# GCNEWS

The Newsletter of Galactic Center Research

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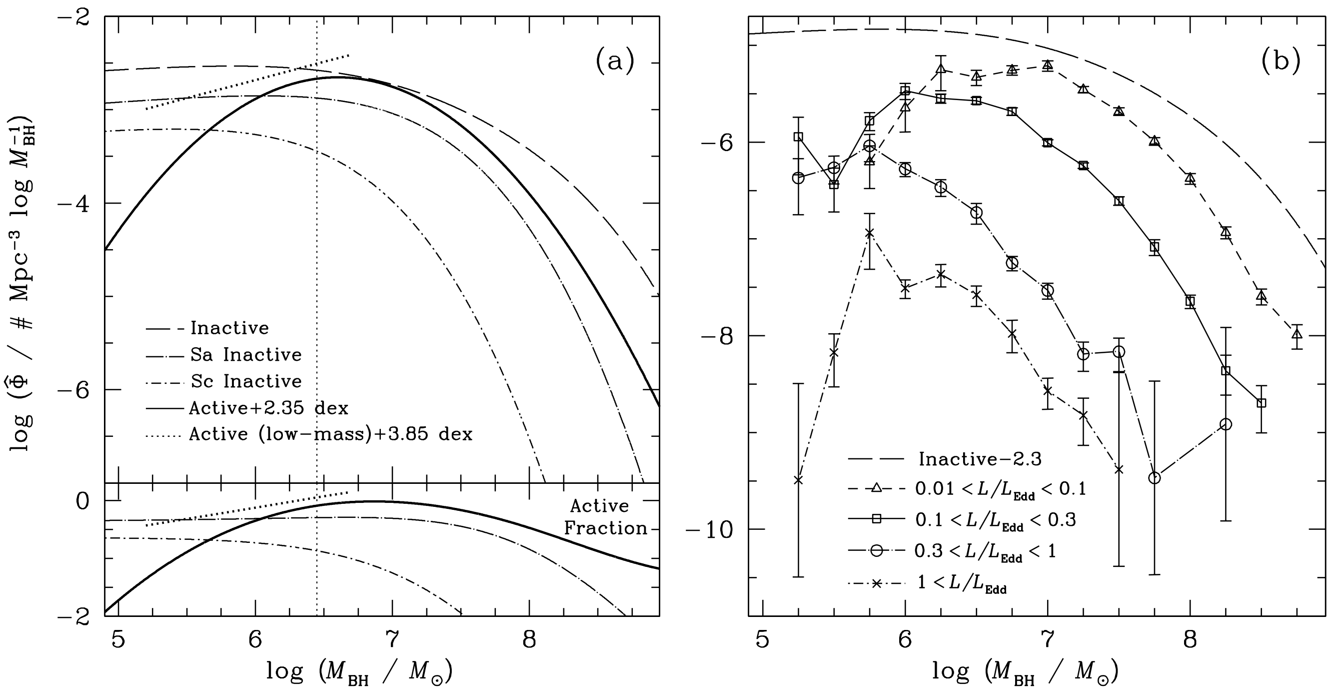
## The Mass Function of Active Black Holes in the Local Universe




Comparison of the mass functions of inactive supermassive black holes (analogs to Sgr A*) and supermassive black holes in broad-line hosting galaxies. The ratio between the total inactive mass function and each population is shown in the bottom panel. The vertical line indicates the point at which the conversion from galaxy luminosity to BH mass becomes quite uncertain. Also shown is a comparison of the inactive BH mass function (*dashed*) with the active mass function in different Eddington ratio bins (*solid symbols*). It is clear that all high-mass BHs are radiating at very low Eddington ratios. For more details, see invited article by Greene & Ho. (Figure courtesy J. Greene)

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# In the News

*Joseph Lazio & Sera Markoff*

Our ability to observe the Galactic Center in ever-increasing detail has made it a field unto itself, driving the creation of this forum as well as the interest in the frequent GC-related meetings (three of which are listed in this issue!). However, Sgr A* itself is also important in the greater context of accreting supermassive black holes and their apparently cyclical accretion/growth cycles. To understand black hole growth, we need to understand black hole feeding, and Sgr A*'s current "starvation phase" can provide clues about how AGN evolve over time. If we further want to understand how Sgr A* fits into the greater scheme of accreting supermassive black holes, we need to study samples of nearbly galaxies with similar mass distributions. In this Volume, we are pleased to be able to present a brief summary of some of the recent pioneering work by Jenny Greene and Luis Ho, on the mass function of these nearby members of Sgr A*'s extended family.

Though 2006 may have been a year of Galactic center meetings, this year appears to be quite active as well. There were a number of results reported at the American Astronomical Society's winter meeting, which we summarize here, and we know of a number of meetings already in which the Galactic center will be taking an important, if not leading, role.

Finally, we have 18 abstracts submitted for this issue! Thanks to all of these authors for sharing their work. Please continue to submit your recent publication information to GC News (including the link to `astro-ph`).

**International GC Research & Meetings**

## Galactic Center Mini-workshop

A Galactic center mini-workshop was held at NAOJ, on 2006 July 6. This meeting focused on the semicircular structures of the molecular gas found in the Galactic center. Summarised by the conference organiser, Mami Machida.

### Part 1: Discovery of Molecular Loops in the Galactic Center

**Molecular Loops in the Galactic Center** They presented a magnetic floatation model in which molecular loops discovered by the NANTEN telescope are formed due to the magnetic buoyancy caused by the Parker instability. (**Fukui, Yasuo**, Nagoya Univ.)

**Molecular Loops—Detailed Discussion** They discussed about the forth quadrant loops: Loop 1 and 2. The kinetic energy involved in a loop is estimated to be $10^{51}$ erg for a velocity dispersion of 30 km s$^{-1}$. The position-velocity diagram showed that loop foot points have a large velocity span and are connected by a bridge. (**Kudo, Natsuko**, Nagoya Univ.)

**Molecular Loops—Comparison with CO and H I** They compared the distribution of CO with H I gas in Loop 1 and 2. They found a good correlation between CO and H I. (**Torii, Kazufumi**, Nagoya Univ.)

### Part 2: Observations at Other Wavelengths

**Vertical Structure in Edge-on Galaxy NGC 891** They found that a prominent spur structure of molecular gas is emerging vertically from the disk in NGC 891. They suggested that this spur may be ejected from the Galactic disk due to a superbubble or formed by the Parker instability. (**Handa, Toshihiro**, Univ. of Tokyo)

**High Excitation Molecular Gas in CMZ** They discovered a vast amount of high-temperature and low-density gas with a large velocity dispersion in the central molecular zone of the Galaxy. These high excitation gas and wide velocity dispersion indicate that local expansions are the origin of compact molecular gas structures. (**Oka, Tomoharu**, Univ. of Tokyo)

**Magnetic Field Structure of SNRs** Supernova remnants (SNRs) are one of the efficient accelerators of cosmic rays. Hard X-ray observations show that the acceleration efficiency at shock fronts of SNRs is very high. From TeV gamma-ray observations, they suggested that a few hundred undiscovered SNRs may exist. (**Bamba, Aya**, RIKEN)

**Magnetic Field in the CMZ** According to the infrared observations, the magnetic field in the Galaxy is aligned with the Galactic plane. In the CMZ, the magnetic field strength is estimated to be milligauss. (**Nakagawa, Takao**, JAXA)

## Part 3: Theories and Numerical Simulations of the Parker Instability

**Origin of Molecular Loop Structures** They considered that molecular loop structures are created by the Parker instability. If the strength of the magnetic field is about 100 $\mu$G, the molecular gas sliding down along the magnetic fields can generate velocity dispersion of as high as 50 km $s^{-1}$. (**Matsumoto, Ryoji**, Chiba Univ.)

