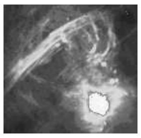

GCNEWS

The Newsletter of Galactic Center Research

Edited by Sera Markoff, Loránt Sjouwerman, Joseph Lazio, Cornelia Lang & Rainer Schödel

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email: gcnews@aoc.nrao.edu **http://www.aoc.nrao.edu/~gcnews/**

Orbits of Stars in the Central 1.5 x 1.5 arcsec^2

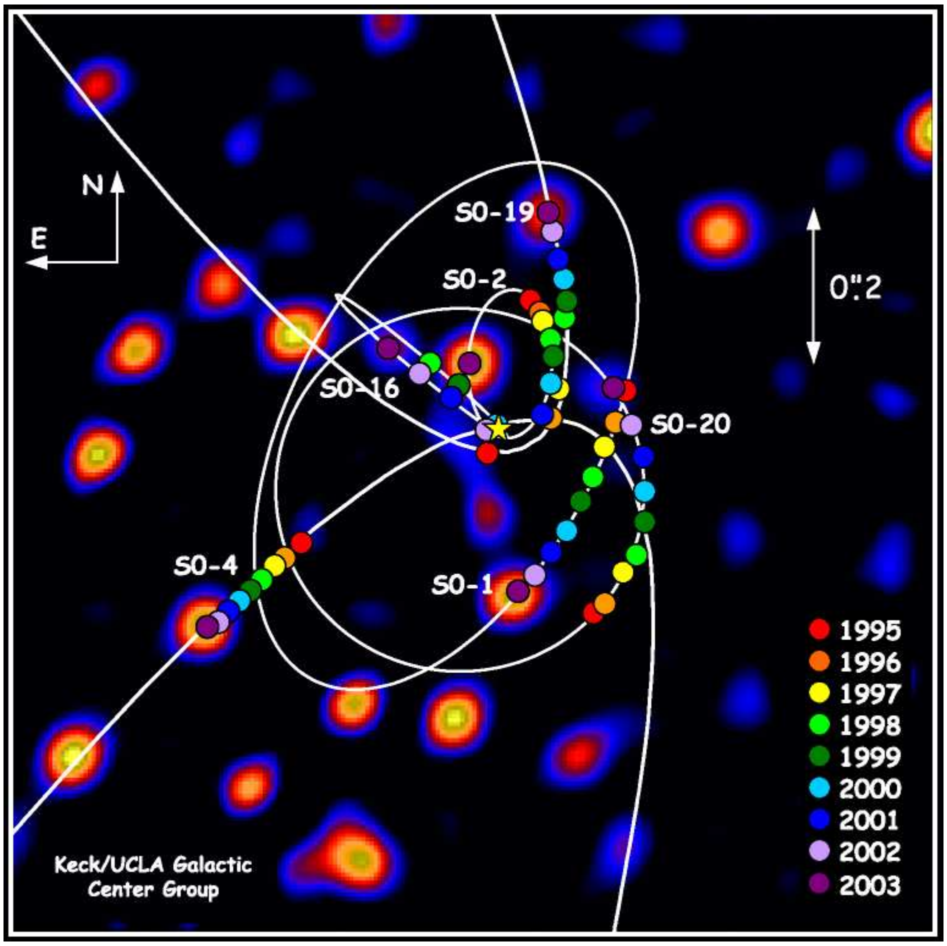

Figure 1 From Ghez's article. The central 1.5 arcsec x 1.5 arcsec of our Galaxy. In the background, an image of the stars taken in 2003 is displayed and, in the foreground, colored dots show the positions of some of these stars over almost a decade of time (multiple measurements are taken every year, but only the annual averages are shown here for clarity). Also plotted are the best fitting simultaneous orbital solutions. These orbits, and a simple application of Kepler's Laws, provide the best evidence yet for a supermassive black hole, which has a mass of 4 million times the mass of our Sun. Animated version of this can be found at `http://www.astro.ucla.edu/~jlu/gc/pictures/orbitsMovie.shtml`.

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In the News

Sera Markoff

Welcome to the first GCNEWs of 2004, the product of a rapidly growing collaboration. Along with the additions of Cornelia Lang and Joseph Lazio to the rotating editorial "crew", we are pleased to announce new European representation in the form of Rainer Schödel! We hope a Japanese member will soon follow, so stay tuned as we continue to develop. We would also like to take this moment to again thank Angela Cotera and Heino Falcke for all their hard work creating GCNEWs and keeping it running all these years.

The possibility of an IAU working group for the Galactic Center is also still in the works. Joseph has been in contact with Patricia Whitelock, president of the IAU Division VII: The Galactic System, regarding the possibility of bringing GCNews into the IAU. She has suggested that we form a working group focussed on low-luminosity galactic centers. Under the aegis of such a working group would be not only Sgr A* and its environs, but also M31*, M81*, and other such nearby objects. We welcome input on this possibility. Does it seem useful to form such a working group and try to explore the potential connections between nearby low-luminosity nuclei? Alternately, would such a working group, with its larger focus, dilute the impact of new discoveries in the Milky Way's Galactic center? We welcome your input and, if you favor the establishment of a working group, suggestions for a name.

In this Volume

If you have not already noticed, we have an extremely jam-packed GCNEWs this time around! Since our last issue, where we included the Ghez et al. abstract about Sgr A*'s dramatic identification in the infrared (IR), Genzel et al. reported their new results in Nature. The detections from both groups have dominated Galactic Center discussions ever since, and are generating a level of excitement on par with *Chandra's* X-ray discoveries a few years ago. Finally, there is a solid constraint on the "submm bump" emission in the IR, and now that they know where to look for it, we can expect simultaneous observations to really nail down Sgr A*'s quiescent and flaring broadband behavior. We are extremely pleased to be able to bring you summaries of these new results with back-to-back articles from both observing groups. Sgr A* has turned out to be as active in the IR as the X-rays, and the preliminary data show signs of a much shorter periodicity than the 106 day cycle seen in the radio (e.g. Zhao, Bower & Goss 2001, ApJ, 547, 29L). In addition to the articles here, the web addition has enhanced images and movies of some of the results, so please be sure to take a look at the online version: **http://www.aoc.nrao.edu/ gcnews/gcnews/Vol.17**.

In the Abstracts section, we also have an article by Zhao et al. reporting on a possible correlated radio/X-ray event, and a new detection of Sgr A* at low frequencies by Nord et al. Several groups have also reported new molecular and dust studies of the GC region, as well as one theoretical model paper suggesting we may be seeing signs of old Gamma-ray Bursts in our Galaxy via ultrahigh energy cosmic rays!

GC Conference Cameos

Sera Markoff & Joseph Lazio

Sgr A* has been getting a lot of press lately, especially because of the new results showcased in the next sections. In the following we summarize some of the GC-related results presented at conferences recently.

Sera had the pleasure of attending a small "Micro-Workshop on Sgr A*" at the Radcliffe Institute for Advanced Study last November. The meeting was an advanced seminar on the "Formation and Evolution of Stars Near the Galactic Center", organized by Andrea Ghez, Alyssa Goodman, Josh Grindlay and Ramesh Narayan, and which featured three days of in-depth discussion. Along with the organizers, speakers included Mark Reid, Mark Morris, Fred Adams, Volker Bromm, Frank Shu, Lee Hartmann, Tal Alexander, Jeremy Goodman, Brad Hansen, Milos Milosavljevic and Eve Ostriker. Eve did the conference summary talk, which is currently posted online in both slide and pdf format at: `http://cfa-www.harvard.edu/~agoodman/Presentations/Galactic_Center_03/`, and Radcliffe may be posting the rest of the talks so stay tuned.

The Micro-Workshop was chaired by Jim Moran, and contained both observational and theoretical talks about IR and submm variability in Sgr A*, and possible interpretations. The speakers included Ramesh Narayan, Fred Baganoff, Reinhard Genzel, Andrea Ghez, Jun-Hui Zhao, Feng Yuan and Sera. The IR results presented are the same as what we have in this volume, and please see the abstract by Zhao et al. for the radio flare.

There was also a strong GC presence at the winter AAS meeting in Atlanta (January 4–8). Some of these presentations built upon work described at the GC Workshop in Kona last year, while other presentations contained new material. We describe briefly those papers with a GC component at the AAS meeting, with apologies to anybody whose work we might have missed. We give the AAS paper number in parentheses at the end of each summary.

Papers can be grouped generally into a small number of topics. There were a number of studies of the interstellar medium in the GC.

- J. Hewitt et al. searched a number of supernova remnants, including Sgr A East, for OH(1720 MHz) maser emission, which is a sensitive probe of the interface between a SNR and a molecular cloud. (39.17)
- LaRosa et al. reported new observations of nonthermal filaments, showing new NTFs with unusual orientations, and suggesting that the GC magnetic field may not be ordered globally. (112.04)
- Staguhn et al. detected a significant amount of warm dust from submillimeter observations of AFGL 5376, a source likely associated with a large-scale shock and the GC Lobe. (112.09)
- Magnani et al. reported new 3.3 GHz observations of the CH molecule in the GC. They find that the CH and CO angular distributions also have similar velocity distributions. (112.21)

There is also a growing recognition of the importance of massive stars in the GC:

- De Pree et al. conducted a survey of UCHIIs, including those in the Sgr B2 region, as part of an effort to determine the initial mass function of massive stars. (76.04)
- Lang et al. reported multi-wavelength observations of the Quintuplet and Arches stellar clusters. These observations revealed a number of interactions between the stellar winds of members of the clusters as well as the effects of the clusters on their surroundings. (112.05)

The Chandra X-ray Observatory continues to be an important tool in observing the GC:

- As part of a Galactic plane survey in the X-ray (ChamPlane), Grindlay et al. and Laycock et al. surveyed Baade's window and a field toward the GC as part of a comparison of the population of accretion-powered X-ray sources in the GC versus that in the Galactic bulge. Zhao et al. conducted a deep optical(!) survey of the GC region. Their motivation was to identify X-ray counterparts, which they were able to do for many soft X-ray sources but they had considerably poorer success in finding optical counterparts for hard X-ray sources. The soft X-ray sources are likely to be foreground sources, while the hard X-ray sources could be in the GC. (99.04, 99.05, and 112.02)
- Muno et al. used a spectral analysis of a deep Chandra field centered on Sgr A* to study the diffuse X-ray emission. They find indications for a hot (8 keV), high-pressure environment in the central 40 pc (17'). (110.03)
- Hong et al. reanalyzed all of the Chandra data toward the GC with the aim of detecting as many compact, hard X-ray sources as possible. (112.03)

