 $M_{\odot}$. In the core of the cluster, the slope at the flat point is $\Gamma = -0.26$ whereas in the halo of the cluster, the slope is $\Gamma = -1.21$. This means that the core stars have greater masses on average than the stars in the halo. Therefore the authors claim that there is a high production of high mass stars in the core. The authors claim that a type of physical process, called primordial segregation, has influenced this formation of high mass stars.

4.5 Summary and Discussion

Stolte *et al.*present two theories to explain the present-day MF of the Arches cluster: rapid dynamical segregation and the selective process of high-mass star production instead of low-mass star production. They also show that the point at which the slope of the MF changes from negative to positive is around 6-7 $M_{\odot}$. This result indicates a bias towards high mass stars in the core and low mass stars in the halo.

Current theories suggest that these mass preferences are determined by the initial condition of the molecular cloud core and environmental conditions such as temperatures, densities, turbulent pressures and magnetic fields. The authors then assert that the peculiarity of the Arches Cluster is only a result of the drastic environmental conditions experienced by star clusters within close proximity to the Galactic center.

For further study, they suggest that a larger field around the cluster is used in order to be certain that the Galactic Center played a role in the large discrepancy in the high- to low-mass stars ratios and whether dynamical segregation plays a valid role in the truncation of the Arches MF at low masses.

4.6 REFERENCES

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