**Two-dimensional Simulations of Galactic Loops** They carried out two-dimensional MHD simulations of the Parker instability. It successfully reproduced the two loop-like structures observed in the Galactic center region. (**Nozawa, Satoshi**, Ibaraki Univ.)

**Three-dimensional Simulations of Galactic Disks** They carried out three-dimensional MHD simulations of Galactic gas disks. They showed that the magnetic flux buoyantly rise from the disk. (**Machida, Mami**, NAOJ)

## Part 4: Theories of the Phenomenon in Galactic Disks

**Magnetic Field Amplification** Due to the Galactic rotation, the Galactic gas disk subjects to MRI and becomes turbulent. When the gas is isothermal, magnetic flux tubes can be created. (**Sano, Takayoshi**, Osaka Univ.)

**Formation of Molecular Gas Cloud** They studied the conditions for the molecular cloud formation by the Parker instability. (**Koyama, Hiroshi**, Kobe Univ.)

**Particle Acceleration inside the Galaxy** They investigated whether the shock formed by the Parker instability can be the origin of the particle acceleration for the energy range between $10^{15}$ and $10^{18}$ eV or not. They concluded from the rough estimation that the Parker instability is likely to be the origin of cosmic-ray acceleration. (**Asano, Katsuaki**, NAOJ)

The proceedings of this meeting are published in PDF format (in Japanese).

# American Astronomical Society Meeting

As is usually the case, there were a host of new results reported at the winter meeting of the Amer. Astron. Soc. (2007 January 5–10 in Seattle). One of the plenary sessions ("Hypervelocity Stars") even dealt with the debris ejected from the Galactic center. Below we list papers we saw at the AAS that concerned the Galactic center. Numbers in parentheses after the author list indicate the abstract number.

### Sgr A*

- "Flaring Activity of Sgr A*: Adiabatic Expansion of Nonthermal Plasma," F. Yusef-Zadeh et al. (112.07)
- "Hypervelocity Stars Ejected from the Galactic Center," W. R. Brown (138.01)
- "Discovery of Variable Iron Fluorescence from Reflection Nebulae in the Galactic Center," M. P. Muno et al. (254.10)

### The Galactic Center Environment

- "The Galactic Center: High-resolution Imaging and Temperature Determination of Dense Molecular Clouds," J. Ott et al. (017.11)
- "Comparison of $^{13}$CO Line and Far-Infrared Continuum as a Diagnostic of Dust and Molecular Gas Physical Conditions—Implications for the $N(H_2)/I(CO)$ Conversion Factor," W. F. Wall (055.01)
- "A Wide Area Map of The Galactic Center at 1.1 mm," E. A. Mills et al. (172.01)
- "Modeling the Galactic Center Magnetic Field Using Synchrotron Flux Density Ma ps," B. J. Cowin & M. Morris (172.02)
- "A High-resolution Polarimetric Survey of the Central 200 pc of the Galaxy," T. M. Freismuth et al. (172.16)
- "An H I Absorption Survey of the Central 250 pc of the Galactic Center: Distance Constraints & Understanding the Complex ISM," K. I. Clubb & C. C. Lang (172.24)

### Stars in the Galactic Center

- "High Resolution Radio Observations of the Nebulae of Luminous Blue Variable Stars," A. Mercer et al. (101.05)
- "First Results from a Galactic Center Search for Pulsars and Transients:A Rotating Radio Transient Candidate," J. S. Deneva et al. (159.08)
- "New Hot Stars in the Galactic Center," J. Mauerhan (172.03)
- "Spectroscopic Observations of the Galactic Center with OSIRIS," T. Do et al. (172.25)

- “The Proper Motion of the Arches Cluster: Cluster Membership and Understanding the Origin of Massive Young Clusters near the Galactic Center,” A. Stolte et al. (254.06)

**Extreme Physics in the Galactic Center**

- “The Search for Dark Matter and New Physics using the Gamma Ray Large Area Space Telescope (GLAST) Large Area Telescope (LAT),” L. L. Wai et al. (037.01)
- “Gamma-rays from Dark Matter in the Galactic Center,” D. P. Finkbeiner (037.0 2)

**Astrometry in the Galactic Center**

- “43 GHz SiO Masers for Phase Calibration with VERA in the Galactic Center,” R. M. Edmonds et al. (172.07)
- “Gravitational Lensing and the Distance to the Galactic Center,” E. L. Gutbrod & S. Levine (172.12)

## Upcoming GC Meetings

## Bursts, Pulses and Flickering: Wide-Field Monitoring of the Dynamic Radio Sky

June 12-15 2007, Kerastari, Greece

**Final details**

We included the full announcement last issue, but just a reminder that the registration and hotel booking is open in April, with pre-registration encouraged. Please see the webpage for more details:

http://www.atnf.csiro.au/Dynamic2007/

## GC2007: Celebrating 15 years of Precision Astronomy in the Galactic Center - Hot Topics and Observational Challenges

June 17-23, 2007, Ringberg Castle, Germany

In 1992, the first observations of a star in a close orbit around the supermassive blackhole at the Galactic Center were obtained. Today we know that this star, ”S2”, has a period of 15 years, so 2007 we can celebrate the first revolution of ”S2”. We are doing so by organizing a scientific workshop to be held at Schloss Ringberg (Ringberg castle), Bavaria (http://www.schloss-ringberg.de/). The main focus of the conference will be stellar dynamics in the Galactic Center. A full day will also be dedicated to the topic of Sgr A*. Because accomodation is limited to 65, the meeting will not have an open registration. For more details see the conference website:

http://www.mpe.mpg.de/ir/meetings/ringberg2007/index.php

SOC: Tal Alexander, Fred Baganoff, Marcella Carollo, Andreas Eckart, Heino Falcke, Karl Gebhardt, Reinhard Genzel (Chair), Ortwin Gerhard, Andrea Ghez, Abraham Loeb, Mark Morris, Eliot Quataert, Mark Reid, Daniel Rouan, Jonathan Tan

## A Population Explosion: The Nature and Evolution of X-ray Binaries in Diverse Environments

October 28-November 2 2007, St. Petersburg Beach, FL

In recent years, technological advances in X-ray astronomy have led to the discovery of a large number of previously undetected high-energy sources, increasing by an order of magnitude the known population of X-ray binaries in the Galaxy. This meeting will address the current state of observational and theoretical research into the X-ray binary population as a whole, incorporating studies of both the previously known, well-studied systems and the newly discovered populations, and examine the feedback and interaction of X-ray binaries with their environment within our own Galaxy and in external galaxies. We would especially like to highlight research on recently discovered populations of accreting binaries, including the faint hard X-ray sources in the Galactic Centre, obscured sources identified with INTEGRAL, supergiant fast X-ray transients, and extragalactic binaries.