Of course Sgr A* continues to command attention as the closest example of a nearby supermassive black hole:

- Larson et al. investigated the extent to which gravitational waves could be produced by an interaction between a supermassive black hole, such as Sgr A*, and a compact object, such as a stellar-mass black hole, from the surrounding stellar cluster. (81.11)
- Nord et al. reported the lowest frequency detection to date of Sgr A*, at 330 MHz. (99.01)
- Broderick & Blandford investigated a number of mechanisms for forming circular polarization, such as has been detected from Sgr A*, near the event horizon of a supermassive black hole. (104.01)

Finally, the GC is playing an important role in astronomy education efforts. Ciccarelli & Maddalena are using 5 and 10 GHz observations of the GC with the Green Bank Telescope as the basis for an educational program to train future teachers and students about the different ways in which objects can radiate. (59.04)

On the Road Towards a Deeper Understanding of Sgr A* and its Environment

R. Schödel[1] , *R. Genzel*[2], *F. Baganoff*[3] *& A. Eckart*[1]
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The last two years have been enormously fruitful for our NIR GC research. The NIR camera/AO system CONICA/NAOS at the ESO VLT unit telescope 4 was commissioned in late 2001/early 2002. The excellent imaging quality of the VLT in combination with the Paranal site, where the GC passes close to zenith, and the superb performance of the AO system (with its unique NIR wavefront sensor) are an ideal combination for deep, high resolution (40 milli-arcseconds at 1.7μm) observations of the Milky Way's nuclear star cluster. Thanks to the new instrumentation we could finally confirm the existence of a stellar cusp around Sgr A*. Also, we can now measure stellar positions with an accuracy of $1-2$ mas and derive meaningful proper motions of stars within about 40 mpc of Sgr A* with a time base of just two years. Two breakthroughs of the last two years were the determination of the orbit of S2 and the discovery of NIR flares and quiescent emission from Sgr A*. Below, we summarize some of the most important recent results and provide some outlook on the new measurements to come soon. We also report on the first simultaneous NIR/X-ray measurements of the emission from Sgr A*.

1 Confirmation of the Stellar Cusp Around Sgr A*

Due to the inhomogeneous distribution of the few dozen brightest stars in the nuclear cluster the location of Sgr A* does not coincide with the peak of the light distribution (Allen & Sanders, 1986). However, with star counts based on deep, high-resolution NIR NACO/VLT images we could recently show with unprecedented accuracy that Sgr A* is indeed located (to $\pm 0.2''$ or about 8mpc) at the very center of the nuclear stellar cluster (Genzel et al., 2003; cf. also Scoville et al., 2003). Furthermore, we confirmed the existence of a stellar cusp within $\sim 1.5''$ around Sgr A*, as expected from theoretical considerations (e.g. Bahcall & Wolf, 1977, 1978; Young 1980; Murphy, Cohn, & Durisen, 1991) and indicated in earlier data (Alexander, 1999). The cusp follows a density law of the form

$$\rho(r) = 1.2 \times 10^6 \left(\frac{r}{10''}\right)^{-\alpha} \quad [M_\odot \mathrm{pc}^{-3}],$$

with $\alpha = 1.4 \pm 0.1$ (Genzel et al., 2003). With these numbers, the density is expected to exceed a few times 10^8 $M_\odot pc^{-3}$ at distances $\leq 0.1''$ from the central black hole.

We also found new evidence that the stellar population in the cusp has distinctive characteristics compared to the outer cluster: The cusp KLF displays a lack of RC/HB stars and of giant stars, which may be due to mass segregation and/or destruction of stellar envelopes in the dense environment (Genzel et al., 2003). There is also the now well known, enigmatic population of blue, early-type stars (e.g. Genzel et al., 1997; Eckart, Ott, & Genzel, 1999; Figer et al., 2000; Gezari et al., 2002) in the immediate surroundings of the black hole. Only recently, Ghez et al. (2003) could show that one of these stars has indeed the spectroscopic characteristics of an O-type star (confirmed by Eisenhauer et al., 2003). Currently, there exist no satisfactory models on how such stars can form at this location or migrate there during their lifetime. Alternatively, they might be a different class of objects, similar to blue stragglers (see the discussions in Ghez et al., 2003 and Genzel et al., 2003). Slit-spectroscopy is unfortunately notoriously difficult in the extremely dense nuclear star cluster. However, we can hope for breakthroughs with the AO integral-field spectrometer SPIFFI/SINFONI at the ESO VLT, which will be commissioned this year. Understanding the properties of the enigmatic stellar population in the cusp is certainly one of the most intriguing subjects of GC study in the near future, not only for observation (spectroscopy, stellar dynamics), but also for theory (e.g. importance of stellar collisions in the dense cluster with high velocity dispersion).

2 Dynamics of the Stars in the Cusp

2.1 Velocity Dispersion Measurements, Anisotropy

In the last decade, measurements of the velocity dispersion in the central star cluster brought strong evidence for the black hole nature of Sgr A* (Eckart & Genzel, 1996, 1997; Ghez et al., 1998; Genzel et al., 2000). However, compared to the recent estimates of the black hole mass through individual stellar orbits, $M_{BH} = 3.5 - 4.0 \times 10^6\ M_\odot$ (Schödel et al., 2002; Ghez et al., 2003; Schödel et al., 2003; Eisenhauer et al., 2003), the dispersion measurements resulted in lower mass estimates, around $2.6 \times 10^6\ M_\odot$. Although the reason for this discrepancy is not yet fully understood, we believe that it is most probably due to incomplete sampling of the cluster. A critical assumption of the statistical mass estimators is the availability of a sufficiently complete census of the stellar cluster. Earlier proper motion experiments (Eckart & Genzel, 1996, 1997; Ghez et al., 1998) included just around a dozen high-speed stars in the central cusp due to the use of poorer instrumentation (no AO), smaller telescopes and/or due to conservative approaches in data analysis.

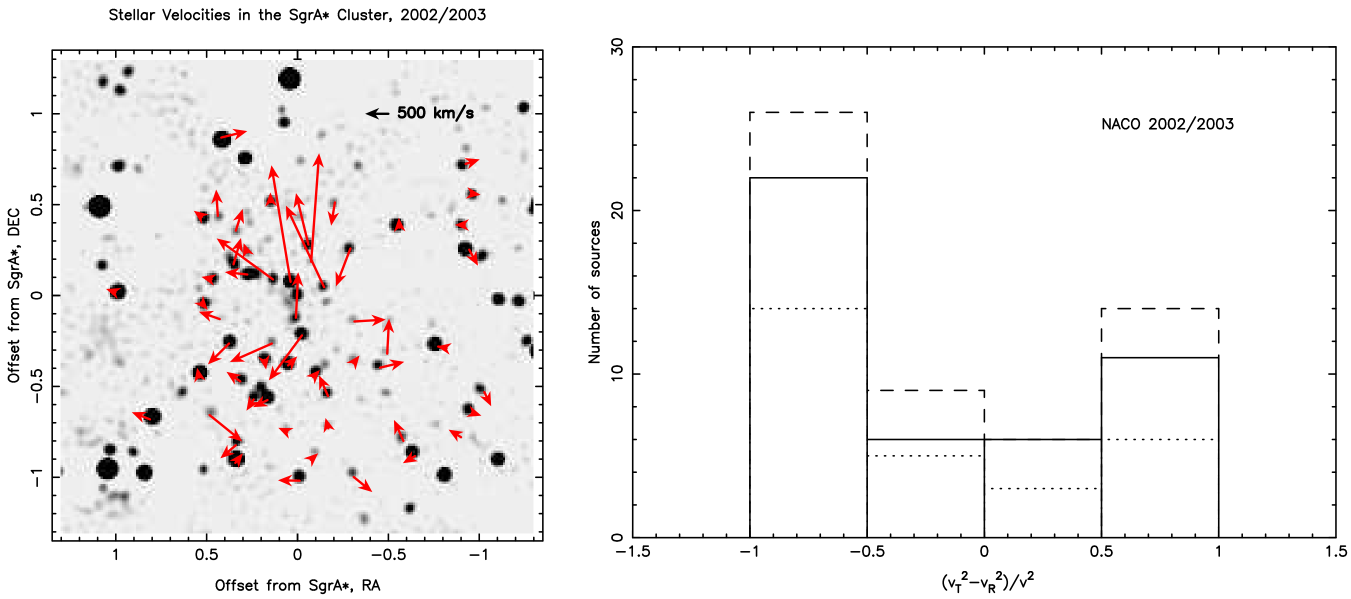

Figure 1 Left panel: Stellar velocities within 1.2″ of Sgr A*, derived from the NACO 2002/2003 imaging data, superposed on a NACO June 2003 LR deconvolved and beam restored K-band image. The source at the origin of the coordinate system is Sgr A* in a flaring state. Right panel: Histograms of the anisotropy parameter $\gamma_{TR} = (v_T^2 - v_R^2)/v^2$ for the proper motions shown in the left panel. v is the proper motion velocity and v_T and v_R are its projected radial and tangential components. Stars on radial orbits have $\gamma_{TR} = -1$, on tangential orbits$\gamma_{TR} = +1$ (see Genzel et al., 2000, for a discussion of the anisotropy estimator γ_{TR}). Dotted lines: Stars at projected distances $< 0.6''$ from Sgr A*; solid lines: stars at projected distances $< 1''$; dashed lines: stars at projected distances $< 1.2''$.

A recent, more rigorous approach by Schödel et al. (2003) resulted in an estimated enclosed dark mass of $3.4 \times 10^6\ M_\odot$. Also, the deep, high-resolution AO GC images obtained with NACO/VLT since early 2002 allow pinpointing the location of the brighter ($m_K \leq 17$) stars within 1″ of Sgr A* with an accuracy of the order ≤ 2 mas, which allows for extracting proper motions with a time base of just two years. The measured proper motions (based on 5 epochs of observations) are shown in the left panel of Figure 1 and represent so-far the most complete sample. The enclosed mass, estimated with a Leonard-Merritt mass estimator is $4.0 \pm 0.8\ M_\odot$.

