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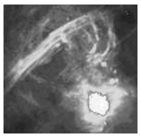

The Newsletter of Galactic Center Research

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Approaching the Event Horizon through VLBI Imaging of Sagittarius A*

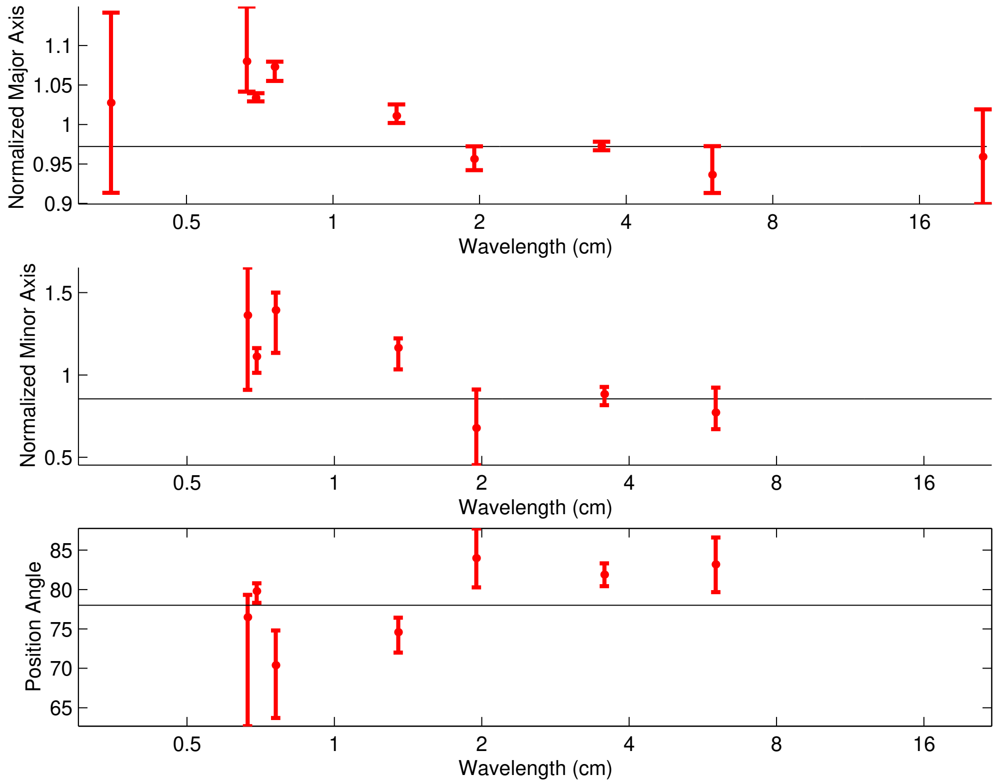

Figure 1 : From Doeleman & Bower's article. Major axis size, minor axis size, and position angle of elliptical Gaussian models for Sgr A* as a function of wavelength normalized by a λ^2 scattering law (solid line, Bower et al. 2004). The deviation in the short wavelength sizes from the scattering law indicates the detection of an intrinsic source size. Included is the 3.5 mm measurement in the major axis, also made with closure amplitude techniques (Doeleman et al. 2001).

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In the News

Joseph Lazio & Cornelia Lang

Welcome to the second GCNEWS of 2004. Since the last GCNEWS, we've seen a number of new results on the size and nature of Sgr A* itself and ongoing studies of the interstellar medium in this unique region. Many GC folks have also taken a pause to commemorate the (almost accidental!) discovery of Sgr A* which occurred only a little over 30 years ago.

In other news, we welcome Robin Hernnstein to our editorial staff. As always, please feel free to contact any of us with GC newsworthy items or future article ideas. We also remind our readers to *please* submit their abstracts to GCNEWS. As you know, GCNEWS promises rapid delivery of your results to fellow GC researchers. While *astro-ph* is a valuable resource, GCNEWS directly targets those readers with an acknowledged interest in GC science.

In this Volume

In this volume, we report on a conference devoted to Sgr A*and its environment, and also provide an update of GC research presented at the summer AAS meeting in Denver.

We are especially excited to have a comprehensive, invited review article by Sheperd Doeleman and Geoff Bower. In their article, they demonstrate how far we have come in understanding the structure of SgrA* since its discovery. Their article describes the methods used to model and constrain the size of the radio source from radio interferometric data and also highlights future observational prospects - they point out that we are poised on the edge of being able to use such techniques to image the shadow of Sgr A*.

A number of GC abstracts have come in this spring and summer (and as mentioned before, we could always use more!) and are listed at the end of the issue.

Happy 30th Sgr A*!

Cornelia Lang

A small workshop commemorating the 30$^{\rm th}$ anniversary of the discovery of Sgr A*, the radio source associated with the supermassive black hole at the center of our Galaxy, was held in Green Bank, West Virginia, on March 25 and 26. There were 60 participants from a variety of international and national institutes and many of the NRAO scientific staff. The program consisted of a day and a half of scientific talks, a banquet, and a ceremony and dedication of a plaque on the 45-foot telescope that commemorates the original discovery. A reception for all participants and Green Bank staff followed at the Green Bank Science Center.

The discovery of the compact radio source at the center of the Milky Way was made by Bruce Balick and Bob Brown in 1974 February. They had originally been searching for compact regions of star formation in the vicinity of the Galactic Center. The placement of the 45-foot telescope near Huntersville, West Virginia, as the 35 km outstation for the NRAO Green Bank radio link interferometer (consisting of three, 85-foot antennas at Green Bank), was crucial for resolving out the extended confusion from Sgr A West and providing spatial resolutions of $0.3''$ (at 3.7 cm) and $0.7''$ (at 11 cm) and detecting the very compact radio source, Sgr A*.

An opening review talk on massive objects at the centers of galaxies was given by Roger Blandford, followed by a series of historical talks given by the original observers, Bruce Balick and Bob Brown, and the Green Bank site director at that time, Dave Hogg. A number of fascinating letters from Balick to Brown were shown which provided additional insight into the details of the discovery (also summarized recently by Goss, Brown, & Lo 2003, Astron. Nachr., S1, 1). Roy Booth, K. Y. Lo, and Ron Ekers also presented accounts of early work on the size and structure of Sgr A*based on some of the first aperture synthesis studies at Jodrell Bank, Owens Valley Radio Observatory, and the VLA.

Following the historical talks on the discovery of Sgr A*, a series of talks on recent results were presented. Don Backer gave an overview of interstellar scattering properties toward Sgr A*, and Geoff Bower and Zhi-Qiang Shen reported on VLBA closure phase techniques used to constrain the size of this compact source. Results on the linear and circular polarization of Sgr A* were given by Geoff Bower. Andrea Ghez, Rainer Schödel, Jun Hui-Zhao and Fred Baganoff confirmed that variability of Sgr A* on a number of timescales has now been detected across the spectrum from radio to near-IR to X-rays. Progress reports by Ramesh Narayan, Sera Markoff, Eliot Quataert, and Fulvio Melia followed, describing the various models to explain the spectrum, polarization, and variability of Sgr A*. Perspectives on the current state and characteristics of the modeling were given by Heino Falcke. The stellar and interstellar environment surrounding Sgr A* was discussed in a series of talks on

Figure 2 : The discoverers of Sgr A*, Bruce Balick (right) and Bob Brown (left) receive a commemorative poster from NRAO director Fred Lo (far left). In the background the commemorative plaque attached to the 45-foot telescope. *(Photo by Bill Saxton)*

Friday morning. The scientific talks concluded at noon with a thoughtful review by Mark Morris.