We have established five major topics for this five-day conference, and plan to devote one day to each topic:

1. X-ray binary jets at high and low luminosities, and their effect on the XRB environment
2. Faint X-ray binary populations, especially the in Galactic Centre
3. Obscured populations (INTEGRAL sources, SFXTs)
4. Extragalactic X-ray binary populations and ULXs
5. X-ray binary population synthesis and stellar evolution

SOC: Stefanie Wachter (Spitzer Science Center/Caltech), Reba Bandyopadhyay (University of Florida) (co-chairs), Sera Markoff (University of Amsterdam) Jocelyn Bell Burnell (University of Oxford), Philipp Podsiadlowski (University of Oxford), Tom Maccarone (University of Southampton), Rob Fender (University of Southampton), Michael Muno (Caltech), John Tomsick

(University of California, Berkeley), Saku Vrtilek (Harvard/CfA), Phil Charles (SAAO)

The deadline for registration and submitting abstracts is 1 June 2007, using the secure server on the conference website:

http://conference.astro.ufl.edu/XRAYBIN/

Attendance at the meeting will be limited to 170 participants. For more details see the webpages.

# The Mass Function of Active Black Holes in the Local Universe

**Jenny E. Greene[1,2] & Luis C. Ho[3]**

[1]Department of Astrophysical Sciences, Princeton University, [2]Hubble Fellow, [3]The Observatories of the Carnegie Institute of Washington

## Introduction: Demographics of Supermassive Black Holes

Our Galactic Center contains the nearest, and best-studied, supermassive black hole (BH). No observations of external galaxies may compete in angular resolution or depth. Still, we may learn whether our own supermassive BH is typical through the study of the demographics of nearby BHs, which has seen spectacular progress in the past decade. Dynamical measurements of the motions of stars or gas in the centers of nearby spheroids have revealed that BHs are a ubiquitous component of galaxy nuclei (e.g., Kormendy 2004) and that the mass of the BH is tightly correlated with the mass and structure of the surrounding spheroid (e.g., the $M_{\rm BH} - \sigma_*$ relation; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002).

Sgr A*, with a mass of $3.5 \times 10^6$ $M_\odot$ (e.g., Ghez et al. 2005; Eisenhauer et al. 2005), happens to be amongst the lowest dynamical BH masses known. This does not, however, represent a real physical limit on supermassive BH masses. Rather, selection biases caused by the requirements of dynamical mass modeling severely limit the dynamic range in BH mass probed by these methods. Specifically, spiral bulges have been avoided because of dust, which limits the exploration of low-mass bulges. At the same time, resolving the gravitational sphere of influence of a $\sim 10^5$ $M_\odot$ BH is currently impossible beyond the Local Group. Therefore, at the present time, our only technique for probing the full distribution of supermassive BH masses is to use active galactic nuclei (AGNs; e.g., Greene & Ho 2004). We are particularly interested in the lowest BH masses because, while they constitute a negligible fraction of the present-day BH mass density, they provide one of the only nearby analogs of primordial BHs which "seeded" the growth of the large AGN we see today.

Here we present a newly selected sample of local broad-line AGNs from the Sloan Digital Sky Survey (SDSS; York et al. 2000), where local in this context means systems with redshifts $z < 0.35$. We wish to examine the full range of BH masses in active systems; in particular, this will provide otherwise inaccessible information about the lowest-mass AGNs. At the same time, a comparison between the active and inactive BH mass function will show that the incidence of nuclear activity depends on BH mass. Locally, galaxies of similar mass to the Milky Way are far more likely to be active than are giant elliptical galaxies.

A warning is in order. In contrast to the measurements of Sgr A*, our ability to measure BH masses in active systems is very imprecise (factor of $\sim 4$ uncertainties). Furthermore, we are sensitive only to the most vigorous accretion in the local Universe, with typical Eddington ratios of $\sim 10\%$. Nevertheless, as we will see, there is quite interesting information in the shape of the mass function of this population.

## Methods

BHs are identified by the presence of broad Balmer emission lines (specifically H$\alpha$), where broad here means significantly broader than the narrow emission lines in the region (i.e., H$\alpha$+[N II] $\lambda\lambda$6548, 6583 and [S II] $\lambda\lambda$6716, 6731) and the line widths range from $\sim 700-10,000$ km s$^{-1}$. These are broad-line AGNs (sometimes called Type 1 AGNs), and not only does the broad emission tell us that the gas is moving in the very deep gravitational potential of a supermassive BH, but we can use the gas motions to estimate a virial mass for the central object. The typical emission region for the broad-line emitting gas can be measured based on the lag between variability in the AGN continuum and the corresponding variability in the broad emission flux. From these "reverberation mapping" experiments we derive average scaling relations between the AGN luminosity and the emission-region size (e.g., Kaspi et al. 2005). Combined with the average gas velocity measured by the broad-line width, we may then derive a "virial" mass for the central object.

There are $\sim 8700$ broad-line AGNs in the Fourth Data Release of the Sloan Digital Sky Survey, and Figure 1 shows the raw distributions in BH mass and Eddington ratio. The Eddington ratio is, in the usual way, the ratio of bolometric luminosity to the Eddington luminosity. However, keep in mind that unlike the case of the Galactic Center, we do not in general have the luxury of exquisite multi-wavelength data, and thus the "bolometric" luminosities here