These recent works support our assumption that the earlier, lower mass estimates were due to incomplete sampling. One must also keep in mind the possible influence of other factors such as the slope of the central cluster (for an ample discussion, see Genzel et al., 2000), which leads to additional correction factors. However, these corrections are of the order $\leq 10\%$.

Due to the enormous stellar number density in the cusp the nuclear cluster should relax rapidly via two-body collisions and display an isotropic velocity structure. Nevertheless, Genzel et al. (2000) found some indications of a prevalence of radial orbits in the cusp, which could be confirmed by the work of Schödel et al. (2003). Our newest, most complete proper motion data set (about 50 stars within 40 mpc of Sgr A*) still supports the weak $(2 - 3\sigma)$ but consistent finding of radial anisotropy (right panel in Figure 1). We find an anisotropy parameter $\langle\beta\rangle = 1 - \langle\sigma_t^2\rangle/\langle\sigma_r^2\rangle = 0.6 \pm 0.05$ (Schödel , 2004). Of course, this finding might be due to small number statistics and/or reflect a perhaps random property of just the few brightest stars in the cluster (also, the error might be

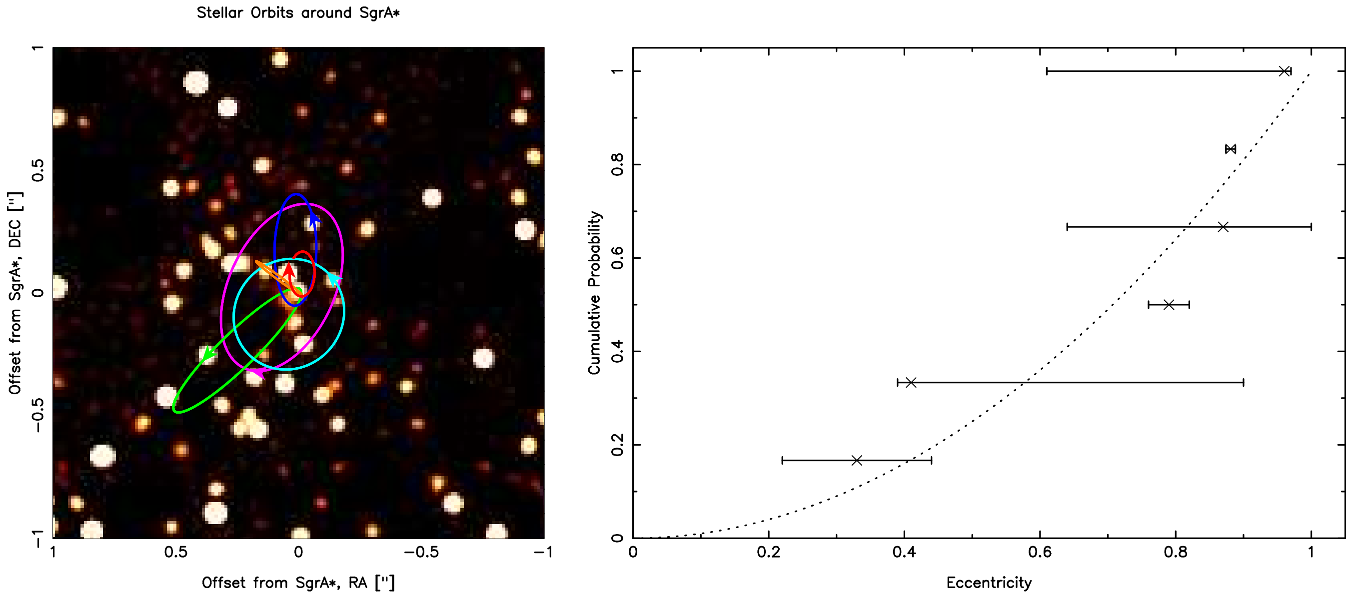

Figure 2 Left panel: Lucy-Richardson deconvolved and beam-restored high-resolution (FWHM$\sim$ 60 milliarcseconds) near-infrared (2.2μm) image of the central $1'' \times 1''$ of the nuclear stellar cluster. The image was obtained with CONICA/NAOS at the ESO VLT in June 2003. On this image Sgr A* can be seen in its flaring state as a point source at the origin of the coordinate system. The Keplerian orbits of six stars, as they were determined by a decade of continued observations, are over-plotted onto the image. Arrows indicate the locations of the respective stars and their direction of motion. Right panel: Dotted line: Cumulative probability distribution function of the eccentricities of test particles orbiting a point mass in a spherical, isotropic system. The crosses and their error bars mark the eccentricities measured for the 6 stars S1, S13, S12, S14, S2, and S8 (starting at the lowest eccentricity).

underestimated due to systematic errors not taken into account). On the other hand, should the anisotropy be confirmed further, it might give us a – not yet understood – clue to the formation of the cusp or some of its constituents.

2.2 Individual Orbits

The determination of Keplerian orbits of individual stars around Sgr A* in the last two years was an enormous breakthrough. Above all, the orbit of the star S2 has been measured with high accuracy It allowed to exclude dark cluster or fermion ball alternatives to the black hole scenario with high confidence, to measure the black hole mass independent of any statistical assumption, and to locate its position with an accuracy of < 2 mas (Schödel et al., 2002, 2003; Ghez et al., 2003). Calculating the position (and its uncertainty) of S2 relative to Sgr A* in 2002.3 with the orbital elements given by Ghez et al. (2003, astro-ph/0306130) and by Eisenhauer et al. (2003), we obtain a relative offset of the dynamical center of the first solution from the latter one of 0.0 ± 2.9 mas E and 0.8 ± 2.0 mas N. This means that the two groups' results are in excellent agreement and that the position of Sgr A* is now known with an accuracy of ~ 1 milli-arc-second.

Eisenhauer et al. (2003) used the orbit of S2 for the first geometrical determination of the distance to the Galactic Center, R_0. Consistent with earlier indirect distance estimates, they found a value $R_0 = 7.9 \pm 0.4$ kpc and a black hole mass of 3.6 ± 0.6 $M_\odot$ (including the uncertainty of the distance).

Ghez et al. (2003a) and Schödel et al., 2003/Schödel 2004 determined and/or constrained the orbits of an additional five stars near Sgr A*. Although these orbits are not known as accurately as the orbit of S2, they provide, for the first time, direct – i.e. without any statistical assumptions – insight into the dynamics of the cluster. As for the distribution of the orbital eccentricities, they agree with an isotropic cluster, but cannot exclude radial anisotropy due to the large uncertainties and due to the limited number of stars with observed orbital motion. We show the cumulative probability function of the eccentricities along with the theoretical distribution for a cluster in the potential of a point mass in the right panel of Figure 2 (taken from Schödel 2004). Schödel et al. (2003) showed that one can generally expect an overall slight bias toward discovering orbits with eccentricities $e \geq 0.9$ in the cusp.

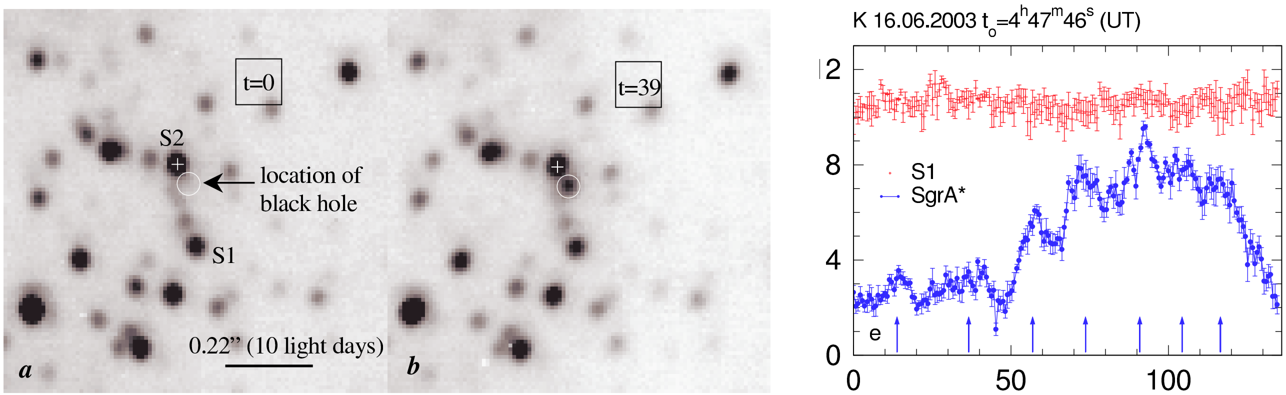

Figure 3 Left panel: First detection of a NIR flare of Sgr A* with NACO/VLT on May 9, 2003,in the H-band (1.7μm). The flaring source is easily detected in the right image, that was taken 39 min after the left image. The position of the flare is offset a mere -1.4 ± 3.0 mas in R.A. and -0.2 ± 3.0 in Dec. from the dynamical position of Sgr A*. The star S2 is marked by a cross, the position of Sgr A* is indicated by a white circle. Right panel: De-reddened light curve of a Sgr A* NIR flare on June 16, 2003, observed with NACO/VLT. For comparison, the steady emission of the star S1 near Sgr A* is shown in the plot (red data points). Arrows in the plot of the K-band flare indicate substructure peaks of the flare.

However, since all the orbits (with perhaps one exception) have semi-major axes $a < 20$ mpc (Schödel , 2004), they might rather be biased toward lower eccentricities.

The latest development in the analysis of individual orbits is using the available proper motion information to fit all orbits simultaneously and thus gain additional information, e.g. on the proper motion (or rather lack thereof) of Sgr A* relative to the surrounding cluster of stars (see Ghez et al., astro-ph/0306130).