Following the scientific program, a dedication ceremony was held at the 45-foot antenna, where NRAO director Fred Lo presented Bruce Balick and Bob Brown with commemorative framed posters (see picture). A plaque on the 45-foot antenna and an informational adjacent sign for visitors were unveiled. An informal scientific session was held on Friday evening to discuss prospects for future millimeter and sub-millimeter VLBI observations of Sgr A*. The next generation of telescopes will provide an excellent opportunity for imaging on the scale of the event horizon, allowing for detailed tests of accretion models and general relativity.

The scientific program, PDF and PPT versions of the talks, and photographs are available at `www.aoc.nrao.edu/~gcnews/GCconfs/SgrAstar30/`.

GC appearances at Denver AAS in June 2004

Cornelia Lang

A number of GC results were presented at the summer American Astronomical Society meeting in Denver, Colorado (May 30–June 3). We describe briefly those papers with a GC component at the AAS meeting, with apologies to anybody whose work we might have missed. The AAS paper number is in parentheses at the end of each summary.

The enigmatic, magnetic "non-thermal filaments" (NTFs) in the GC made an appearance in a number of presentations and posters this summer:

- F. Yusef-Zadeh et al. presented a talk entitled "A Radio Survey of the GC Region: Detection of Numerous Linear Filaments" in which he presented a 20 cm survey of a 300 pc region around the GC and a several-degree region toward low Galactic longitudes along the Galactic plane. A number of NTFs were discovered in this image. (17.03)

- J. Hewitt et al. followed up on these results and presented high resolution images from this 20 cm survey, highlighting a number of the new filamentary features and their associations with compact, star forming regions. (59.03)

- T. Freismuth et al. presented recent work on the peculiar NTF known as the "Snake." For the first time, the orientation of the intrinsic magnetic field in this object has been revealed to lie along the NTF, even in the region where the Snake undergoes substantial "kinks." Large rotation measures (> 4000 rad m^{-2}) are also observed toward much of the Snake. (59.05)

The combination of Green Bank single dish data with Very Large Array interferometric data was a highlight of the poster by C. Law et al. (and also the previously mentioned 59.03 poster):

- Law et al. focused on understanding the large-scale radio continuum emission in the GC. In particular, they are interested in one of the Galactic center "Lobes" of extended emission oriented perpendicularly to the plane of the Galaxy. They presented the distribution of spectral index along and across the lobes to quantify the energetics of this feature. (59.02)

There were two press releases by NRAO on the combination of GBT and VLA datasets (59.02, 59.03). See `http://www.nrao.edu/pr/2004/filaments/` and `http://www.nrao.edu/pr/2004/GBTlobe/` for more details.

Several posters were focused on the interstellar medium in the GC region, on large and small scales:

- C. Martin et al. showed results from the submillimeter observatory, AST/RO, on several unusual molecular clumps in the GC region. He had fully-sampled maps in the lines of CO (7→6), CO (4→3) and C I ($^3P_1 \rightarrow {}^3P_0$) which suggest that these clouds are tidally shocked through interactions with the bar potential in the Milky Way. (59.06)

- I. Azcárate et al. investigated the departure from LTE in the GC region by observing nine positions around the GC in H159α and H200β radio recombination lines. They employed the 30-m telescope of the Instituto Argentino de Radioastronomia. (59.01)

- Lang et al. presented their findings from a large-scale survey of H I absorption toward the central 250 pc of the GC in order to clarify the nature of the physical associations of the atomic, ionized and molecular components. In addition, line of sight distances to continuum features can be constrained as well as column densities estimated. Specific results on Sgr B2 and the Radio Arc were shown. (59.04)

Other GC highlights:

- S. Liu et al. demonstrated that nonthermal electrons accelerated by plasma wave turbulence in the central concentration of hot gas may be responsible for portions of the spectrum of Sgr A* and also its variability in the infrared and X-ray wavebands. (17.01)

- N. Weinberg et al. outlined the prospects for observing stellar dynamics in the neighborhood of Sgr A* using the proposed Thirty Meter Telescope (TMT). The TMT will allow astronomers to measure the mass of the black hole and the distance to the GC with accuracies better than about 0.1%. Some relativistic effects (such as prograde orbital procession) will also be detectable. (17.02)

Approaching the Event Horizon through VLBI Imaging of Sagittarius A*: Recent Results and Future Experiments

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1. Introduction

At the recent Sgr A* birthday conference in Green Bank, WV, a number of exciting results, which are bringing us closer to a better understanding of the dynamics and processes at work in the Galactic Center, were reported. Among these results are several that focus on the ultra-compact region surrounding the central mass. In the NIR, Sgr A* has now been observed in both a quiescent and flaring state (Genzel et al. 2003; Ghez et al. 2004) with flare rise times that restrict the emission to be within a volume of tens of Schwarzschild radii across. A possible approximately 17 min. periodicity observed in the flares can be explained as a relativistic modulation of the accretion flow near the last stable orbit of a 3.6 million solar mass black hole. X-ray flares of Sgr A* observed by both *Chandra* and *XMM-Newton* (Baganoff et al. 2001; Goldwurm et al. 2001) exhibit similar rise/decay times with commensurate limitations on the volume of origin. Furthermore, detection of linear polarization at wavelengths shorter than 3 mm (Aitken et al. 2000; Bower et al. 2003) places important constraints on the accretion rate and accretion process within hundreds of Schwarzschild radii of the black hole. These results provide important input to models of Sgr A* emission, but they are not direct measurements of size or structure.

Due to the proximity of Sgr A*, high resolution imaging techniques can achieve unprecedented linear resolution of this black hole. NIR interferometry with current instruments such as the VLTI have a maximum resolution of about 100 Schwarzschild radii. In the far future, space-based X-ray interferometry may obtain a resolution of 10^{-2} Schwarzschild radii. Only very long baseline interferometry (VLBI) at mm and submm wavelengths currently provides the means to directly image Sgr A* on scales comparable to the Schwarzschild radius. In as much as Sgr A* can be taken as the Rosetta Stone for more massive and more luminous AGN, VLBI observations have the potential to provide us with a unique and detailed view of AGN cores on scales where relativistic effects and strong gravity dominate.

The basic observing challenge is that Sgr A* lies behind a screen of turbulent interstellar plasma that scatters radio waves and broadens VLBI images. This broadening scales as λ^2, requiring VLBI observations over a range of wavelengths and with an emphasis on the short wavelength end. The most recent VLBI results (Bower et al. 2004), conclusively detect a 24 $R_{\rm sch}$ intrinsic size at 7 mm wavelength, providing the most stringent mass density lower limits to date for Sgr A*.

In this article we summarize the current state of VLBI observations of Sgr A* and the methods used to extract sizes and structures. We also discuss the future possibilities for VLBI at shorter wavelengths that will provide us with angular resolutions as fine as 20 microarcseconds, or approximately 2 $R_{\rm sch}$.