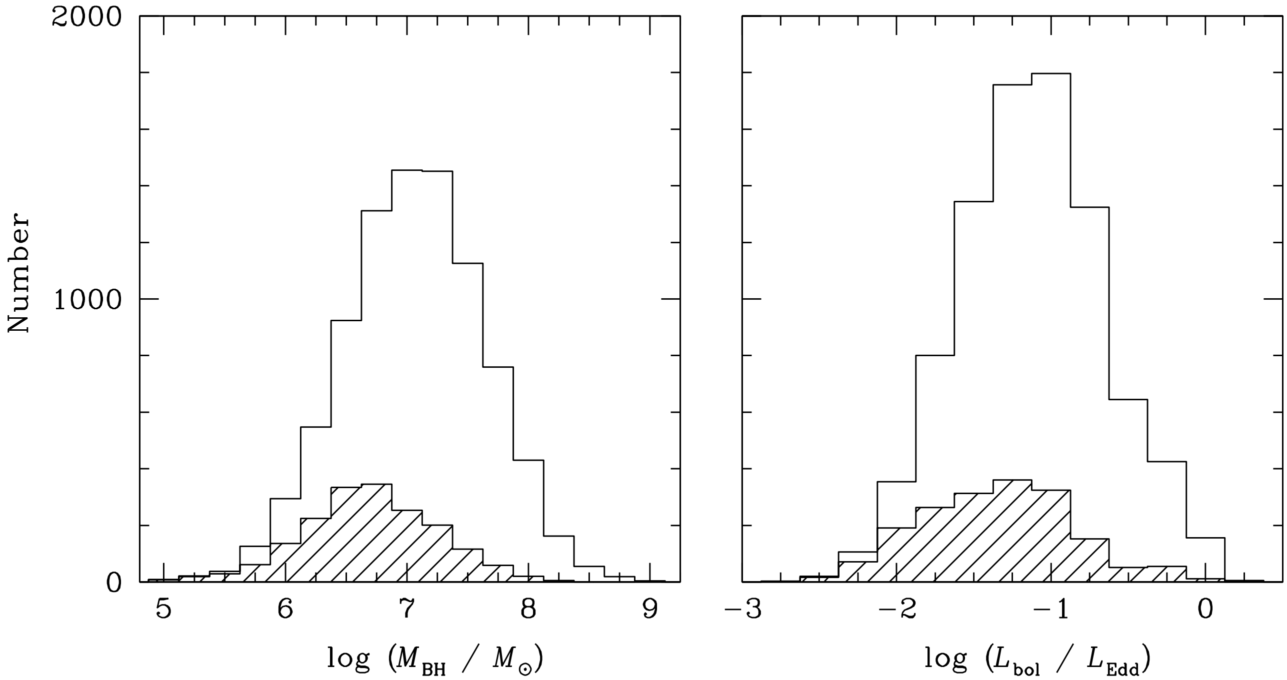


Figure 1 Distributions of BH mass (*left*) and $L_{\rm bol}/L_{\rm Edd}$ (*right*) for the entire sample of broad-line AGNs. $M_{\rm BH}$ is calculated from the AGN luminosity and line-width. The Eddington ratio is derived assuming an average bolometric correction of $L_{\rm bol} = 2.34 \times 10^{44} (L_{\rm H\alpha}/10^{42})^{0.86}$ ergs s$^{-1}$. The galaxies targeted in the SDSS main sample are indicated with the shaded histogram. Note that while the galaxy-selected AGNs are uniformly at low luminosities, they span the entire range of $M_{\rm BH}$ in the sample. Massive BHs are predominantly in low-accretion states at the present time.

are simply scaled optical luminosities. In principle, one could do better using cross-correlations between the SDSS and either *ROSAT*, *Chandra*, or *XMM-Newton*. The main message of Figure 1 is that our typical source has a mass of $\sim 10^7\ M_\odot$ and radiates at $\sim 10\%$ of its Eddington limit. These objects are significantly more active than Sgr A* (indeed we would never detect an object radiating at the level of Sgr A*), and in general somewhat more massive. However, recall that a low-mass BH will have a low luminosity even when radiating at its Eddington limit, and so we must account for rather severe selection effects before we draw any strong conclusions about the distribution of BH mass in active systems.

We can account for selection effects in a straightforward manner by assigning each AGN a maximum observable volume; faint objects get a large weight because they are only detectable in a small volume. Both the selection effects imposed by the SDSS targeting algorithm and the effect of our own spectroscopic selection algorithms are folded into the calculation. In Figure 2 we show the resulting BH mass function, appropriately weighted. Even this technique is limited at the lowest BH masses and Eddington ratios, since an entire class of objects is completely undetectable by our techniques. Sgr A*, were it active at $\sim 10\%$ of Eddington, would be detectable in our survey out to a considerable volume. As one moves to even lower BH mass, both the AGN and the galaxy grow fainter and fainter. Therefore, the low-mass BHs that we do find tend to live in relatively luminous host galaxies. These complications make a determination of the slope of the BH mass function at low masses particularly challenging. To mitigate these effects, we fit mass functions in very narrow redshift and luminosity bins, over which the completeness is uniform. The dotted line in Figure 3*a* represents our best fit slope at low mass. We find evidence for a declining space density below $\sim 10^{6.5}\ M_\odot$ at the $\sim 3\,\sigma$ level.

## Mass-dependent Duty Cycle

Our measurement of the space density of active BHs as a function of BH mass, combined with a measurement of the total distribution of BH mass in the Universe today, allows us to address how often a given system is active (the duty cycle) as a function of BH mass. Since there are tight correlations between BH mass and bulge luminosity, observed galaxy luminosity functions can be converted into an estimate for the total local BH mass. We use the techniques outlined in Marconi et al. (2004) to derive the inactive BH mass function shown as the long-dashed line in Figure 3*a*. The shapes of the active and inactive mass functions are quite different, meaning that the duty cycle

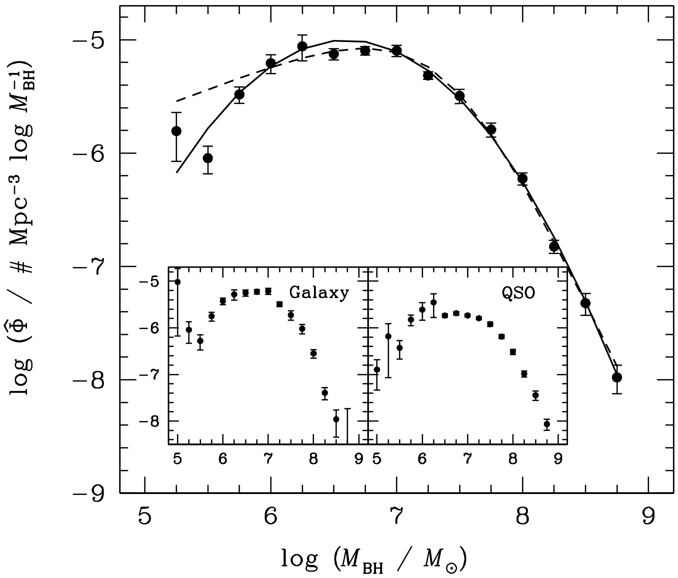


Figure 2 Volume-weighted BH mass function in bins of 0.25 dex (# Mpc$^{-3}$ log $M_{\rm BH}{}^{-1}$). Each object is weighted by its maximum observable volume. In the inset are shown the mass functions for objects targeted as galaxies (*left*) and QSOs (*right*), respectively. Although we are subject to significant incompleteness both at higher and lower masses, we argue that there is truly a turnover in active galaxy masses at both lower and higher BH masses. We have fit the mass function with both a double power-law (dashed line) and a log-normal function (solid line).

is a strong function of BH mass. The charactistic inactive BH has a mass of $10^8$ $M_{\odot}$, while the active mass function peaks a bit below $10^7$ $M_{\odot}$. Heckman et al. (2004) found a very similar behavior in low-redshift narrow-line AGNs. Their BH masses are derived from measurements of bulge stellar velocity dispersions, while our masses do not rely directly on the $M_{\rm BH} - \sigma_*$ relation, and so it is comforting that our two techniques agree.

BHs with masses similar to Sgr A* dominate the active ($L_{\rm bol}/L_{\rm Edd} \approx 10\%$) BH population at low redshift. This is not terribly surprising. The most massive BHs are found in massive elliptical galaxies, which are gas-poor and are not forming many stars today.

They, and their BHs, presumably finished growing at higher redshift. Low-mass galaxies have younger stars, and a more ready supply of gas and they are more likely to display nuclear activity. Nevertheless, in detail the strong mass dependence must be explained quantitatively. For one thing, massive elliptical galaxies do have continuing gas supplies, either from late accretion and merging, or more simply just from the mass loss of the stars in the galaxy (e.g., Faber & Gallagher 1976). At the same time, we know that Sgr A* has a ready supply of gas and is relatively inactive; our observations suggest that BHs of comparable mass to Sgr A* are active 0.4% of the time. A $10^9$ $M_{\odot}$ BH is ten times less likely to be active today. These more massive BHs, however, are increasingly likely to be active at increasingly low accretion rates (e.g., Fig. 3*b*; Ho et al. 1997). Models of episodic AGN fueling in the local Universe ought to reproduce this observed mass dependence in the active fraction (e.g., Ciotti & Ostriker 2001).