3 Emission from Sgr A*

When observing the GC with the ESO NACO/VLT on the night from the 8th to the 9th of May, 2003, we experienced the perhaps most exciting event since the start of our GC monitoring program in 1991: We observed live on the real-time display how Sgr A* flared within a few minutes by a factor of 5 and faded again rapidly some 40 minutes later (left panel in Figure 3). For more than a decade we had been waiting for an event like this to happen! The position of the flare was coincident with Sgr A*, with an offset of -1.4 ± 3.0 mas in R.A. and -0.2 ± 3.0 in Dec. from the position of Sgr A* as determined from the orbit of S2. In subsequent observations in June we detected another 2 flares and found an additional one in a retrospective analysis of the data from 2002. With a total of four flares observed at wavelengths between 1.7 and 3.8μm we estimated a flaring rate (assuming Poisson statistics) of 2 to 6 flares per day. Also, we detected a variable 'quiescent' source at the position of Sgr A*. Our results were published in *Nature* in October 2003 (Genzel et al., 2003a). Independently, A. Ghez and collaborators reported the detection of a variable source at the position of Sgr A* at 3.8μm with the Keck telescope (Ghez et al., 2003, astro-ph/0309076, who also report on more than 6 orbits).

The short rise-and-fall time scales (≤ 5 min) of the flares suggest that they come from within 10 Schwarzschild radii of the black hole. They have durations between 40 and 85 min, similar in scale to the X-ray flares (Baganoff et al., 2001). As for the SED of the flares, it is not well constrained in the NIR regime because we do not have any simultaneous measurements at different wavelengths so far. There is some indications that the flares have a blue color in the NIR regime (Genzel et al., 2003a). Should this prove to be true, then this would pose a serious problem for current theories of Sgr A* emission. In that case, the flares might be related to individual accretion events.

Most intriguingly, in two flares observed 24h apart in June 2003, we detected 17 min quasi-periodic oscillations (Figure 3, right panel). The oscillations have a frequency that is higher than the orbital frequency at the last stable orbit around a Schwarzschild black hole and suggest that we might have witnessed emission from material near the last stable orbit of a Kerr black hole. We determined a lower limit for the black holes spin of $a = J/(GM_{BH})/c = 0.52(\pm0.1, \pm0.08, \pm0.08)$, where G is the gravitational constant, M_{BH} the mass of the black hole, J its spin, and c the speed of light. The errors in brackets include the influence of the uncertainties of M_{BH}, the flare modulation frequency, and the distance to the GC. Should the quasi-periodicity of the flares be confirmed by upcoming observations then

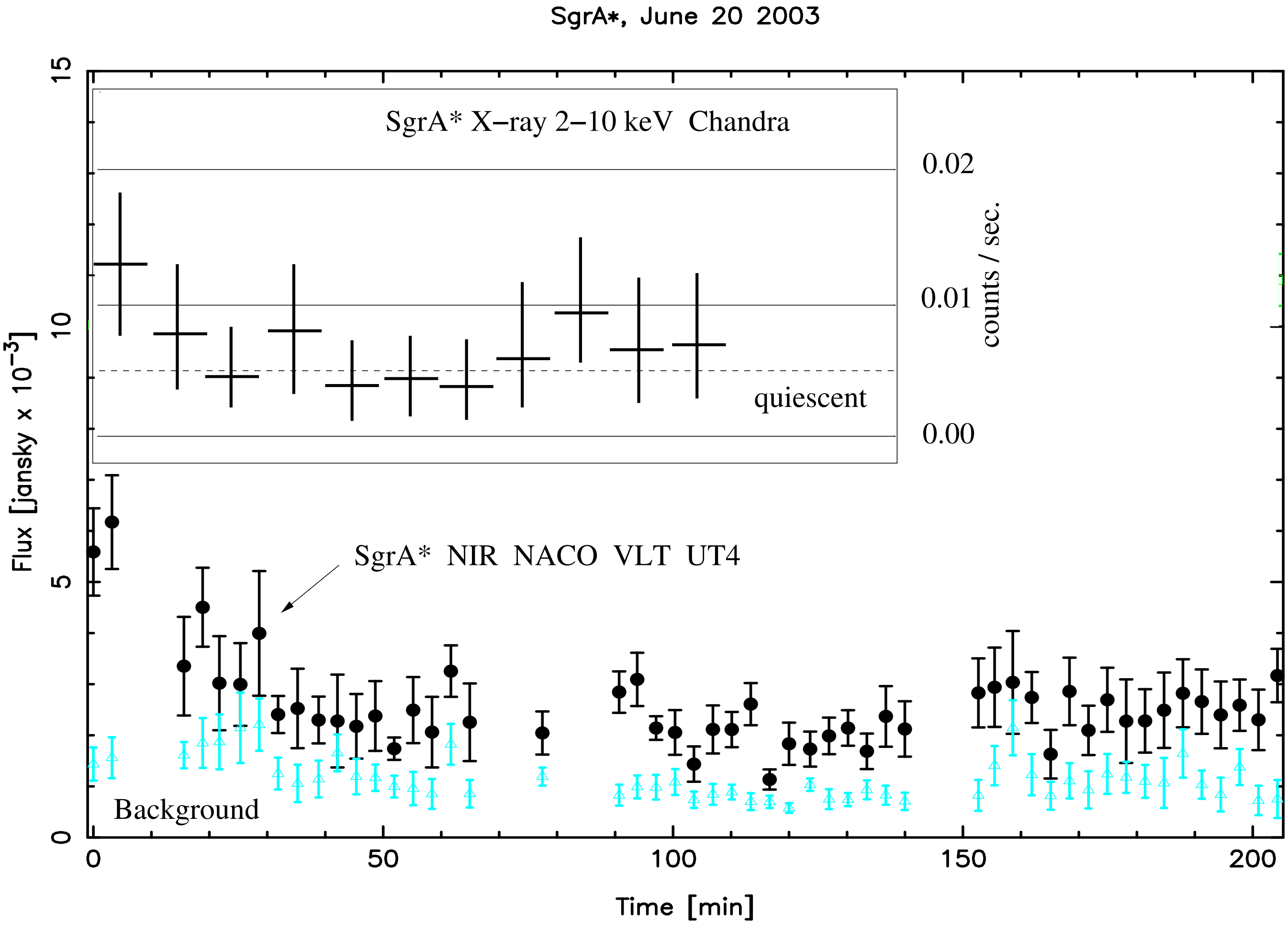

Figure 4 NIR flux variation of Sgr A* during the coordinated Chandra/VLT observations of the GC by Eckart, Morris, Baganoff, Schödel et al. (in preparation 2004). The X-ray and NIR light curves plotted with a common time axis. X-ray light curve as observed by the Chandra Observatory. Straight solid lines in the inserted box represent the 0.00, 0.01, and 0.02 counts per second levels. The straight dashed line represent the X-ray IQ-state flux density level. The lowest light curve (triangles with error bars) show the fluctuation of the flux in a random region of the image without significant source detection. The observations started on 20 June 2003 at 00:16:51.50 (UT).

we could, for the first time, directly measure fundamental properties of our Milky Way's central black hole apart from its mass.

A decisive question for the emission mechanism is the relation between the flares at X-ray and NIR wavelengths. In an upcoming paper Eckart, Baganoff, Morris, Schödel et al. report on the first simultaneous near-infrared/X-ray detection of the SgrA* counterpart (Figure 4). The observations were carried out using the NACO adaptive optics instrument at the ESO VLT and the ACIS-I aboard the Chandra X-ray observatory. A fading flare of Sgr A* with >2 times the interim-quiescent flux was detected at the beginning of the NIR observations. This flare was also detected in the X-domain with a 2 - 10 keV luminosity of about 6×10^{33} erg/s. The data therefore represent the first simultaneous NIR/X-ray measurement of the interim-quiescent and flaring state of SgrA*. They find that the flaring state can be conveniently explained with a synchrotron self-Compton model involving up-scattered sub-millimeter photons from a compact source component showing bulk relativistic motion. The size of that component is assumed to be of the order of the Schwarzschild radius. The overall spectral indices $\alpha_{NIR/X-ray}$ ($S_\nu \propto \nu^{-\alpha}$) of both states are quite comparable with a value of $\sim$1.3. Since the interim-quiescent X-ray emission is extended, the spectral index for the interim-quiescent state is probably only a lower limit for the compact source Sgr A*. A conservative estimate of the upper limit of the time lag between the end of the NIR and X-ray flare is of the order of 15 minutes.

4 New Insights Might Wait Around the Corner!

Very soon, the new GC season will start, with several coordinated radio/sub-mm/X-ray/NIR observing campaigns readily planned. The key question that will be addressed is the frequency and amplitude of the variability of Sgr A* observed simultaneously at different wavelengths. The new observations will provide essential and strong constraints for theoretical models of Sgr A* accretion and emission.

As concerns NIR observations, we are of course highly interested in measuring the flux of the Sgr A* counterpart at various wavelengths with as little time delay as possible. Polarization measurements will provide additional important information on the accretion flow/ejected material. We feel, however, that currently the most exciting aspect of the black hole emission remains the quasi-periodicity of the flares and strongly hope to confirm it.

Parallel to the work on Sgr A* we will of course continue our analysis of the stellar population and its dynamics. Possibly, the coming season will see the first SINFONI/SPIFFI/VLR AO integral-field spectroscopic observations of the Sgr A* cluster that will provide a wealth of new and essential information on the nature and 3D-dynamics enigmatic population of apparently young stars near the black hole.

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Recent Advances Made with a Decade of Diffraction -Limited Data From the W. M. Keck 10m Telescopes

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1 Introduction

The proximity of our Galaxy's center presents an opportunity to build a case for a supermassive black hole and to study the black hole's environment and its effects thereon with much higher spatial resolution than can be brought to bear on any other galaxy. In this contribution, I've reviewed the progress that has been made based on data obtained at the W. M. Keck 10 m telescope. More images and animations can be found at: `http://www.astro.ucla.edu/research/galcenter/`.