2. VLBI Modeling of the Structure of Sgr A*

Traditional VLBI imaging begins by correlating data taken on an array of radio telescopes, yielding complex correlation coefficients for each antenna-antenna baseline for each integration time and bandwidth channel. Each baseline, time, and frequency datum can be placed in a (u, v) plane with axes representing the projected baseline lengths (measured in wavelengths) in the north-south and east-west directions. A single baseline traces out an elliptical path in this plane as the Earth rotates, providing correlation measurements for many baseline lengths and orientations (see Figure 3 for an example). Interferometric imaging hinges on the fact that the (u, v) plane and the "sky" plane are Fourier Transform pairs, so the calibrated correlation data are transformed from the (u, v) plane to make a sky image. Typically, this image must go through a further process of deconvolution to remove the effects of sparse sampling in the (u, v) plane.

Phase and amplitude calibration of VLBI data assume that calibration parameters can be "stationized," so that the proper calibration for a baseline is the product of two complex gains, one for each antenna in the baseline. This is a valid way to describe the array response under most circumstances. Unfortunately, it can be difficult to obtain

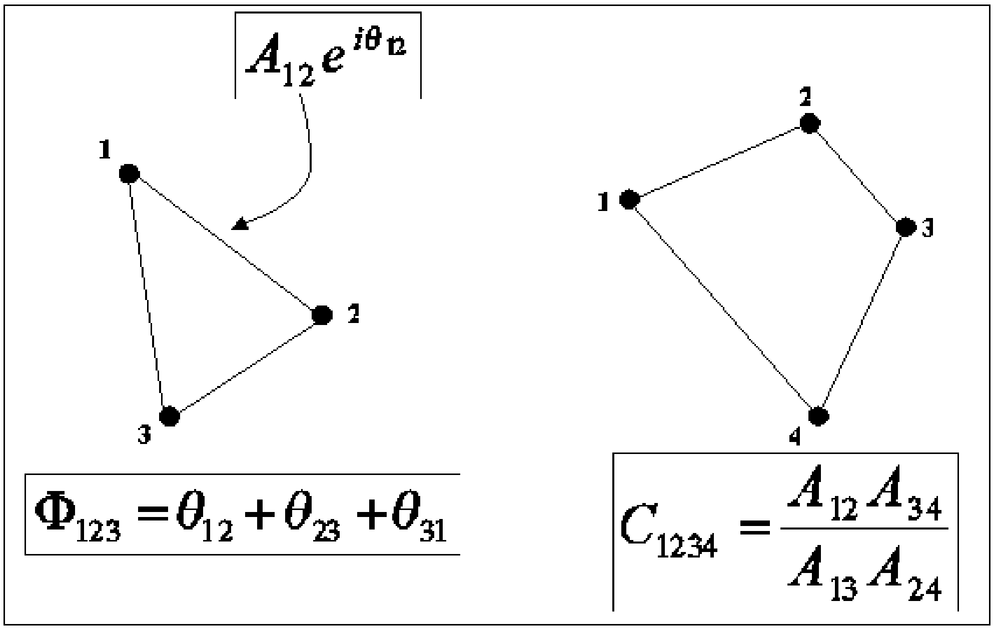

Figure 1 : Closure quantities used in VLBI analysis. Left shows triangle of stations over which closure phase is computed. Baseline 12 is labeled with the measured complex correlation for that antenna pair. On the right is a quadrangle of baselines used to compute a closure amplitude. Expressions for each closure quantity are below each diagram. Closure quantities are independent of calibration of the antennas in the array.

calibration measurements with the frequency or the accuracy necessary to produce a high quality image. With this assumption of station-based calibration, however, one can compute two quantities which are independent of the calibration, the closure phase and the closure amplitude. The closure phase is a sum of the interferometric phase around a triangle of antennas (three baselines in a closed loop); all sources of station-based errors cancel and leave a quantity that directly relates to source structure. Similarly, the closure amplitude is calculated by forming the ratio of products of complex correlation data around a closed loop of four antennas (Figure 1).

Calibration is especially difficult for mm VLBI experiments and even more so for mm VLBI experiments targeting Sgr A*. Contributions to errors in the calibration include low sensitivity, variable atmospheric opacity, variable atmospheric path length, antennas deformation under gravity, and antenna pointing errors. These problems are all the more severe for the case of Sgr A*, which is observed only at low elevation from the Northern hemisphere. Thus, it is often preferable to directly model the closure quantities and perform a χ^2 minimization to determine the most likely structure given a family of parameterized source models. The relatively simple structure of Sgr A* and the relatively small number of VLBI data points make this approach both computationally tractable and an efficient way to search for structural asymmetries and deviations from the scattering law.

3. Current VLBI Results

Closure amplitude analysis of Sgr A* VLBI observations was first carried out by Doeleman et al. (2001) using data at 3.5 mm wavelength taken with a six station array including 3 Very Long Baseline Array (VLBA) antennas, the Kitt Peak 12-m, the Owens Valley mm array, and the Berkeley-Illinois-Maryland Array at Hat Creek. The sparse (u, v) coverage and low sensitivity of these observations limited the complexity of source models that could be considered for the structure of Sgr A*. A broad range of possible elliptical Gaussian models was searched, but the data were adequately fit by a more simple circular Gausssian brightness distribution with a full width half maximum (FWHM) size of 0.18 ± 0.02 milliarcseconds. This size is, within the errors, consistent with the expected scattering size at 3.5 mm wavelength, and the experiment placed a strong upper limit of 0.13 mas (20 $R_{\rm sch}$) on any intrinsic structure at this wavelength. This result cast some doubt on earlier 7 mm wavelength VLBI results which claimed to have detected intrinsic structure using conventional VLBI calibration and analysis methods (Lo et al. 1998).

Prompted by these results, Bower et al. (2004) recently applied closure amplitude and closure phase analysis to longer wavelength data obtained with the VLBA. The VLBA data span 6 cm to 7 mm wavelength and include a total of 19 experiments. For each data set, we computed the closure amplitudes and closure phases, and used a nonlinear χ^2-minimization technique to search through a range of possible source structures. All data were consistent with the source as a single elliptical Gaussian. Though the data do not support a two-component model, formal limits can be set on the flux density of a potential secondary component of a few percent to about 20% of the flux density of the main component. Under the assumption that the source is an elliptical Gaussian, we fit a major axis size, minor axis size and position angle (Figure 2). Combining the VLBA data at 2 cm and longer wavelengths with archival Very Large Array data at 20 cm, we are able to calibrate the scattering law to better than 1% as well. The major and minor axis sizes at these long wavelengths are fully consistent with a λ^2 law. At 7 mm, however, the difference between our measured size and the expectation of the scattering law is 40 microarcseconds: a detection of intrinsic structure in Sgr A* at the 7σ level. This difference translates to an intrinsic size for Sgr A* of 24 ± 2 Schwarzschild radii at 7 mm observing wavelength. We are able to obtain a similar, although less accurate, measurement at 1.3 cm, which implies a wavelength dependence of the intrinsic size that is roughly proportional to $\lambda^{1.5}$.

The upper limit on the intrinsic size at 3.5 mm of 20 Schwarzschild radii determined by Doeleman et al. shows that the size continues to decrease with decreasing wavelength. New results from VLBA imaging at 3.5 mm presented by Shen et al. at the Sgr A* 30$^{\rm th}$ birthday meeting indicate a size of 10 Schwarzschild radii. Altogether, these are the highest resolution observations of any black hole system in units of the event horizon.