Another interesting feature in the mass function is the apparent decrease in the duty cycle as one moves to even lower BH mass ($< 10^6$ $M_{\odot}$), although in general such galaxies are increasingly gas rich. BHs of such low mass are approaching the putative masses of seed BHs in the early Universe, and this downturn could signify a real physical lower limit to the mass of supermassive BHs. We know, in fact, that dwarf galaxies do not always contain a BH. For instance, M33, a bulgeless galaxy in the Local Group, does not appear to contain a nuclear BH (Gebhardt et al. 2001). On the other hand, we do not know how to convert the observed galaxy luminosity function into BH mass in this regime, since dwarf galaxies do not necessarily contain bulges. A combination of detailed study of the host galaxies of low-mass BHs (Greene et al. in prep) and alternate search techniques for low-mass BHs (e.g. deep radio surveys) should help disentangle whether the duty cycle or space density is declining faster at low BH mass.


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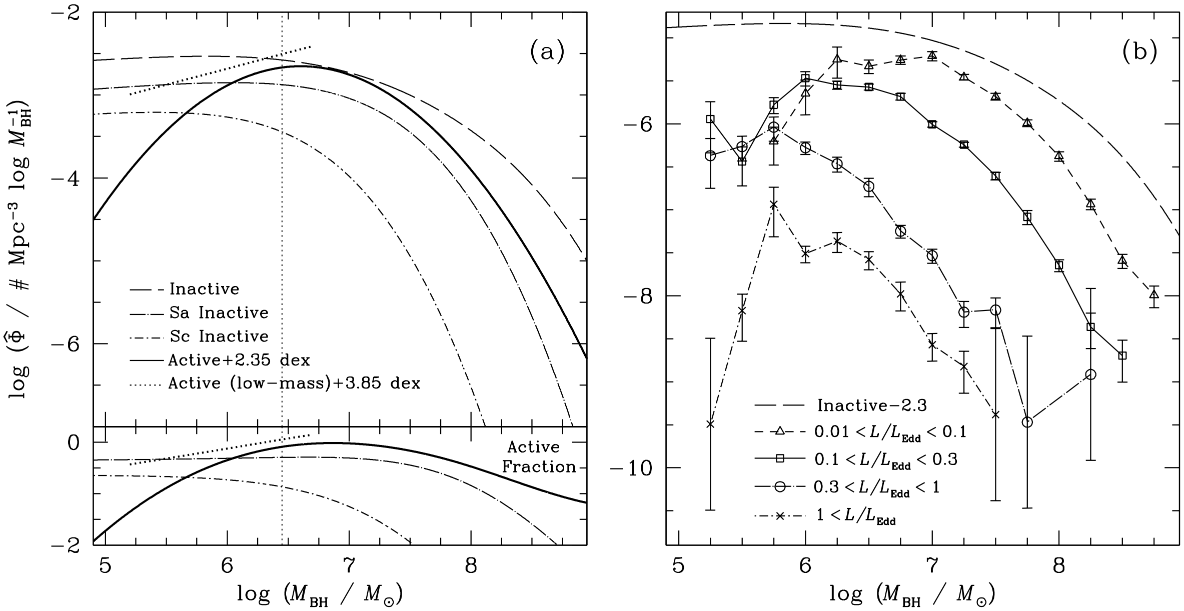


Figure 3 (*a*) Comparison of the inactive BH mass function with the broad-line BH mass function. The inactive mass function is derived using the formalism of Marconi et al. (2004). We show the log-normal fit to the active BH mass function (*solid*) and the best-fit power law to the lowest-mass, lowest-$z$ bin to demonstrate the uncertainty in slope and break position at the low-mass end. The ratio between the total inactive mass function and each population is shown in the bottom panel. The vertical line indicates the point at which the conversion from galaxy luminosity to BH mass becomes quite uncertain. (*b*) Comparison of the inactive BH mass function (*dashed*) with the active mass function in different Eddington ratio bins (*solid symbols*). Bins with $> 3$ points are shown. It is clear that all high-mass BHs are radiating at very low Eddington ratios.


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# Abstracts

## The Arches Cluster Mass Function

*Sungsoo S. Kim(1), Donald F. Figer(2), Rolf P. Kudritzki(3), & F. Najarro(4)*

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We have analyzed $H$- and $K_s$-band images of the Arches cluster obtained using the NIRC2 instrument on Keck with the laser guide star adaptive optics (LGS AO) system. With the help of the LGS AO system, we were able to obtain the deepest ever photometry for this cluster and its neighborhood, and derive the background-subtracted present-day mass function (PDMF) down to 1.3 $M_\odot$ for the $5''$–$9''$ annulus of the cluster. We find that the previously reported turnover at 6 $M_\odot$ is simply due to a local bump in the mass function (MF), and that the MF continues to increase down to our 50 % completeness limit (1.3 $M_\odot$) with a power-law exponent of $\Gamma = -0.91$ for the mass range of $1.3 < M/M_\odot < 50$. Our numerical calculations for the evolution of the Arches cluster show that the $\Gamma$ values for our annulus increase by 0.1–0.2 during the lifetime of the cluster, and thus suggest that the Arches cluster initially had $\Gamma$ of $-1.0 \sim -1.1$, which is only slightly shallower than the Salpeter value.

Ref.: ApJ, 2006, 653, L113
Email: figer@cis.rit.edu
Eprint: astro-ph/0611377

## Flaring Activity of Sgr A*: Expanding Hot Blobs

*F. Yusef-Zadeh, M. Wardle, D. A. Roberts, C. O. Heinke, C. D. Dowell, W. D. Cotton, G. C. Bower, & F. K. Baganoff*

Sgr A* is considered to be a massive black hole at the Galactic center and is known to be variable in radio, millimeter, near-IR, and X-rays. Recent multi-wavelength observing campaigns show a simultaneous X-ray and near-IR flare, as well as submillimeter and near-IR flares from Sgr A*. The flare activity is thought to be arising from the innermost region of Sgr A*. We have recently argued that the duration of flares in near-IR and submillimeter wavelengths implies that the burst of emission expands and cools on a dynamical time scale before the flares leave Sgr A*. The detection of radio flares with a time delay in the range of 20 and 40 min. between 7 and 12 mm peak emission implies adiabatic expansion of a uniform, spherical hot blob due to flare activity. We suspect that this simple outflow picture shows some of the characteristics that are known to take place in microquasars, thus we may learn much from comparative study of Sgr A* and its environment vs. microquasars.