After almost a decade of astrometry from diffraction-limited speckle imaging, we have moved the case for a supermassive black hole at the Galactic Center from a possibility to a certainty. Thanks to our recent ability to determine the orbits of individual stars, we have confined the central dark mass of 4 million times the mass of the sun to within 90 AU, or equivalently, 1,000 Schwarzschild radii (see §2 & Figure 1, on the cover and `http://www.astro.ucla.edu/~jlu/gc/pictures/orbitsMovie.shtml`). With the advent of adaptive optics, we have significantly expanded our studies of the Galaxy's central black hole through the addition of diffraction-limited spectroscopy and deep imaging at wavelengths other than 2.2 microns (for animation of the benefits of Adaptive Optics for studies of the Galactic Center see `http://www.astro.ucla.edu/~jlu/gc/pictures/aoMovie.shtml`). Spectroscopy has revealed that the stars orbiting in such close proximity are apparently massive and young; the origin of these stars is difficult to explain, given the strong tidal forces, and may provide key insight into the growth of the central black hole (see §3.1 & Figure 2). Further insight into the origin of a slightly different population of young stars, the He-I emission line stars, has come from a number of spatially resolved bowshocks (see §3.2 & Figure 3). Thermal infrared imaging (3.8 microns) has led to the direct detection of plasma associated with the central black hole. This source is variable on timescales as short as 40 min, implying that the emission arises quite close to the black hole, within 5 AU, or 80 Schwarzschild radii and providing a new, constantly accessible, window into the physical conditions of the plasma in close proximity to the central black hole (see §4 & Figure 4, also `http://www.astro.ucla.edu/~jlu/gc/pictures/sgraMovieLp.shtml`).

2 Stellar Proper Motions: The Case for a Supermassive Black Hole

Significant progress on mapping out the distribution of dark matter at the center of the Milky Way has been made recently with diffraction-limited near-infrared studies of the central stellar cluster. The first phase of these experiments yielded proper motion velocities (Eckart & Genzel 1997; Ghez et al. 1998; Genzel et al. 2000), which suggested that $\sim 3 \times 10^6 M_\odot$ of dark matter is confined to within 0.015 pc. This increased the implied minimum dark matter density by 3 orders of magnitude to $10^{12} M_\odot/pc^3$ and eliminated a cluster of dark objects as a possible explanation of the Galaxy's central dark mass concentration (Maoz et al. 1998), but still left the fermion ball hypothesis (e.g., Tsiklauri & Viollier 1998) as an alternative to a single supermassive black hole. The velocity dispersion measurements also localized the dark matter's centroid to within 100 mas and at a position consistent with the nominal location of the unusual radio source Sgr A* (Ghez et al. 1998), whose emission is posited to arise from accretion onto a central supermassive black hole (e.g., Lo et al. 1985). The detection of acceleration for three stars – S0-1, S0-2, and S0-4 – directed towards the same center, localized the dark mass to within 30 mas, increased the dark matter's minimum density to $10^{13} M_\odot/pc^3$, and thereby further strengthened both the case for a supermassive black hole and its association with the radio source Sgr A* (Ghez et al. 2000; Eckart et al. 2002).

Deviations from linear motions also initiated a new phase for these proper motion experiments - that of direct orbital studies. By making a number of assumptions, including fixing the central mass to the value obtained from the velocity dispersion analysis and its location to that inferred for Sgr A* by Menten et al. (1997), Ghez et al. (2000) and Eckart et al. (2002) obtained first crude orbital solutions; these experiments revealed that orbital periods for S0-2 and S0-1 could be as short as 15 and 35 years, respectively. With more of the orbit being traced, more precise orbital analyses have been carried out for S0-2 by Schödel et al. (2002), who dropped the mass assumption, and by Ghez et al. (2003) and Eisenhauer et al. (2003), who dropped both the mass and center of attraction assumptions and added radial velocity measurements. Most recently, we've carried out an analysis in which the orbits for multiple (8) stars are derived *simultaneously* so that they jointly constrain the central dark object's properties: its mass, its position and, for the first time using orbits, its motion on the plane of the sky (Ghez et al. 2004b). This analysis pinpoints the Galaxy's central dark mass to within 1.5 milli-arcsec (mas) and limits its proper motion to 0.8 ± 0.7 mas y^{-1} with respect to central stellar cluster. This localization of the central dark mass is consistent with our derivation of the position of the radio source Sgr A* in the infrared reference frame (± 7 mas), but with an uncertainty that is a factor 5 times smaller, which greatly facilitates searches for near infrared counterparts to the central black hole. The estimated central dark mass from orbital motions is $(4.0 \pm 0.3) \times 10^6 (\frac{R_o}{8kpc})^3 M_\odot$; this is a more direct measure of mass than those obtained from velocity dispersion measurements, which are as much as a factor of two smaller. Also, for the first time, the limiting source of uncertainty in the absolute mass is R_o, the Galactic center's distance, which adds an additional 19% uncertainty in the estimated mass. For stars in this sample, the closest approach is achieved by S0-16, which confines the mass to within a radius of a mere 90 AU (= 0.0004 pc = 1,000 R_{sh}) and increases the inferred dark mass density by four orders of magnitude compared to earlier analyses based on velocity and acceleration vectors, making the Milky Way the strongest existing case for a supermassive black hole at the center of any normal type galaxy.

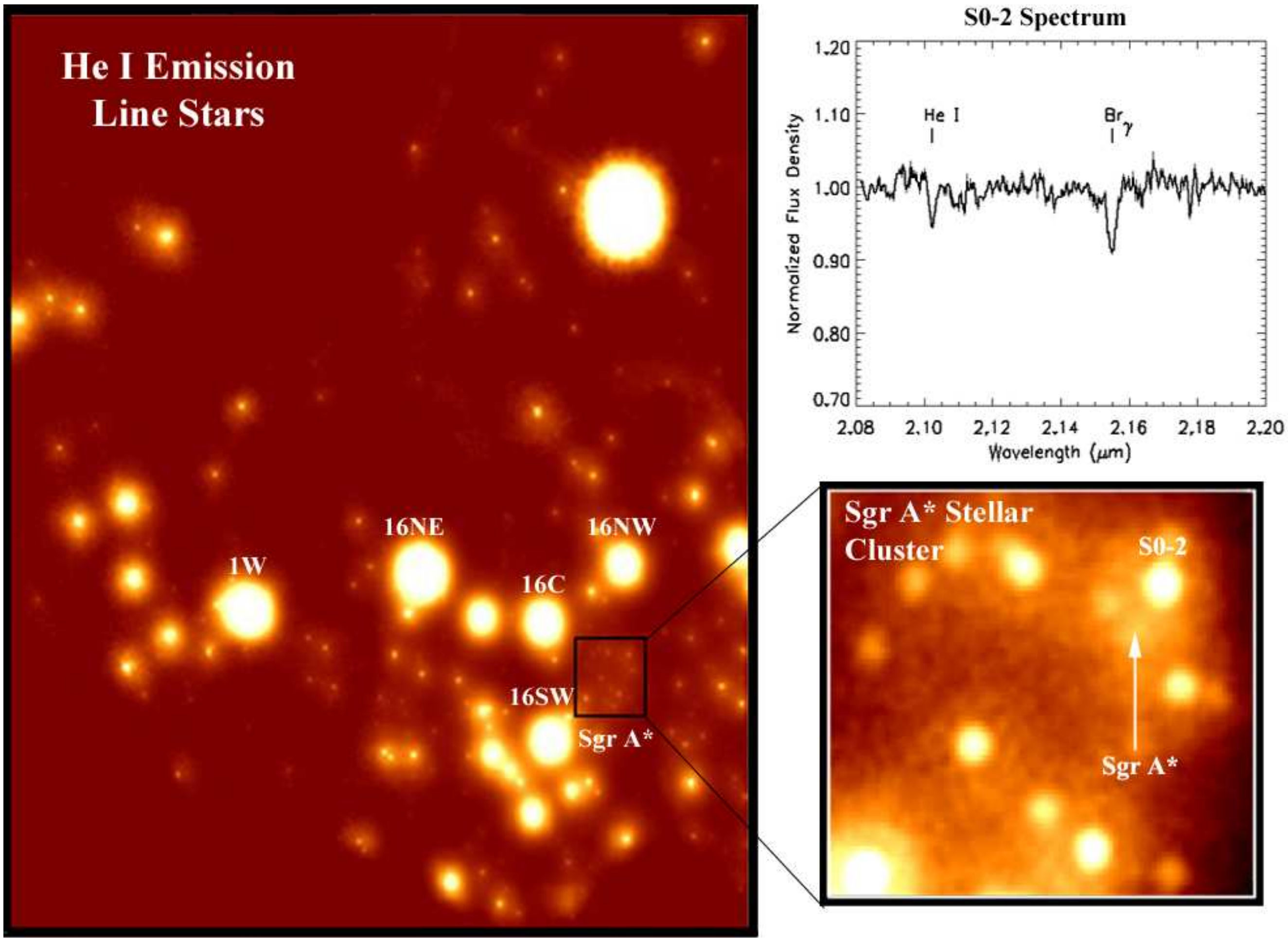

Figure 2: *Left* A 7″ × 10″ K-band image scaled to show the location of the closest He-I emission line stars, which were the first stars to raise the debate of how star formation might proceed in the vicinity of the black hole. *Bottom Right* A blow-up of 1″ × 1″ region containing the Sgr A* cluster, a region centered on the black hole which shows a stellar density enhancement and which contains stars that appear to be young and massive, that are an order of magnitude closer to the central black hole than the He-I stars, dramatically amplifying the problem of star formation in the vicinity of a black hole. *Top Right* A spectrum of S0-2, which shows features that are consistent with an O9 main-sequence star.

3 A Paradox of Youth

3.1 Stellar Spectroscopy in the central $1'' \times 1''$

With the introduction of an adaptive-optics-fed spectrometer on the W. M. Keck 10 m telescope, we have obtained the first detection of spectral absorption lines in one of the high-velocity stars in the vicinity of the Galaxy's central supermassive black hole (see Figure 2; Ghez et al. 2003). Both Br γ (2.1661 μm) and He I (2.1126 μm) are seen in absorption in S0-2 with equivalent widths (2.8 $\pm$ 0.3 Å & 1.7 $\pm$ 0.4 Å) and an inferred stellar rotational velocity (220$\pm$40 km/s) that are consistent with that of an O8-B0 dwarf, which suggests that it is a massive ($\sim$15 $M_\odot$), young (<10 Myr) main sequence star. Less direct measurements of other stars within the central $1'' \times 1''$, which are known collectively as the Sgr A* stellar cluster, imply that these stars might be similarly young; specifically, their similar 2 μm luminosities and the lack of CO absorption in spectra of individual stars (Genzel et al. 1997; Gezari et al. 2002) or in integrated spectra of the Sgr A* stellar cluster (Eckart, Ott, & Genzel 1999; Figer et al. 2000) lead one to conclude that they, like S0-2, have hot photospheres consistent with massive young stars.