We can draw several conclusions based on these results. The compact size strongly excludes Bondi-Hoyle accretion flows and advection dominated accretion flows for Sgr A*. This is in agreement with the low mass accretion-rate interpretation of linear polarization measurements (Bower et al. 2003). The wavelength-dependence of the size also excludes a homogeneous synchrotron source explanation. The exact nature of the accretion and emission region is still uncertain, however. Both radiatively inefficient accretion flows and jet models can reproduce the intrinsic size.

We can use the measured size along with the upper limit to proper motion of the black hole (most recently reported by Reid et al. at the 30$^{\rm th}$ birthday meeting) to limit the mass density of the black hole to 4×10^4 M$_\odot$ AU^{-3}. This density rules out all but the most exotic alternatives to a supermassive black hole scenario for the central mass at the Galactic Center, and makes Sgr A* the leading candidate for a massive black hole.

4. VLBI at Shorter Wavelengths: Imaging the Shadow of the Black Hole

The intrinsic size of Sgr A* decreases strongly with decreasing wavelength. If the power-law that we observe continues to even shorter wavelengths, then the source will become comparable to the event horizon scale around a wavelength of 1.3 mm. On this scale, the image will be severely distorted by propagation effects in the strong gravity of the black hole (Falcke, Melia, & Agol 2000; Takahashi et al. 2004). Radiation traveling close to the black hole will be gravitationally lensed and appear in a ring with an inner radius of 5 Schwarzschild radii. Detection of this ring will provide the tightest constraint ever placed on the mass density of a black hole. Asymmetries in the image may also reveal information about the spin of the black hole. These observations may also detect the motion of matter around the black hole: The period of the last stable orbit around the black hole is approximately 20 min.

Sgr A* is the best candidate for these measurements. We show in Table 1 other potential sources for this measurement. The closest candidate is M87, which has an event horizon radius about half that of Sgr A*. The maximum wavelength for the experiment is set by the shadow diameter and by the wavelength at which the image becomes optically thin. An Earth-baseline has a resolution of 34 microarcseconds at 1.3 mm, just sufficient to detect the hole. The spectrum becomes optically thin somewhere in the millimeter wavelength band, although the exact wavelength is unknown. It is likely that observations will have to be made at 1.3 and 0.8 mm wavelength.

These are technically demanding observations. Current efforts to image Sgr A* with VLBI are limited by the high detection thresholds at wavelengths much shorter than 7 mm and by limited baseline coverage. The baseline scarcity at longer wavelengths follows from the larger scattering size of Sgr A* and the tendency of long baselines to resolve the observed structure. At the short wavelength range, the number of available telescopes that can participate in VLBI drops off sharply, which results in a poorly sampled (u, v) plane.

There are two major developments on the horizon which will dramatically change the landscape for VLBI of Sgr A*. The first is a new generation of VLBI recording technology which will, over the next 5–10 years, enable data rates approximately 64 times higher than current sustainable rates at the VLBA (Whitney, Lapsley, & Doeleman 2003). A VLBI array with these wideband systems will improve continuum sensitivity by a factor of 8. The

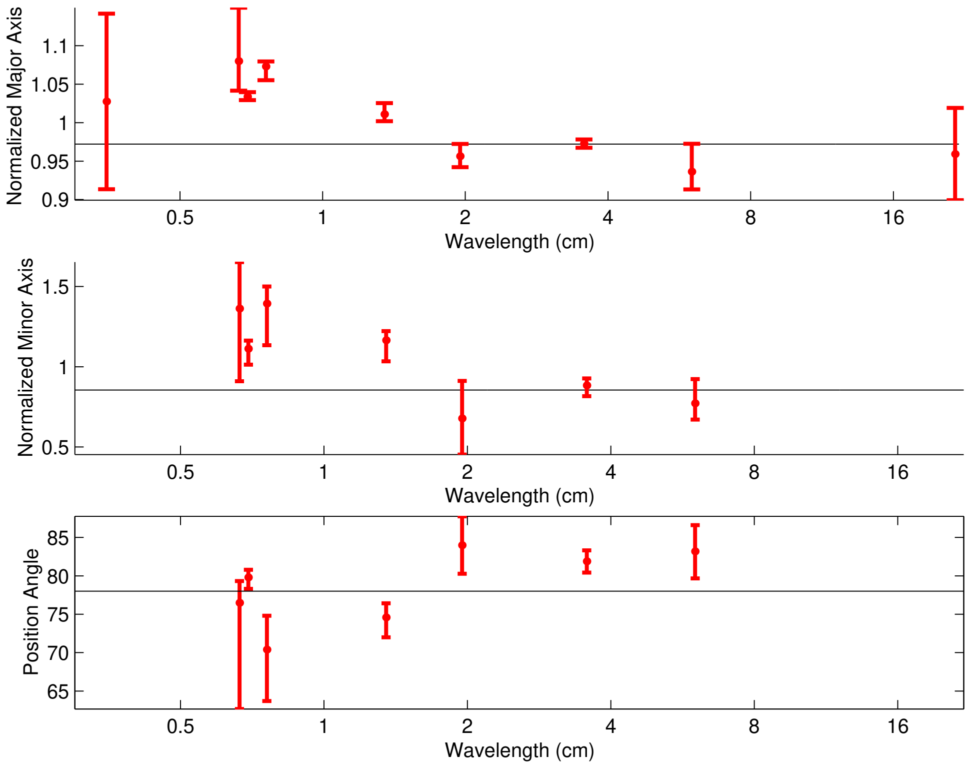

Figure 2 : Major axis size, minor axis size, and position angle of elliptical Gaussian models for Sgr A* as a function of wavelength normalized by a λ^2 scattering law (solid line, Bower et al. 2004). The deviation in the short wavelength sizes from the scattering law indicates the detection of an intrinsic source size. We include the 3.5 mm measurement in the major axis, also made with closure amplitude techniques (Doeleman et al. 2001).

Table 1 : VLBI Imaging of Black Hole Shadows

Source	Black Hole Shadow Diameter
Sgr A*	64 μarcsec
M87	38
NGC 4649	24
Cen A	10

second important advance will be the commissioning of several new large aperture mm and submm telescopes that can join a short wavelength VLBI array providing long, sensitive baselines yielding exceptionally high angular resolution. These new telescopes—ALMA, CARMA, and the SMA among them—can potentially provide a further increase in sensitivity of a factor of 10 for some VLBI baselines. The combination of increased bandwidth and larger telescopes will result in an overall boost of VLBI sensitivity at wavelengths shorter than 3 mm by about 2 orders of magnitude. Table 2 shows how we expect the sensitivity and number of antennas for 1.3 mm VLBI to evolve over the next decade. Within 3 to 5 years, the sensitivity will be sufficient to make a 10 to 20σ detection of Sgr A* on most baselines in 10 seconds.