Ref.: IV Microquasar Workshop, astro-ph/0612156
Email: zadeh@northwestern.edu
Eprint: astro-ph/0612156

## The Possibility of Detecting Sagittarius A* at 8.6 $\mu$m from Sensitive Imaging of the Galactic Center

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Sagittarius A* (Sgr A*) at the center of the Milky Way is a black hole accreting at extremely sub-Eddington rates. Measurements of its emission in the infrared and X-ray domains are difficult due to its faintness and high variability. The Galactic center was observed at 8.6 $\mu$m in order to detect a mid-infrared (MIR) counterpart to Sgr A*, parallel to NIR observations. The goal was to set constraints on possible emission mechanisms. Imaging data were acquired with the adaptive-optics assisted NIR instrument NACO and the MIR instrument VISIR at

the ESO VLT. We present MIR imaging data of an unprecedented quality in terms of spatial resolution and sensitivity. An extended ridge of emission is found to be present in the immediate vicinity of Sgr A* thereby rendering any detection of a point source difficult. No MIR point source related to Sgr A* was detected during the observations. We derive a tight upper limit of $22 \pm 14$ mJy (dereddened) on any possible point source present during the observations in the night of 4/5 June 2006. The absence of a flare in simultaneous observations at 2.2 $\mu$m and the low limits on any possible variability in the MIR strongly suggest that Sgr A* was in a quasi-quiescent state during this night. During the night from 5 to 6 June 2006, Sgr A* was found to be variable on a low level at 3.8 $\mu$m. No point source at 8.6 $\mu$m was detected during the simultaneous MIR observations. Due to the poorer atmospheric conditions, a higher upper limit of $60 \pm 30$ mJy was found for Sgr A* at 8.6 $\mu$m during the second night. The observations are consistent with theoretical predictions. If the published models are correct, the observations demonstrate successfully that a 8.6 $\mu$m counterpart of Sgr A* can be easily detected in its flaring state. Spectral indices derived from simultaneous observations of flaring emission from Sgr A* at NIR and MIR wavelengths will enable us to distinguish between different kinds of flare models.

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## A Faint, Steep Spectrum Burst from the Radio Transient GCRT J1745−3009

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GCRT J1745−3009 is a transient bursting radio source located in the direction of the Galactic center. It was discovered in a 330 MHz VLA observation from 2002 September 30–October 1 and subsequently rediscovered in a 330 MHz GMRT observation from 2003 September 28 by Hyman et al. Here we report a new radio detection of the source in 330 MHz GMRT data taken on 2004 March 20. The observed properties of the single burst detected differ significantly from those measured previously, suggesting that GCRT J1745−3009 was detected in a new physical state. The 2004 flux density was $\sim 0.05$ Jy, $\sim 10\times$ weaker than the single 2003 burst and $\sim 30\times$ weaker than the five bursts detected in 2002. We derive a very steep spectral index, $\alpha = -13.5 \pm 3.0$, across the bandpass, a new result previously not detectable due to limitations in the analysis of the 2002 and 2003 observations. Also, the burst was detected for only $\sim 2$ min., in contrast to the 10 min. duration observed in the earlier bursts. Due to sparse sampling, only the single burst was detected in 2004, as in the 2003 epoch, and we cannot rule out additional undetected bursts that may have occurred with the same $\sim 77$ min. periodicity observed in 2002 or with a different periodicity. Considering our total time on source throughout both our archival and active monitoring campaigns, we estimate the source exhibits detectable bursting activity $\sim 7\%$ of the time.

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## Photometric Stellar Variability in the Galactic Center

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We report the results of a diffraction-limited, photometric variability study of the central $5'' \times 5''$ of the Galaxy conducted over the past 10 yr using speckle imaging techniques on the W. M. Keck I 10-m telescope. Within our limiting magnitude of $m_K < 16^{\mathrm{m}}$ for images made from a single night of data, we find a minimum of 15 K[2.2 $\mu$m]-band variable stars out of 131 monitored stars. While large populations of binaries have been posited to exist in this region, both to explain the presence of young stars in the vicinity of a black hole and because of the high stellar densities, only two binaries are identified in this study. First is the previously identified Ofpe/WN9 equal mass eclipsing binary star IRS 16SW, for which we measure an orbital period of $19.448 \pm 0.002$ days. In contrast to recent results, our data on IRS 16SW show an asymmetric phased light curve with a much steeper fall-time than rise-time, which may be due to tidal deformations caused by the proximity of the stars in their orbits. Second is the WC9 Wolf-Rayet star IRS 29N; its observed photometric variation over a few year time-scale is likely due to episodic dust production in a binary system containing two windy stars. Our sample also includes 4 candidate Luminous Blue Variable (LBV) stars (IRS 16NE, 16C, 16NW, 16SW). While 2 of them show variability, none show the characteristic of LBVs large increase or decrease in luminosity. However, our time baseline is too short to rule them out as LBVs. Nonetheless, the lack of evidence for these stars to be LBVs and their coexistence with a significant surrounding population of well established Wolf-Rayet stars is consistent with needing only a single recent starburst event at the Galactic center to account for all of the known, young, massive stars. Among the remaining variable stars, the majority are early-type stars and three are possibly variable due to line of sight extinction variations. For the 7 OB stars at the center of our field of view that have well-determined 3-dimensional orbits, we see no evidence of flares or dimming of their light, which limits the possibility of a cold, geometrically-thin inactive accretion disk around the supermassive black hole, Sgr A$^*$.

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## Far-Infrared detection of $H_2D^+$ toward Sgr B2

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We repport on the first far-IR detection of $H_2D^+$, using the Infrared Space Observatory, in the line of sight toward Sgr B2 in the Galactic center. The transition connecting the ground level of o-$H_2D^+$, $1_{1,1}$, with the the $2_{1,2}$ level at 113 K is observed in absorption against the continuum emission of the cold dust of the source. The line is broad, with a total absorption covering 350 km s$^{-1}$, i.e., similar to that observed in the fundamental transitions of $H_2O$, OH, and CH at $\sim$179, 119, and 149 $\mu$m, respectively. For the physical conditions of the different absorbing clouds the $H_2D^+$ column density ranges from 2 to $5 \times 10^{13}$ cm$^{-2}$, i.e., near an order of magnitude below the upper limits obtained from ground based submillimeter telescopes. The derived $H_2D^+$ abundance is of order a few $10^{-10}$, which agrees with chemical models predictions for a gas at a kinetic temperature of $\simeq$20 K.

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## A Possible Link Between the Galactic Center HESS Source and Sgr A*

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Recently, HESS and other air Cerenkov telescopes have detected a source of TeV $\gamma$-rays coincident with the Galactic center. It is not yet clear whether the $\gamma$-rays are produced via leptonic or hadronic processes, so it is important to consider possible acceleration sites for the charged particles which produce the $\gamma$-rays. One exciting possibility for the origin of these particles is the central black hole, Sgr A*, where the turbulent magnetic fields close to the event horizon can accelerate protons to TeV energies. Using a realistic model of the density distribution in a 6 pc $\times$ 6 pc $\times$ 6 pc cube at the Galactic center, we here calculate the trajectories followed by these TeV protons as they gyrate through the turbulent medium surrounding Sgr A*. Diffusing out from the black hole, the protons produce TeV $\gamma$-rays via $\pi^0$ decay following a collision with a proton in the surrounding medium. After following over 222,000 such trajectories, we find that the circumnuclear ring around Sgr A* can reproduce the observed 0.1–100 TeV HESS spectrum and flux if the protons are injected into this medium with an effective power-law index $\approx 0.75$, significantly harder than the observed photon index of 2.25. The total energy in the steady-state 1–40 TeV proton population surrounding Sgr A* is inferred to be $\approx 2 \times 10^{47}$ ergs. Only 31% of the emitted 1–100 TeV protons encounter the circumnuclear torus, leaving a large flux of protons that diffuse outward to contribute to the Galactic ridge emission observed by HESS on scales of $\gtrsim 1^\circ$.