While the presence of young stars in close proximity to the Galactic black hole has long been recognized as a problem in the context of the young He I emission line stars (Sanders 1992, Morris 1993), this problem is much worse for the Sgr A* cluster stars, whose distances from the black hole are an order of magnitude smaller. At S0-2's apoapse distance of 0.01 pc, inferred from the orbital solutions, the Roche density is 10^{14} cm^{-3}, whereas the maximum density determined for even the nearby circumnuclear disk, located at radii of $\sim$ 1-3 pc, is only about 10^5 cm^{-3} (e.g., Jackson et al. 1993). Furthermore, at present, the region over which S0-2 is currently orbiting contains only a very low-density plasma, as evidenced by weak Br-γ line emission (Figer et al. 2000; Gezari et al. 2002). It is therefore challenging to form these stars given the tremendous tidal forces presented by the black hole. Several ideas proposed to account for the apparently young He I emission line stars may be applicable to the Sgr A* cluster stars; 1) that the early-type stars are the result of stellar mergers in this dense environment (Lee 1996; Genzel et al. 2003a), 2) that they are exotic objects masquerading as normal stars (Morris 1993; Alexander & Morris 2003), 3) that they were formed by a cataclysmic compression of an already dense cloud which wandered into this region (Morris 1993; Levin & Beloborodov 2003), and 4) that they were formed elsewhere as part of a massive cluster, but migrated inwards rapidly by dynamical friction Gerhard 2001; Kim & Morris 2003; Portegies-Zwart, McMillian & Gerhard 2003; Hansen & Milosavljevic 2003). None of these possibilities is altogether satisfactory, leaving the stars in the Sgr A* cluster as a paradox of apparent youth in the vicinity of a supermassive black hole.

3.2 Spatially Resolved Bowshocks Reveal the True Orbits of He-I Emission-Line Like Stars

Our diffraction-limited images have resolved the mystery of an enigmatic class of cool, featureless sources known as the "Northern Arm sources", due to their coincidence with the Northern Arm structure of gas and dust orbiting/infalling towards the central black hole. The detected bowshocks reveal these sources to be O/WR stars, which are massive young stars - analogous to the He-I emission line stars observed at comparable radii, that are plowing through the Northern Arm (Tanner et al. 2002, 2003, 2004). This increases the population of young massive stars within the central parsec, but more importantly, the bowshock geometry, their association with the Northern Arm, and their measured proper motions provide 6 phase-space coordinates, allowing us, for the first time, to test the hypothesis that this population of stars falls within two planes (Levin & Beloborodov 2003; Genzel et al. 2003b); these observations are not entirely consistent with the two-plane hypothesis (Tanner et al. 2004).

4 Infrared Detection of Sgr A*

Our investigations into Sgr A* began with searches in our 36 nightly 2.2 μm maps for possible counterparts to the $\sim$3 hour flares detected by *Chandra* (Hornstein et al. 2002, 2003) [1] More recently, we have detected Sgr A* at L'(3.8 μm) with the W. M. Keck II 10-meter telescope (Ghez et al. 2004a). On four separate nights, its observed L' magnitude ranges from 12.2 to 13.8, which corresponds to a dereddened flux density of 4 - 17 mJy; no other source in this region shows such large variations in flux density - a factor of 4 over a week and a factor of 2 over 40 min. At these wavelengths, we did not detect a quiescent or steady state level; if it exists, it has to be below 4 mJy. In addition, it has a K-L' color greater than 2.1, which is at least 1 mag redder than any other source detected at L' in

[1] The lack of a detection in these earlier maps are inconsistent with flares of the amplitude reported by Genzel et al. 2003 occurring 4-6 times a day, which may suggest that Sgr A* is more active now than it has been in the recent past. Furthermore a few of these non-detections are below the current 2.2 μm "quiescent" level.

its vicinity. Based on this source's coincidence with the Galaxy's dynamical center, its lack of motion, its variability, and its red color, we conclude that it is associated with the central supermassive black hole. The short timescale for the 3.8 μm flux density variations implies that the emission arises quite close to the black hole, within 5 AU, or 80 R_s. We suggest that both the variable 3.8 μm emission and the X-ray flares arise from the same underlying physical process, possibly the acceleration of a small populations of electrons to ultrarelativistic energies. In contrast to the X-ray flares which are only detectable $\sim$2% of the time (e.g., Baganoff et al. 2001; Goldwurm et al. 2003), the 3.8 μm emission provides a new, constantly accessible, window into the physical conditions of the plasma in close proximity to the central black hole. This coming year is likely to bring many more exciting results on the variability of radiation from Sgr A* with several coordinated campaigns planned, involving facilities covering the X-ray, infrared, sub-mm, and radio portions of its spectrum.

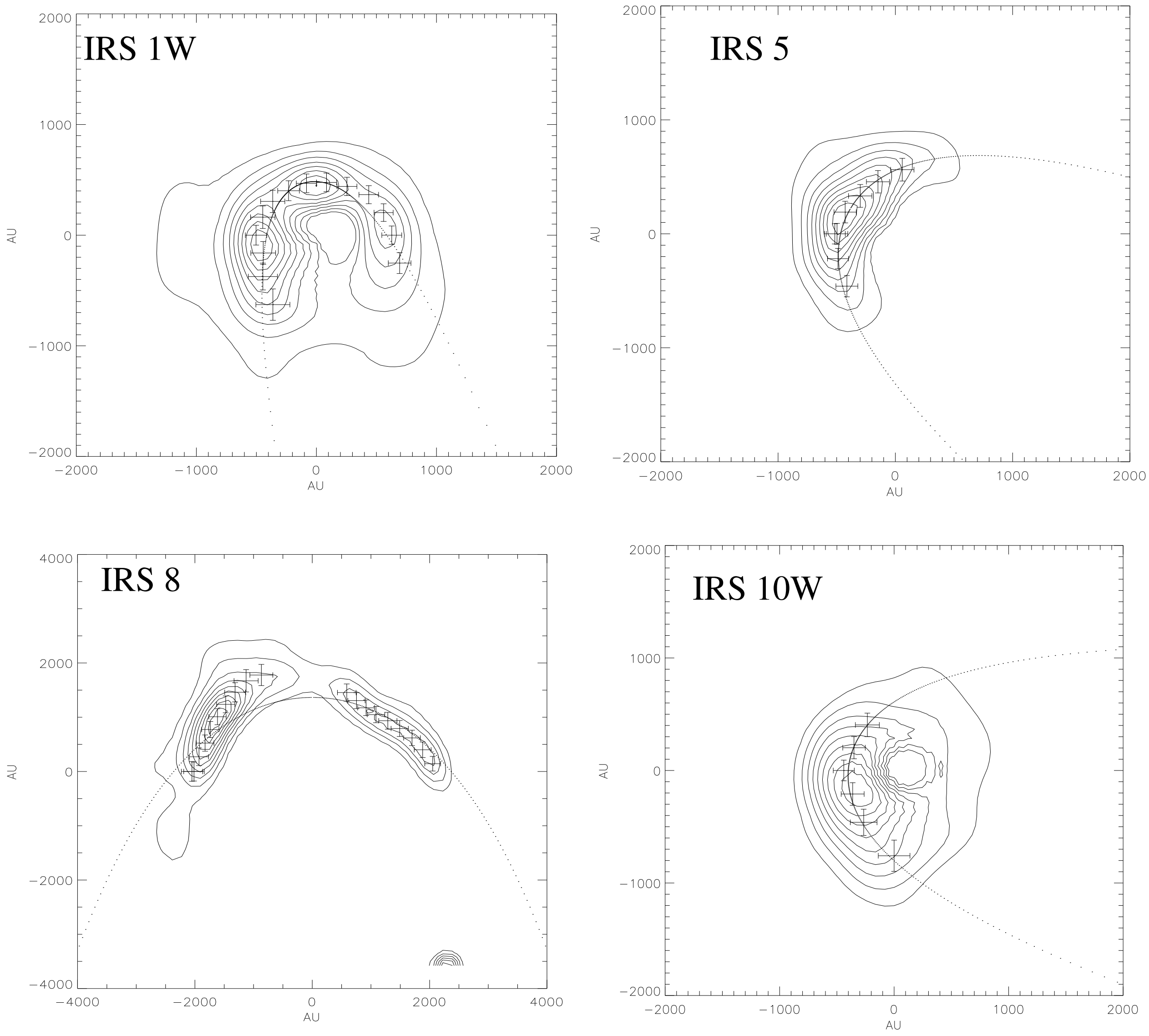

Figure 3: Spatially resolved structure detected around Northern Arm Sources. These observations are consistent with bowshocks (the dotted lines are the best fits to the data with a simple model of a projected bowshock) generated by stars with luminosities and outflow properties comparable the broad-line He-I emission line stars as they plow through the flow of the Northern-Arm material. When combined with a model of the Northern Arm flow and proper motion measurements, this provides estimates of the 3 dimensional radius and velocity vectors and thus an estimate of the 3 dimensional orbits for IRS 1W and 10W.