A collaboration including Haystack Observatory, IRAM, MPIfR-Bonn, and the University of Arizona has carried out VLBI tests at 2.3, 2.0, and 1.3 mm, with a focus on addressing the technical difficulties involved in extension of VLBI to mm and submm wavelengths. These efforts have been successful, with productive experiments conducted at 2.3 and 2.0 mm in 2002 April, and at 2.3 and 1.3 mm in 2003 April. Among the results were VLBI images of SiO maser emission around the evolved star VY Canis Majoris in the $v = 1$, $J = 3 \rightarrow 2$ ro-vibrational transition

Table 2 : Evolution of 1.3 mm VLBI Capability Over the Next Decade

Present: 0.5 Gb s^{-1}		3–5 yrs: 4 Gb s^{-1}		5–10 yrs: 16 Gb s^{-1}	
Antenna	SEFD (Jy)	Antenna	SEFD (Jy)	Antenna	SEFD (Jy)
Kitt Peak	22 000	JCMT	7800	ALMA	100
Pico Veleta	2500	APEX	5500		
P. de Bure	2500	CARMA	2500	ALMA-SMTO = 0.005 Jy	
SMTO	15 000	LMT	500	ALMA-LMT = 0.026 Jy	
		SMA	2500		
		CSO	15 000		
PicoV-PdeB = 0.4 Jy		LMT-CARMA = 0.06 Jy		Resolution (8000 km) = 34 μas	
PicoV-KittPeak = 1.15 Jy		LMT-SMTO = 0.15 Jy		Integration Time = 10 seconds	

The predicted evolution of 1.3 mm VLBI capabilities over the next decade. Under each sustainable recording data rate (present, 3–5 yrs, 5–10 yrs) are lists of antennas that can be added to a VLBI array characterized by their System Equivalent Flux Density (lower numbers imply more sensitivity). Below the antennas are baseline detection thresholds: the flux density required for detection in a 10 second integration time for the given data recording rate. The boxes in the lower right of the table contains the angular resolution of a 1.3 mm VLBI array and the expected integration time set by the atmosphere.

at 2.3 mm (Doeleman et al. 2003). This series of experiments also set successive world records for angular resolution, the most recent of which is 34 microarcseconds, achieved in 2003 April on the Pico Veleta-SMTO baseline at 1.3 mm, on the quasar 3C 454.3. This VLBI development extends previous moderate baseline length experiments at 2 mm (Greve et al. 2002) and at 1.3 mm (Greve et al. 1995; Krichaum et al. 1997). Sgr A* has already been detected on the 1150 km Pico Veleta-Plateau de Bure VLBI baseline at 1.3 mm (Krichbaum et al. 1998).

The technical challenges in extending VLBI to these short wavelengths will require continued development. A major obstacle is decorrelation of the VLBI signal by turbulence in the atmosphere, which sets limits on the effective integration time and the detection thresholds. Techniques to increase the integration time, or "coherence time," include using water vapor radiometers to measure changes in the atmospheric path length and sophisticated averaging techniques. Water vapor radiometers may also be important for achieving the phase stability required for phase-referenced astrometry that will make high time resolution imaging possible.

Antenna receiver electronics may also limit coherent integration times, especially in the domain of long (> 10 seconds) integration times made possible through the use of phase correction techniques. The noise introduced by local oscillators used in the receiver increases with decreasing observing wavelength, and careful testing of the signal paths in each VLBI antenna is necessary. At many sites, we replace standard frequency references with specialized oscillators for VLBI observations to ensure spectral purity and time stability. At the heart of each VLBI system is a hydrogen maser which produces a reference tone stable enough that signals from different VLBI stations can be correlated. But, as we approach wavelengths shorter than 1.3 mm, even hydrogen masers introduce some decorrelation in the VLBI signal. It is expected that within roughly 10 years, new frequency standards based on optically trapped and cooled atoms will exceed the stability of masers and become useful for short wavelength VLBI.

For the new arrays, CARMA and ALMA, it will be important to ensure that all antennas in each array can be phased together to provide a single large aperture. In principle this is not difficult, but it can require specialized observing modes to phase the dishes in real-time before the summed signal for all antennas is recorded by the VLBI system. The phased ALMA will be the most sensitive short wavelength facility and provides crucial north-south baselines that are currently poorly sampled. Furthermore, baselines to ALMA will be sensitive enough (see Table 2) that all baselines to ALMA will be able to detect Sgr A* within an atmospheric coherence time. Once in this regime, the VLBI array becomes quasi-phase stable with ALMA baselines providing real-time phase correction for the entire array, and less sensitive baselines can simply integrate in time until Sgr A* is detected. Figure 3 shows the baseline coverage possible using a 1.3 mm array of seven antennas including ALMA.

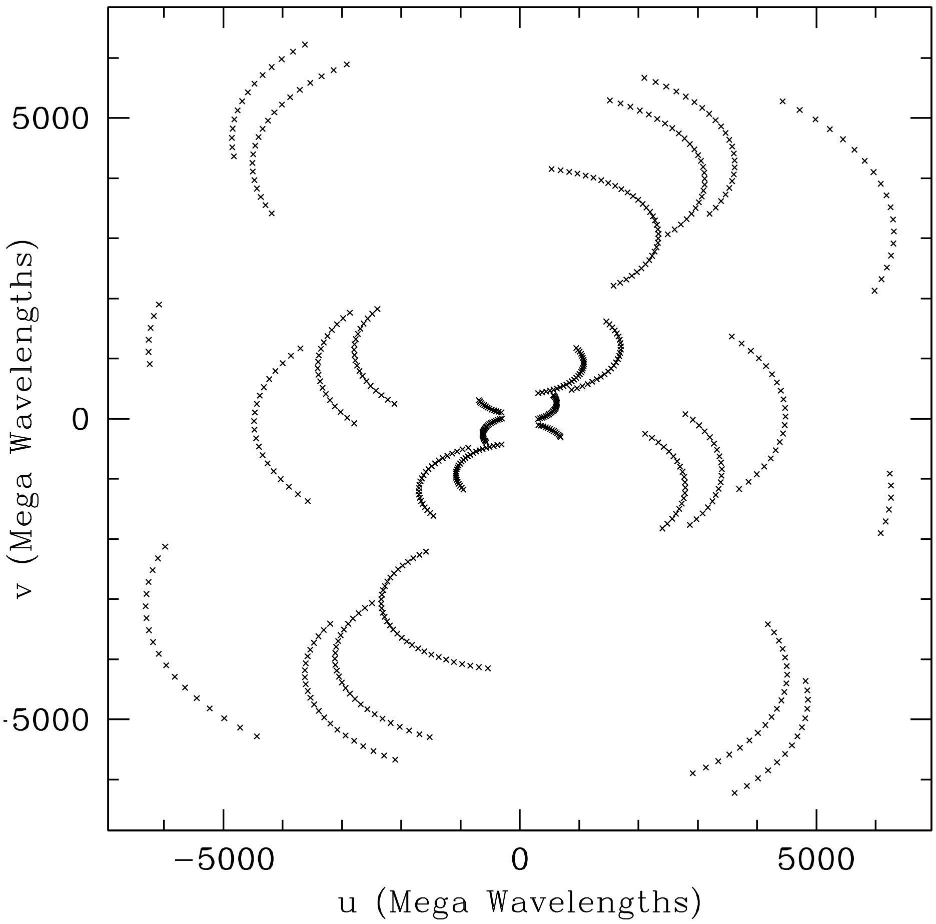

Figure 3 : Baseline coverage possible for a 1.3 mm VLBI experiment using ALMA, LMT, SMTO, JCMT/SMA, CARMA, IRAM 30-m, and Plateau de Bure. The lowest elevation at any site is 10° and Sgr A* is visible to at least three antennas at any time to ensure a closure quantity is available. The angular resolution of this array will be approximately 29 μas, about 5 Schwarzschild radii of the central black hole.

5. Summary

Sgr A* is a critical testing ground for studying astrophysics in the strong gravity of a black hole. In addition to probing gas dynamics and emission physics in this extreme environment, a high resolution VLBI image of Sgr A* will provide one of the tightest constraints on the mass density of a black hole possible.