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## A Symbiotic Scenario for the Rapid Formation of Supermassive Black Holes

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The most massive black holes, lurking at the centers of large galaxies, must have formed less than a billion years after the Big Bang, as they are visible today in the form of bright quasars at redshift larger than six. Their early appearance is mysterious, because the radiation pressure, generated by infalling ionized matter, inhibits the rapid growth of these black holes from stellar-mass black holes. It is shown that the supermassive black holes may form timeously through the accretion of predominantly degenerate sterile neutrino dark matter onto stellar-mass black holes. Our symbiotic scenario relies on the formation of, first, supermassive degenerate sterile neutrino balls through gravitational cooling and, then, stellar-mass black holes through supernova explosions of massive stars at the center of the neutrino balls. The observed lower and upper limits of the supermassive black holes are explained by the corresponding mass limits of the preformed neutrino balls.

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## Properties of the Radio-Emitting Gas Around Sgr A*

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We show that the radial profiles of the temperature and density of the electrons as well as the magnetic field strength around the massive black hole at the Galactic center, Sgr A*, may be constrained directly from existing radio data without any need to make prior assumptions about the dynamics of the emitting gas. The observed spectrum and wavelength-dependent angular size of Sgr A* indicate that the synchrotron emission originates from an optically-thick plasma of quasi-thermal electrons. We find that the electron temperature rises above the virial temperature within tens of Schwarzschild radii from the black hole, suggesting that the emitting plasma may be outflowing. Constraints on the electron density profile are derived from polarization measurements. Our best-fit results differ from expectations based on existing theoretical models. However, these models cannot be ruled out as of yet due to uncertainties in the source size measurements. Our constraints could tighten considerably with future improvements in the size determination and simultaneous polarization measurements at multiple wavelengths.

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## The Cosmic Ray Distribution in Sagittarius B

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The HESS instrument has observed a diffuse flux of $\sim$ TeV $\gamma$-rays from a large solid angle around the

Galactic center (GC). This emission is correlated with the distribution of gas in the region suggesting that the $\gamma$-rays originate in collisions between cosmic ray hadrons (CRHs) and ambient matter. Of particular interest, HESS has detected $\gamma$-rays from the Sagittarius (Sgr) B molecular cloud complex. Prompted by the suggestion of a hadronic origin for the gamma rays, we have examined archival 330 and 74 MHz Very Large Array radio data and 843 MHz Sydney University Molonglo Sky Survey data covering Sgr B, looking for synchrotron emission from secondary electrons and positrons (expected to be created in the same interactions that supply the observed $\gamma$ rays). Intriguingly, we have uncovered non-thermal emission, but at a level exceeding expectation. Adding to the overall picture, recent observations by the Atacama Pathfinder Experiment telescope show that the cosmic ray ionization rate is ten times greater in the Sgr B2 region of Sgr B than the local value. Lastly, Sgr B2 is also a very bright X-ray source. We examine scenarios for the spectra of CRHs and/or primary electrons that would reconcile all these different data. We determine that (i) a hard ($\sim E^{-2.2}$), high-energy ($\gtrsim$ TeV) population CRHs is unavoidably required by the HESS $\gamma$-ray data, and (ii) the remaining broadband, non-thermal phenomenology is explained either by a rather steep ($\sim E^{-2.9}$) spectrum of primary electrons or a ($\sim E^{-2.7}$) population of CRHs. No single, power-law population of either leptons or hadrons can explain the totality of broadband, non-thermal Sgr B phenomenology.

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## The ISO LWS high resolution spectral survey towards Sagittarius B2

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A full spectral survey was carried out towards the Giant Molecular Cloud complex, Sagittarius B2 (Sgr B2), using the ISO Long Wavelength Spectrometer Fabry-Pérot mode. This provided complete wavelength coverage in the range 47–196 $\mu$m (6.38–1.53 THz) with a spectral resolution of 30–40 km s$^{-1}$. This is an unique dataset covering wavelengths inaccessible from the ground. It is an extremely important region of the spectrum as it contains both the peak of the thermal emission from dust, and crucial spectral lines of key atomic (OI, CII, OIII, NII and NIII) and molecular species ($NH_3$, $NH_2$, NH, $H_2O$, OH, $H_3O^+$, CH, $CH_2$, $C_3$, HF and $H_2D^+$). In total, 95 spectral lines have been identified and 11 features with absorption depth greater than $3\sigma$ remain unassigned. Most of the molecular lines are seen in absorption against the strong continuum, whereas the atomic and ionic lines appear in emission (except for absorption in the OI 63 $\mu$m and CII 158 $\mu$m lines). Sgr B2 is located close to the Galactic Centre and so many of the features also show a broad absorption profile due to material located along the line of sight. A full description of the survey dataset is given with an overview of each detected species and final line lists for both assigned and unassigned features.

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## The Galactic Center as a point source of neutrons at EeV energies

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The central region of our Galaxy is a very peculiar environment, containing magnetic fields in excess of 100 mG and gas densities reaching $\sim 10^4$cm$^{-3}$. This region was observed as a strong source of GeV and TeVs gammas, what suggests that a mechanism of proton-neutron conversion could be taking place therein. We propose that the Galactic Center must also be a source of EeV neutrons due to the conversion of ultra high energy cosmic ray protons into neutrons via p-p interactions inside this region. This scenario should be falsifiable by the Pierre Auger Observatory after a few years of full exposure.

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## Stellar and wind properties of massive stars in the central parsec of the Galaxy

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How star formation proceeds in the Galactic Center is a debated question. Addressing this question will help us understand the origin of the cluster of massive stars near the supermassive black hole, and more generally starburst phenomena in galactic nuclei. In that context, it is crucial to know the properties of young massive stars in the central parsec of the Galaxy. The main goal of this study is to derive the stellar and wind properties of the massive stars orbiting the supermassive black hole SgrA* in two counter-rotating disks. We use non-LTE atmosphere models including winds and line-blanketing to reproduce H and K band spectra of these stars obtained with SINFONI on the ESO/VLT. The GC massive stars appear to be relatively similar to other Galactic stars. The currently known population of massive stars emit a total $6.0 \times 10^{50}$ s$^{-1}$ (resp. $2.3 \times 10^{49}$ s$^{-1}$) H (resp. He I) ionising photons. This is sufficient to produce the observed nebular emission and implies that, in contrast to previous claims, no peculiar stellar evolution is required in the Galactic Center. We find that most of the Ofpe/WN9 stars are less chemically evolved than initially thought. The properties of several WN8 stars are given, as well as two WN/C stars confirmed quantitatively to be stars in transition between the WN and WC phase. We propose the sequence (Ofpe/WN9 / LBV) → WN8 → WN/C for most of the observed GC stars. Quantitative comparison with stellar evolutionary tracks including rotation favour high mass loss rates in the Wolf-Rayet phase in these models. In the OB phase, these tracks nicely reproduce the average properties of bright supergiants in the Galactic Center.