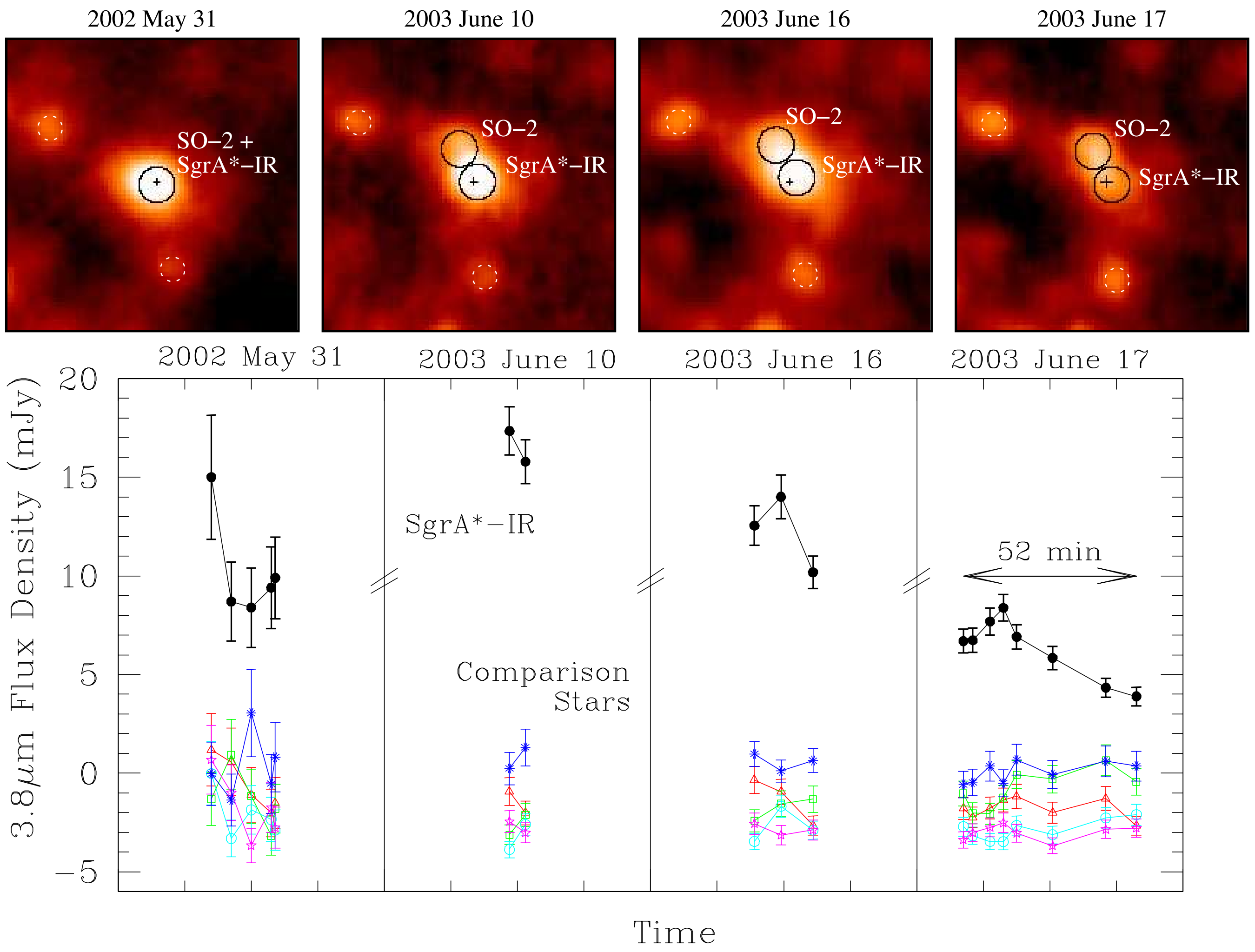

Figure 4: *(Top)* A 1.2″ × 1.2″ region of the L'(3.8 μm) Galactic center images obtained with the adaptive optics systems on the W. M. Keck II 10-meter telescope during the nights of 2002 May 31, 2003 June 10, 2003 June 16, and 2003 June 17. In each image, a cross denotes the dynamically determined position of the central black hole and its uncertainties. An L' source, SgrA*-IR, is coincident with this position in all images; while in 2002 SgrA*-IR is blended with the stellar source S0-2, S0-2's significant orbital motion makes it well resolved from SgrA*-IR in the 2003 images. Clear intensity variations are detectable in these nightly images, in which SgrA*-IR is at its brightest in 2003 June 10, when it dominates over S0-2, and its faintest in 2003 June 17, when it is somewhat dimmer than S0-2. *(Bottom)* Dereddened 3.8 μm flux densities for SgrA*-IR and 5 nearby stellar sources of similar brightness. A panel of 80 minutes for each of the four nights of observations is shown. The comparison sources are S0-1 (cyan circles), S0-3 (red triangles), S0-4 (green squares), S0-6 (blue asterisks), and S0-11 (magenta stars); a 8 mJy offset has been subtracted from their measured flux densities. While the stellar sources show no significant variation, SgrA*-IR has varied by a factor of 4 over the course of a week, 2003 June 10-17, and a factor of 2 within 40 minutes on the night of 2003 June 17. An animation of this data set can be found at `http://www.astro.ucla.edu/~jlu/gc/pictures/sgraMovieLp.shtml`.

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Abstracts

From the Circumnuclear Disk in the Galactic Center to thick, obscuring tori of AGNs

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We compare three different models of clumpy gas disk and show that the Circumnuclear Disk (CND) in the Galactic Center and a putative, geometrically thick, obscuring torus are best explained by a collisional model consisting of quasi-stable, self-gravitating clouds. Kinetic energy of clouds is gained by mass inflow and dissipated in cloud collisions. The collisions give rise to a viscosity in a spatially averaged gas dynamical picture, which connects them to angular momentum transport and mass inflow. It is found that CND and torus share the same gas physics in our description, where the mass of clouds is 20 - 50 $M_\odot$ and their density is close to the limit of disruption by tidal shear. We show that the difference between a transparent CND and an obscuring torus is the gas mass and the velocity dispersion of the clouds. A change in gas supply and the dissipation of kinetic energy can turn a torus into a CND-like structure and vice versa. Any massive torus will naturally lead to sufficiently high mass accretion rates to feed a luminous AGN. For a geometrically thick torus to obscure the view to the center even super-Eddington accretions rates with respect to the central black hole are required.

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Odin observations of H_2O in the Galactic Centre

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The Odin satellite has been used to detect emission and absorption in the 557-GHz $H_2{}^{16}O$ line in the Galactic Centre towards the Sgr A* Circumnu-

clear Disk (CND), and the Sgr A +20 $km\,s^{-1}$ and +50 $km\,s^{-1}$ molecular clouds. Strong broad H_2O emission lines have been detected in all three objects. Narrow H_2O absorption lines are present at all three positions and originate along the lines of sight in the 3-kpc Spiral Arm, the −30 $km\,s^{-1}$ Spiral Arm and the Local Sgr Spiral Arm. Broad H_2O absorption lines near −130 $km\,s^{-1}$ are also observed, originating in the Expanding Molecular Ring. A new molecular feature (the "High Positive Velocity Gas" - HPVG) has been identified in the positive velocity range of ≈ +120 to +220 $km\,s^{-1}$, seen definitely in absorption against the stronger dust continuum emission from the +20 $km\,s^{-1}$ and +50 $km\,s^{-1}$ clouds and possibly in emission towards the position of Sgr A* CND. The 548-GHz $H_2{}^{18}O$ isotope line towards the CND is not detected at the 0.02 K (rms) level.

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18-cm VLA observations of OH towards the Galactic Centre. Absorption and emission in the four ground-state OH lines

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The OH distribution in the Sgr A Complex has been observed in the 1612-, 1665-, 1667- and 1720-MHz OH transitions with the Very Large Array (VLA) in BnA configuration. Maps are presented with a channel velocity resolution of about 9 $km\,s^{-1}$ and with angular resolutions of 4"x3". Some clear results are highlighted here, such as absorption from the Circumnuclear Disk (CND) and the OH-Streamer inside the CND near Sgr A*, strong absorption towards most of the eastern and western parts of the Sgr A East shell, lack of absorption towards both Sgr A West and the compact HII-regions to the east of Sgr A East, and double-lobed structure of the High Negative Velocity Gas (HNVG) oriented northeast and southwest of Sgr A*, and finally compact, point-like maser emission in all four transitions, in particular a 1720-MHz maser at −132$km\,s^{-1}$ in the CND as counterpart to a 1720-MHz maser at +132$km\,s^{-1}$ in the CND.

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Detection of Sagittarius A* at 330 MHz with the Very Large Array

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We report the detection of Sagittarius A*, the radio source associated with our Galaxy's central massive black hole, at 330 MHz with the Very Large Array. Implications for the spectrum and emission processes of Sagittarius A* are discussed and several hypothetical geometries of the central region are considered.

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Observations of gas and dust at the Galactic Centre

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The Infrared Space Observatory Long wavelength Spectrometerhas been used to map distribution of the emission from a sample of 22 atomic, molecular and ionised lines toward the Circumnuclear Disk at the Galactic Centre. The CND disc is clearly seen in the maps of molecular lines such as CO and OH, whilst the central region dominates in other atomic and ionised lines. The spectrum toward Sgr A star is best represented by the sum of a 58 K blackbody, superposed with 22 identifiable emission or absorption features, including four lines each attributed to CO and OH, two broad features that may be indicative of a complex of solid state features, two H2O lines, and the rest being various atomic or ionised atomic lines.

Ref.:
Email: g.j.white@kent.ac.uk
Eprint: astro-ph/0311611

Evolution of the Dark Matter Distribution at the Galactic Center

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Annihilation radiation from neutralino dark matter at the Galactic center (GC) would be greatly enhanced if the dark matter were strongly clustered around the supermassive black hole (SBH). The existence of a dark-matter "spike" is made plausible by the observed, steeply-rising *stellar* density near the GC SBH. Here the time-dependent equations describing gravitational interaction of the dark matter particles with the stars are solved. Scattering of dark matter particles by stars would substantially lower the dark matter density near the GC SBH over 10^{10} yr, due both to kinetic heating, and to capture of dark matter particles by the SBH. This evolution implies a decrease of several orders of magnitude in the observable flux of annihilation products compared with models that associate a steep dark matter spike with the SBH.

Ref.:
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43 GHz SiO Masers and Astrometry with VERA in the Galactic Center

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We present Very Large Array (VLA) observations of 43 GHz SiO ($J = 1 \to 0$, $v = 2$ and $v = 1$) maser emission in a sub-sample of late-type stars in the Inner Galaxy selected on their relatively strong (> 0.5 Jy) 86 GHz SiO masers, and located within 2.5° of the Galactic center. Furthermore we combine these results with a summary of previous surveys for 43 GHz SiO masers in the Galactic center and comment on their use as calibrators for the Japanese "VLBI Exploration of Radio Astrometry" (VERA) network, which is intended to perform sub-milli-arcsecond astrometry in the Galaxy and the Galactic center.