The technical requirements for these experiments are stringent. A number of new developments, however, make these results attainable on the time scale of first light with ALMA. These developments include the new telescopes at mm and submm wavelengths; high bandwidth recording systems; phase correction techniques; and, time standards. Given these technical developments, there is no fundamental obstacle to extending VLBI of Sgr A* to 0.8 mm with an angular resolution of 20 microarcseconds (2 $R_{\rm sch}$). The necessary groundwork for Sgr A* VLBI imaging is underway with long baseline 1.3 mm VLBI experiments planned for early 2005, which will link antennas in Hawaii with the Western US. The recent success of short wavelength VLBI experiments coupled with the rapid pace of VLBI recording technology, suggest that initial 5-station 1.3 mm VLBI imaging of Sgr A* could take place before 2010.

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Abstracts

Intra-day Variation of Sagittarius A* at Short Millimeter Wavelengths

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We have performed the monitoring observations of flux density of Sagittarius A* at short millimeter wavelengths (100 and 140 GHz bands) on seven years in the period from 1996 to 2003 using the Nobeyama Millimeter Array (NMA). We found intra-day variation of Sgr A* in March 2000 flare. The flux density at the peak of the flares increases 100–200% at 100 GHz and 200–400% at 140 GHz (Delta S/S), respectively. The two-fold increase timescale of the flare is estimated to be about 1.5 hours at 140 GHz. The intra-day variation at mm-wavelengths has similar increase timescale as those in the X-ray and infrared flares but has smaller amplitude. This short timescale variability suggests that the physical size of the emitting region is smaller than 12 AU ($\approx 150\ R_s$). The decay timescale of the flare was at most 24 hours. Such a light curve with rapid increase and slow decay is similar to that often observed in outburst phenomena with ejections.

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Diffuse X-ray Emission in a Deep *Chandra* Image of the Galactic Center

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We examine the spectrum of diffuse emission detected in the 17′ by 17′ field around Sgr A* during 625 ks of *Chandra* observations. The spectrum exhibits He-like and H-like lines from Si, S, Ar, Ca, and Fe, that are consistent with originating in a two-temperature plasma, as well as a prominent low-ionization Fe K-α line. The cooler, $kT \approx 0.8$ keV plasma differs in surface brightness across the image between $(0.2 - 1.8) \times 10^{-13}$ erg cm^{-2} s^{-1} arcmin^{-2} (observed, 2–8 keV). This soft plasma is probably heated by supernovae, along with a small contribution from the winds of massive Wolf-Rayet and O stars. The radiative cooling rate of the soft plasma within the inner 20 pc of the Galaxy could be balanced by 1% of the kinetic energy of one supernova every 3×10^5 y. The hotter, $kT \approx 8$ keV component is more spatially uniform, with a surface brightness of $(1.5 - 2.6) \times 10^{-13}$ erg cm^{-2} s^{-1} arcmin^{-2} (observed; 2–8) keV. The intensity of the hard plasma is correlated with that of the soft, but they are probably only indirectly related, because neither supernova remnants nor WR/O stars are observed to produce thermal plasma hotter than $kT \approx 3$ keV. Moreover, a $kT \approx 8$ keV plasma would be too hot to be bound to the Galactic center, and therefore would form a slow wind or fountain of plasma. The energy required to sustain such a freely-expanding plasma within the inner 20 pc of the Galaxy is $\sim 10^{40}$ erg s^{-1}. This corresponds to the entire kinetic energy of one supernova every 3000 y, which is unreasonably high. However, alternative explanations for the $kT \approx 8$ keV diffuse emission are equally unsatisfying. The hard X-rays are unlikely to result from undetected point sources, because no known population of stellar object is numerous enough to the observed surface brightness. There is also no evidence that non-thermal mechanisms for producing the hard emission are operating, as the expected shifts in the line energies and ratios from their collisional equilibrium values are not observed. We are left to conclude that either there is a significant shortcoming in our understanding of the mechanisms that heat the interstellar medium, or that a population of faint ($< 10^{31}$ erg s^{-1}), hard X-ray sources that are a factor of 10 more numerous than CVs remains to be discovered.

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The Spectra and Variability of X-ray Sources in a Deep *Chandra* Observation of the Galactic Center

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We examine the X-ray spectra and variability of the sample of X-ray sources with $L < sub > X < /sub > \approx 10^{31} - 10^{33}$ erg s^{-1} identified within the inner $9'$ of the Galaxy by Muno et al. (2003). Very few of the sources exhibit intra-day or inter-month variations. We find that the spectra of the point sources near the Galactic center are very hard between 2–8 keV, even after accounting for absorption. When modeled as power laws the median photon index is $\Gamma = 0.7$, while when modeled as thermal plasma we can only obtain lower limits to the temperature of $kT > 8$ keV. The combined spectra of the point sources is similarly hard, with a photon index of $\Gamma = 0.8$. Strong line emission is observed from low-ionization, He-like, and H-like Fe, both in the average spectra and in the brightest individual sources. The line ratios of the highly-ionized Fe in the average spectra are consistent with emission from a plasma in thermal equilibrium. This line emission is observed whether average spectra are examined as a function of the count rate from the source, or as a function of the hardness ratios of individual sources. This suggests that the hardness of the spectra may in fact be to due local absorption that partially-covers the X-ray emitting regions in the Galactic center systems. We suggest that most of these sources are intermediate polars, which (1) often exhibit hard spectra with prominent Fe lines, (2) rarely exhibit either flares on short time scales or changes in their mean X-ray flux on long time scales, and (3) are the most numerous hard X-ray sources with comparable luminosities in the Galaxy.

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Metallicity in the Galactic Center: The Arches Cluster

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We present a quantitative spectral analysis of five very massive stars in the Arches cluster, located near the Galactic center, to determine stellar parameters, stellar wind properties and, most importantly, metallicity content. The analysis uses a new technique, presented here for the first time, and uses line-blanketed NLTE wind/atmosphere models fit to high-resolution near-infrared spectra of late-type nitrogen-rich Wolf-Rayet stars and OfI$^+$ stars in the cluster. It relies on the fact that massive stars reach a maximum nitrogen abundance that is related to initial metallicity when they are in the WNL phase. We determine the present-day nitrogen abundance of the WNL stars in the Arches cluster to be 1.6% (mass fraction) and constrain the stellar metallicity in the cluster to be solar. This result is invariant to assumptions about the mass-luminosity relationship, the mass-loss rates, and rotation speeds. In addition, from this analysis, we find the age of the Arches cluster to be 2–2.5 Myr, assuming coeval formation.

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High-Resolution, Wide-Field Imaging of the Galactic Center Region at 330 MHz

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We present a wide field, sub-arcminute resolution VLA image of the Galactic Center region at 330 MHz. With a resolution of $\sim 7'' \times 12''$ and an RMS noise of 1.6 mJy/beam, this image represents a significant increase in resolution and sensitivity over the previously published VLA image at this frequency. The improved sensitivity has more than tripled the census of small diameter sources in the region, has resulted in the detection of two new Non Thermal Filaments (NTFs), 18 NTF candidates, 30 pulsar candidates, reveals previously known extended sources in greater detail, and has resulted in the first detection of Sagittarius A$*$ in this frequency range.