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## Discovery of Hot Supergiant Stars Near the Galactic Center

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We report new results of a campaign to find Wolf-Rayet and O (WR/O) stars and high-mass X-ray binaries (HMXBs) in the Galactic center. We searched for candidates by cross-correlating the *Two-Micron All-Sky Survey* with a deep *Chandra X-ray Observatory* catalog of point sources in the Radio Arches region. Following up with $K$-band spectroscopy, we found two massive stellar counterparts to CXOGC J174555.3-285126 and CXOGC J174617.0-285131, which we classify as a broad-lined WR star of subtype WN6b and an O Ia supergiant, respectively. Their X-ray properties are most consistent with those of known colliding-wind binaries in the Galaxy and the Large Magellanic Cloud, although a scenario involving low-rate accretion onto a compact object is also possible. The O Ia star lies 4.4 pc in projection from the Quintuplet cluster, and has a radial velocity consistent with that of the Quintuplet, suggesting that this star might have escaped from the cluster. We also present the discovery of a B2 Ia supergiant, which we identified as a candidate massive star using 8 $\mu$m *Spitzer* maps of the Galactic center in a region near the known massive X-ray-emitting star CXOGC J174516.1-290315. We discuss the origin of these stars in the context of evolving stellar clusters in the Galactic center.

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## The structure of the nuclear stellar cluster of the Milky Way

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The centre of the Milky Way is the nearest nucleus of a galaxy and offers a unique possibility to study the structure and dynamics of a dense stellar cluster around a super-massive black hole. We present high-resolution seeing limited and AO NIR imaging observations of the stellar cluster within about one parsec of Sgr A*, the massive black hole at the centre of the Milky Way. Stellar number counts and the diffuse background light density were extracted from these observations in order to examine the structure of the nuclear stellar cluster. A detailed map of the variation of interstellar extinction in the central $\sim 0.5$ pc of the Milky Way is presented and used to correct the stellar number counts and diffuse light density. Our findings are as follows: (a) A broken-power law provides an excellent fit to the overall structure of the GC nuclear cluster. The power-law slope of the cusp is $\Gamma = 0.19 \pm 0.05$, the break radius is $R_{break} = 6.0'' \pm 1.0''$ or $0.22 \pm 0.04$ pc, and the cluster density decreases with a power-law index of $\Gamma = 0.75 \pm 0.1$ outside of $R_{break}$. (b) Using the best velocity dispersion measurements from the literature, we derive higher mass estimates for the central parsec than assumed until now. The inferred density of the cluster at the break radius is $2.8 \pm 1.3 \times 10^6 M_\odot\, pc^{-3}$. This high density agrees well with the small extent and flat slope of the cusp. Possibly, the mass of the stars makes up only about 50% of the total cluster mass. (c) Possible indications of mass segregation in the cusp are found (d) The cluster appears not entirely homogeneous. Several density clumps are detected that are concentrated at projected distances of $R = 3''$ and $R = 7''$ from Sgr A*.(e) There appears to exist an under-density of horizontal branch/red clump stars near $R = 5''$, or an over-density of stars of similar brightness at $R = 3''$ and $R = 7''$. (f) The extinction map in combination with cometary-like features in an L'-band image may provide support for the assumption of an outflow from Sgr A*.

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## Black Hole Shadow Image and Visibility Analysis of Sagittarius A*

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The compact dark objects with very large masses residing at the centres of galaxies are believed to be black holes. Due to the gravitational lensing effect, they would cast a shadow larger than their horizon size over the background, whose shape and size can be calculated. For the supermassive black hole candidate Sgr A*, this shadow spans an angular size of about 50 micro arc second, which is under the resolution attainable with the current astronomical instruments. Such a shadow image of Sgr A* will be observable at about 1 mm wavelength, considering the scatter broadening by the interstellar medium. By simulating the black hole shadow image of Sgr A* with the radiatively inefficient accretion flow model, we demonstrate that analyzing the properties of the visibility function can help us determine some parameters of the black hole configuration, which is instructive to the sub-millimeter VLBI observations of Sgr A* in the near future.

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## How to hide large scale outflows: size constraints on the jets of Sgr A*

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Despite significant strides made towards understanding accretion, outflow, and emission processes in the Galactic Center supermassive black hole Sagittarius A*, the presence of jets has neither been rejected nor proven. We investigate here whether the combined spectral and morphological properties of the source at radio through near infrared wavelengths are consistent with the predictions for inhomogeneous jets. In particular, we construct images of jets at a wavelength of 7mm based on models that are consistent with the spectrum of Sgr A*. We then compare these models through closure quantities with data obtained from the Very Long Baseline Array at 7mm. We find that the best-fit jet models give comparable or better fits than best-fit Gaussian models for the intrinsic source found in previous analyses. The best fitting jet models are bipolar, are highly inclined to the line of sight ($\theta \gtrsim 75°$), may favor a position angle on the sky of 105°, and have compact bases with sizes of a few gravitational radii.

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## The INTEGRAL Galactic bulge monitoring program: the first 1.5 years

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The Galactic bulge region is a rich host of variable high-energy point sources. Since 2005, February 17 we are monitoring the source activity in the Galactic bulge region regularly and frequently, i.e., about every three days, with the instruments onboard *INTEGRAL*. Thanks to the large field of view, the imaging capabilities and the sensitivity at hard X-rays, we are able to present for the first time a detailed homogeneous (hard) X-ray view of a sample of 76 sources in the Galactic bulge region. We describe the successful monitoring program and show the first results from the start of the monitoring up to 2006, April 21, i.e., for a period of about one and a half year, during three visibility seasons. We focus on the short (hour), medium (month) and long-term (year) variability in the hard X-ray bands, i.e., 20–60 keV and 60–150 keV. When available, we discuss the simultaneous observations in the soft X-ray, 3–10 keV and 10–25 keV, bands. Almost all the sources in the Galactic bulge region we detect in the 20–60 keV and 60–150 keV bands are variable. During the last two and a half weeks of the third visibility season most of the known persistent (hard) X-ray sources in the Galactic Center region were not detected. Of our sample of sources, per visibility season we detect 32/33 sources in the 20–60 keV band and 8/9 sources in the 60–150 keV band above a signal to noise of 7. On average, we find per visibility season one active bright ($\gtrsim$100 mCrab, 20–60 keV) black-hole candidate X-ray transient and three active weaker ($\lesssim$25 mCrab, 20–60 keV) neutron star X-ray transients. Most of the time a clear anti-correlation can be seen between the soft and hard X-ray emission in some of the X-ray bursters. Hard X-ray flares or outbursts in X-ray bursters, which have a duration of the order of weeks are accompanied by soft X-ray drops. On the other hand, hard X-ray drops can be accompanied by soft X-ray flares/outbursts. During the course of our program we found a number of new sources, IGR J17354−3255, IGR 17453−2853, IGR J17454−2703, IGR J17456−2901b, IGR J17536−2339,

and IGR J17541−2252. We report here on some of the high-energy properties of these sources. The high-energy light curves of all the sources in the field of view, and the high-energy images of the region, are made available through the WWW, as soon as possible after the observations have been performed, at http://isdc.unige.ch/Science/BULGE/.

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