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http://www.aoc.nrao.edu/~lsjouwer/_gps/vera.ps.gz

A Molecular Face-on View of the Galactic Centre Region

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We present a method to derive positions of molecular clouds along the lines of sight from a quantitative comparison between 2.6 *mm* CO emission lines and 18 *cm* OH absorption lines, and apply it to the central kiloparsecs of the Milky Way. With some simple but justifiable assumptions, we derive a face-on distribution of the CO brightness and corresponding radial velocity in the Galactic centre without any help of kinematical models. The derived face-on distribution of the gas is elongated and inclined so that the Galactic-eastern (positive longitude) side is closer to us. The gas distribution is dominated by a barlike central condensation, whose apparent size is $500 \times 200\,pc$. A ridge feature is seen to stretch from one end of the central condensation, though its elongated morphology might be artificial. The velocity field shows clear signs of noncircular motion in the central condensation. The 'expanding molecular ring' feature corresponds to the peripheral region surrounding the central condensation with the Galactic-eastern end being closer to us. These characteristics agree with a picture in which the kinematics of the gas in the central kiloparsec of the Galaxy is under a strong influence of a barred potential. The face-on distribution of the *in situ* pressure of the molecular gas is derived from the CO multi-line analysis. The derived pressure is found to be highest in the central $100\,pc$. In this region, the gas is accumulating and is forming stars.

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86 GHz SiO maser survey of late-type stars in the Inner Galaxy II. Infrared photometry of the SiO Target Stars

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We present a compilation and study of DENIS, 2MASS, ISOGAL, MSX and IRAS 1–25μm photometry for a sample of 441 late-type stars in the inner Galaxy, which we previously searched for 86 GHz SiO maser emission (Messineo et al. 2002). The comparison of the DENIS and 2MASS J and Ks magnitudes shows that most of the SiO targets are indeed variable stars. The MSX colours and the IRAS [12] – [25] colour of our SiO targets are consistent with those of Mira type stars with dust silicate feature at 9.7 μm feature in emission, indicating only a moderate mass-loss rate.

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Email: messineo@strw.leidenuniv.nl
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On The Nature of the Variable Infrared Emission from Sgr A*

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Recent infrared (IR) observations of the center of our Galaxy indicate that the supermassive black hole source Sgr A* is strongly variable in the IR. The timescale for the variability, $\sim$ 30 min, is comparable to that of the X-ray flares observed by *Chandra* and *XMM*, suggesting a common physical origin. In this paper, we investigate the nature of the IR emission in the context of models recently proposed to interpret the X-ray flares. We show that the IR emission in Sgr A* can be well explained by nonthermal synchrotron emission if a small fraction of the electrons in the innermost region of the accretion flow around the black hole are accelerated into a broken power-law distribution, perhaps due to transient events such as magnetic reconnection. The model predicts differences in the variability amplitudes of flares in the IR and X-rays, in general agreement with observations. It also predicts that the IR emission should be linearly polarized, as has indeed been observed during one epoch. IR and X-ray flares analogous to those observed in Sgr A* may be detectable from other accreting SMBHs, provided $L < 10^{-8} L_{EDD}$; at higher luminosities the flaring emission is dominated by thermal synchrotron-self Compton emission, which is likely to be less variable.

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Eprint: astro-ph/0401429

The last Gamma Ray Burst in our Galaxy? On the observed cosmic ray excess at particle energy 10^{18} eV

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Here we propose that the excess flux of particle events of energy near 10^{18} eV from the direction of the Galactic Center region is due to the production of cosmic rays by the last few Gamma Ray Bursts in our Galaxy. The basic idea is that protons get accelerated inside Gamma Ray Bursts, then get ejected as neutrons, decay and so turn back into protons, meander around the inner Galaxy for some time, and then interact again, turning back to neutrons to be observed at our distance from the Galactic Center region, where most star formation is happening in our Galaxy. We demonstrate that this suggestion leads to a successful interpretation of the data, within the uncertainties of cosmic ray transport time scales in the inner Galaxy, and in conjunction with many arguments in the literature.

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Email: gustavo@astro.iag.usp.br
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A Radio Outburst Nearly Coincident with the Large X-ray Flare from Sgr A* on 2002-10-03

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A large radio outburst from Sgr A* was observed during the VLA weekly monitoring program at 2 cm, 1.3 cm and 7 mm, nearly coincident with the brightest X-ray flare detected to date with the XMM-Newton X-ray Observatory on 2002-10-03. The flux density of 1.9±0.2 Jy measured at 7 mm exceeds the mean value (1.00±0.01 Jy) by a factor of 2, one of the two highest increases observed during the past three years (June 2000-October 2003), while less significant increases in flux densities were observed at 1.3 cm and 2 cm. The radio observation started 13.5 hrs after the onset of the X-ray flare (which had occurred over a 45 min duration) and continued for 1.3 hrs. During the observation, there was no significant (¡3σ) change in the radio flux densities at all the three wavelengths, indicating that the radio outburst varied on a timescale of ¿1hr. A spectral index of $\alpha = 2.4^{+0.3}_{-0.6}$ ($S \sim \nu^{\alpha}$) was derived for the outburst component, consistent with an optically thick nonthermal synchrotron source. These results suggest that energetic electrons responsible for the radio outburst might be produced via a process associated with the X-ray flare, then transported to large radii, producing the observed radio outburst. The observation is the first evidence for a correlated variation in the radio and X-ray emissions from Sgr A*.

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A Bow Shock of Heated Dust Surrounding Galactic Center Source IRS 8

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High resolution images in the H and K bands obtained by the Gemini North Telescope of the peculiar Galactic center source, IRS 8, reveal a central pointlike object enveloped in a remarkable bow-shock, whose apex is located 0.2" to the northeast. The $H - K'$ color of the bow shock is considerably redder than that of the central star. A UKIRT K band spectrum reveals that the combined spectrum of the point source and bow shock is nearly featureless and that no shocked line emission (e.g., from H_2) is physically associated with the bow. We interpret the bow as resulting from the interaction of the envelope or wind of the central star of IRS 8 with the extension of the Northern Arm of Sgr A West and/or the Circumnuclear Disk, and its emission as coming from radiatively- and possibly shock-heated dust.

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New Nonthermal Filaments at the Galactic Center: Are They Tracing a Globally Ordered Magnetic Field?

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New high-resolution, wide-field 90 cm VLA[2] observations of the Galactic Center region by Nord et al. have revealed twenty nonthermal filament (NTF) candidates. We report 6 cm polarization observations of six of these. All of the candidates have the expected NTF morphology, and two show extended polarization confirming their identification as NTFs. One of the new NTFs appears to be part of a system of NTFs located in the Sgr B region, 64 pc in projection north of Sgr A. These filaments cross the Galactic plane with an orientation similar to the filaments in the Galactic Center Radio Arc. They extend the scale over which the NTF phenomena is

[2]The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under a cooperative agreement by Associated Universities, Inc.

known to occur to almost 300 pc along the Galactic plane. Another NTF was found in the Galactic plane south of the Sgr C filament but with an orientation of 45° to the Galactic plane. This is only the second of 12 confirmed NTFs that is not oriented perpendicular to the Galactic plane. An additional candidate in the Sgr C region was resolved into multiple filamentary structures. Polarization was detected only at the brightness peak of one of the filaments. Several of these filaments run parallel to the Galactic plane and can be considered additional evidence for non-poloidal magnetic fields at the GC. Together the 90 and 6 cm observations indicate that the Galactic center magnetic field may be more complex than a simple globally ordered dipole field.

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The Variability of Sagittarius A* at Centimeter Wavelengths

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We present the results of a 3.3-year project to monitor the flux density of Sagittarius A* at 2.0, 1.3, and 0.7 cm with the Very Large Array. Between 2000.5 and 2003.0, 119 epochs of data were taken with a mean separation between epochs of eight days. After 2003.0, observations were made roughly once per month for a total of nine additional epochs. Details of the data calibration process are discussed, including corrections for opacity and elevation effects as well as changes in the flux density scales between epochs. The fully calibrated light curves for Sgr A* at all three wavelengths are presented. Typical errors in the flux density are 6.1%, 6.2%, and 9.2% at 2.0, 1.3, and 0.7 cm, respectively. There is preliminary evidence for a bimodal distribution of flux densities, which may indicate the existence of two distinct states of accretion onto the supermassive black hole. At 1.3 and 0.7 cm, there is a tail in the distribution towards high flux densities. Significant variability is detected at all three wavelengths, with the largest amplitude variations occurring at 0.7 cm. The rms deviation of the flux density of Sgr A* is 0.13, 0.16, and 0.21 Jy at 2.0, 1.3, and 0.7 cm, respectively. During much of this monitoring campaign, Sgr A* appeared to be relatively quiescent compared to results from previous campaigns. At no point during the monitoring campaign did the flux density of Sgr A* more than double its mean value. The mean spectral index of Sgr A* is $\alpha = 0.20 \pm 0.01$ (where $S_\nu \propto \nu^\alpha$), with a standard deviation of 0.14. The spectral index appears to depend linearly on the observed flux density at 0.7 cm with a steeper index observed during outbursts. This correlation is consistent with the expectation for outbursts that are self-absorbed at wavelengths of 0.7 cm or longer and inconsistent with the effects of simple models for interstellar scintillation. Much of the variability of Sgr A*, including possible time lags between flux density changes at the different wavelengths, appears to occur on time scales less than the time resolution of our observations (8 days). Future observations should focus on the evolution of the flux density on these time scales.

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Email: herrnstein@aleko.phys.columbia.edu
Eprint: astro-ph/0402543

Announcements

How many of you knew that Sgr A* was only 30? Well, maybe that is not strictly the case, but in our Earth-centric reckoning it may as well be. And in order to commemorate the anniversary of Sgr A*'s discovery as a compact radio core 30 years ago, a small workshop has been organized for March 25-26 at the Green Bank Telescope in West Virginia. Because of the extremely limited size of facilities, participation was capped at about 50 people, and has already been finalized. The program can be found online at `http://www.gb.nrao.edu/workshops/sgraws.shtml`.

Keep your eyes peeled for upcoming meeting announcements. With all the new results coming out, there has been plenty of discussion about the need for another workshop...

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