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http://lwa.nrl.navy.mil/nord/AAAB.pdf

A Jet Model of the Galactic Center Nonthermal Radio Filaments

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Protostellar sources in star forming regions are responsible for driving jets with flow velocities ranging between 300 and 400 km s^{-1}. This class of jets consists of highly collimated outflows which include thermal knots with number densities estimated to be greater than that of their ambient medium. On the other hand, extragalactic FR I jets consist of light fluid with low Mach number burrowing through a denser medium as the magnetized jets radiate nonthermal emission. Both protostellar and extragalactic jets are believed to be launched by accretion disks. Here we consider a jet model in which the characteristics common to both protostellar and extragalactic jets are used to explain the origin of nonthermal filaments in the Galactic center region. We argue that these filaments are analogous to FR I extragalactic sources but are launched by embedded young stars or clusters of stars in star-forming regions.

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Kinematic and structural analysis of the Minispiral in the Galactic Center from BEAR spectro-imagery

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Integral field spectroscopy of the inner region of the Galactic Center, over a field of roughly $40'' \times 40''$ was obtained at 2.06 μm (HeI) and 2.16 μm (Brγ) using BEAR, an imaging Fourier Transform Spectrometer, at spectral resolutions respectively of 52.9 km s^{-1} and 21.3 km s^{-1}, and a spatial resolution of $\simeq 0.5''$. The analysis of the data was focused on the kinematics of the gas flows, traditionally called the "Minispiral", concentrated in the neighborhood of the central black hole, Sgr A*. From the decomposition into several velocity components (up to four) of the line profile extracted at each point of the field, velocity features were identified. Nine distinguishable structures are described: the standard Northern Arm, Eastern Arm, Bar, Western Arc, and five additional, coherently-moving patches of gas. From this analysis, the Northern Arm appears not limited, as usually thought, to the bright, narrow North-South lane seen on intensity images, but it consists instead of a weak, continuous, triangular-shaped surface, drawn out into a narrow stream in the vicinity of Sgr A* where it shows a strong velocity gradient, and a bright western rim. The Eastern Arm is split into three components (a Ribbon and a Tip, separated by a cavity, and an elongated feature parallel to the Ribbon: the Eastern Bridge). We also report extinction of some interstellar structures by other components, providing information on their relative position along the line of sight. A system of Keplerian orbits can be fitted to most of the Northern Arm, and the bright rim of this feature can be interpreted in terms of line-of-sight orbit crowding caused by the warping of the flowing surface at the western edge facing Sgr A*. These results lead to a new picture of the gas structures in Sgr A West, in which large-scale gas flows and isolated gas patches coexist in the gravitational field of the central Black Hole. The question of the origin of the ionized gas is addressed and a discussion of the lifetime of these features is presented.

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In situ acceleration in the Galactic Center Arc

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For the nonthermal radio emission of the Galactic Center Arc in situ electron acceleration is imperative. The observed radio spectrum can be modeled by a transport equation for the relativistic electrons which includes particle acceleration by electric fields, momentum diffusion via scattering by magnetohydrodynamical turbulence and energy losses by synchrotron radiation. The accelerating electric fields can be regarded as a natural consequence of multiple reconnection events, caused by the interaction between a molecular cloud and the Arc region. The radio spectrum and even the recently detected 150 GHz emission, explicitely originating from the interaction regions of a molecular cloud with the magnetized Arc, can be explained in terms of quasi-monoenergetically distributed relativistic electrons with a typical energy of about 10 GeV accelerated in stochastically distributed magnetic reconnection zones.

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Email: lieb@usm.uni-muenchen.de
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Life and Death of Young Dense Star Clusters near the Galactic Center

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We discuss the structural change and degree of mass segregation of young dense star clusters within about 100 pc of the Galactic center. In our calculations, which are performed with GRAPE-6, the equations of motion of all stars and binaries are calculated accurately but the external potential of the Galaxy is solved (semi)analytically. The simulations are preformed to model the Arches star cluster. We find that star clusters with are less strongly perturbed by the tidal field and dynamical friction are much stronger affected by mass segregation; resulting in a significant pile-up of massive stars in the cluster center. At an age of about 3.5 Myr more than 90 per cent of the stars more massive than $\sim 10\,M_\odot$ are concentrated within the half-mass radius of the surviving cluster. Star clusters which are strongly perturbed by the tidal field of the parent Galaxy are much less affected by mass segregation.

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Dust Embedded Sources at the Galactic Center 2 to 4μm imaging and spectroscopy in the central parsec

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We present the first L-band spectroscopic observations for a dozen stellar sources in the central 0.5 pc of the GC stellar cluster that are bright in the 2-4 μm wavelength domain. The L-band data were taken with ISAAC at the VLT UT1 (Antu). With the aid of additional K-band spectroscopic data, we derive optical depth spectra of the sources after fitting their continuum emission with a single reddened blackbody continuum. We also derive intrinsic source spectra by correcting the line of sight extinction via the optical depth spectrum of a late type star that is most likely not affected by local dust emission or extinction at the Galactic Center. The good agreement between the two approaches shows that the overall variation of the line-of-sight extinction across the central 0.5 pc is $\Delta A_K \leq 0.5$ mag. The extinction corrected spectra of the hot He-stars are in good agreement with pure Rayleigh Jeans continuum spectra. The intrinsic spectra of all other sources are in agreement with continuum emission and absorption features due to the dust in which they are embedded. We interprete both facts as evidence that a significant amount of the absorption takes place within the central parsec of the Galactic Center and is most likely associated with the individual sources there. We find absorption features at

$3.0\mu m$, $3.4\mu m$, and $3.48\mu m$ wavelength. Correlations between all three features show that they are very likely to arise in the ISM of the central 0.5 pc. Spacially highly variable hydrogen emission lines seen towards the individual sources give evidence of the complex density and temperature structure of the mini-spiral. In the cases of the sources with featureless K-band spectra like IRS 21 and IRS 1W, they are consistent with massive hot stars embedded in the bow shock created by their motion through the dust and gas of the mini-spiral. It is likely that the bow shock scenario may be applicable to most of the dust embedded sources in the central stellar cluster. Spectroscopy of high MIR-excess sources 0.5" north of the IRS 13 complex is largely consistent with them being YSOs. However, a bow-shock nature of these sources cannot be excluded. The L-band spectrum at the location of SgrA*, is consistent with that of a hot O-type star, such as S2, which was very close to Sgr A* at the time of our observations.

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A cool disk in the Galactic Center?

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We study the possibility of a cool disk existing in the Galactic Center in the framework of the disk-corona evaporation/condensation model. Assuming an inactive disk near the gravitational capture distance left over from an earlier evolutionary stage, a hot corona should form above the disk since there is a continuous supply of hot gas from stellar winds of the close-by massive stars. We study the interaction between the disk and the corona. Whether the cool disk can survive depends on the mass exchange between disk and corona which is determined by the energy and pressure balance. If evaporation is the dominant process and the rate is larger than the Bondi accretion rate in the Galactic Center, the disk will be depleted within a certain time and no persistent disk will exist. On the other hand, if the interaction results in hot gas steadily condensing into the disk, an inactive cool disk with little gas accreting towards the central black hole might survive in the Galactic Center. For this case we further investigate the Bremsstrahlung radiation from the hot corona and compare it with the observed X-ray luminosity. Our model shows that, for standard viscosity in the corona ($\alpha = 0.3$), the mass evaporation rate is much higher than the Bondi accretion rate and the coronal density is much larger than that inferred from Chandra observations. An inactive disk can not survive such strong evaporation. For small viscosity ($\alpha \lesssim 0.07$) we find condensation solutions. But detailed coronal structure computations show that in this case there is too much X-ray radiation from the corona to be in agreement with the observations. From this modeling we conclude that there should be no thin/inactive disk presently in the Galactic Center. However we do not exclude that the alternative non-radiative model of Nayakshin (2004) might instead be realized in nature and shortly discuss this question.

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Email: bifang@MPA-Garching.MPG.DE
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X-Ray Observations of Stellar Clusters Near the Galactic Center

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We report the first detection of X-ray emission from the Quintuplet star cluster and comp are its X-ray emission to that of the Arches star cluster. Four point sources are signif icantly detected near the core of the Quintuplet cluster with a total, absorption-correct ed luminosity of $\sim 1 \times 10^{33}$ ergs s^{-1}. Diffuse, thermal emission is also d etected near the core of the Quintuplet cluster with an absorption-corrected luminosity o f $\sim 1 \times 10^{34}$ ergs s^{-1}. We analyze the diffuse and point-like emission fro m the Arches and Quintuplet and discuss the possibility that they are host to cluster win d outflows. We also present the results of our search for X-ray emission from candidate star clusters in the Galactic center (GC) region. We use extinction estimated by near-IR colors and X-ray spectral fits, as well as other IR properties, to determine if the cand idate clusters are new, GC star clusters. We find that three of the six candidate cluste rs found toward the GC are likely foreground clusters, two of the candidate clusters are not detected in the X-ray data, but have near-IR extinctions consistent with a GC locatio n, and one of the candidate clusters has X-ray and near-IR extinctions consistent with be ing in the GC. The X-ray and IR

emission from the candidate clusters is compared to the known, massive, GC star clusters.

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http://www.astro.northwestern.edu/ claw/docs/

Dynamical Friction on Galactic Center Star Clusters with an Intermediate-Mass Black Hole

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Numerical simulations of the dynamical friction suffered by a Galactic center star cluster harboring an intermediate-mass black hole (IMBH) have been performed. Gerhard has suggested that dynamical friction, which causes a cluster to lose orbital energy and spiral in toward the Galactic center, may explain the presence of a cluster of very young stars in the central parsec, where star formation might be prohibitively difficult because of strong tidal forces. However, numerical simulations by Kim & Morris showed that this is only possible if the cluster initially has an extremely dense core. Hansen & Milosavljević recently suggested that the presence of an IMBH in the cluster core might stabilize the core against tidal disruption during the inspiral through dynamical friction, and thus might easily deliver young stars down to the central parsec. We find that the presence of an IMBH does lower the minimum initial core density required to transport young stars down to the central parsec, but this is possible only when the mass of the IMBH is at least $\sim$ 10 % of the total cluster mass. This fraction is significantly higher than that estimated by Portegies Zwart & McMillan with numerical simulations of IMBH formation by successive merging of stars in the cluster core, so it does not appear that a realistic IMBH can help transport young stars into the central parsec.

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The nature of the Galactic Center source IRS 13 revealed by high spatial resolution in the infrared

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High spatial resolution observations in the 1 to 3.5 micron region of the Galactic Center source known historically as IRS 13 are presented. They include ground-based adaptive optics images in the H, Kp (2.12/0.4 micron) and L bands, HST-NICMOS data in filters between 1.1 and 2.2 micron, and integral field spectroscopic data from BEAR, an Imaging FTS, in the HeI 2.06 micron and the Brγ line regions. Analysis of all these data provides a completely new picture of the main component IRS 13E, which appears as a cluster of seven individual stars within a projected diameter of 0.5" (0.02 pc). The brightest sources, 13E1, 13E2, 13E3 which is detected as a binary, and 13E4, are all massive stars of different type. The star 13E1 is a luminous, blue object, with no detected emission line. 13E2 and 13E4 are two hot, high-mass emission line stars, 13E2 being at the WR stage and 13E4 a massive O-type star. In contrast, 13E3A and B are extremely red objects, proposed as other examples of dusty WR stars, like IRS 21 (Tanner et al. 2002). All these sources have a common westward proper motion indicating they are bounded. Two fainter sources, detected after deconvolution of the AO images in the H and Kp bands, are also identified. One, that we call 13E5, is a red source similar to 13E3A and B, while the other one, 13E6, is probably a main sequence O star in front of the cluster. Considering this exceptional concentration of comoving massive hot stars, IRS 13E is proposed as the remaining core of a massive star cluster, which could harbor an intermediate-mass black hole (IMBH) (Portegies Zwart & McMillan 2002) of $\sim$ 1300 $M_{\odot}$. This detection plays in favor of a scenario, first suggested by Gerhard (2001), in which the helium stars and the other hot stars in the central parsec originate from the stripping of a massive cluster formed several tens of pc from the center.

This cluster would have spiraled towards SgrA*, and IRS 13E would be its remnant. Furthermore, IRS 13E might be the second black hole needed according to a model by Hansen & Milosavljevic (2003) to drag massive main-sequence stars, in the required timescale, very close to the massive black hole. The detection of a discrete X-ray emission (Baganoff et al. 2003) at the IRS 13 position is examined in this context.

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Detection of the Intrinsic Size of Sagittarius A* through Closure Amplitude Imaging

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We have detected the intrinsic size of Sagittarius A*, the Galactic Center radio source associated with a supermassive black hole, showing that the short-wavelength radio emission arises from very near the event horizon of the black hole. Radio observations with the Very Long Baseline Array show that the source has a size of 24 ± 2 Schwarzschild radii at 7 mm wavelength. In one of eight 7-mm epochs we also detect an increase in the intrinsic size of $60^{+25}_{-17}\%$. These observations place a lower limit to the mass density of Sgr A* of 1.4×10^4 solar masses per cubic astronomical unit.

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Email: gbower@astron.berkeley.edu
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Young Massive Clusters in the Galactic Center

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The three young clusters in the Galactic Center represent the closest examples of massive starbursts and they define the upper mass limit of the Galactic cluster mass functions. In this review, I describe the characteristics and content of the Arches, Quintuplet, and Central clusters. They each are more massive than any other cluster in the Galaxy, and the Arches cluster, in particular, has a mass and age that make it ideal for studies of massive stellar evolution and dense stellar systems. A preliminary measurement indicates that the initial mass function in the Galactic center is top-heavy, suggesting an environmental effect that has otherwise been absent in similar observations for Galactic clusters. Given the relatively more evolved nature of the Quintuplet and Central clusters, these clusters contain stars in a wide range of evolutionary states, including Luminous Blue Variables and Wolf-Rayet stars. The Quintuplet cluster provides a particularly interesting view of the most massive stars that are known, the Pistol Star and FMM362. An analysis of the mass spectrum in the Arches cluster suggests an upper mass cutoff of ~150-200 $M_\odot$.

Ref.:
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Announcements

We hear that the Kavli Institute for Theoretical Physics at UCSB will host a 3-day conference on the Galactic Center on 2005 April 14–16. Stay tuned to `http://www.kitp.ucsb.edu/` for more information.

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 . . . .

Please note that the GCNews website is now hosted by NRAO. Although the Max-Plank site, frequently listed by web search engines, should direct you to the new page, please make sure you update your bookmarks! http://www.aoc.nrao.edu/∼gcnews

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