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Orbits and Origins of the Young Stars in the Central Parsec

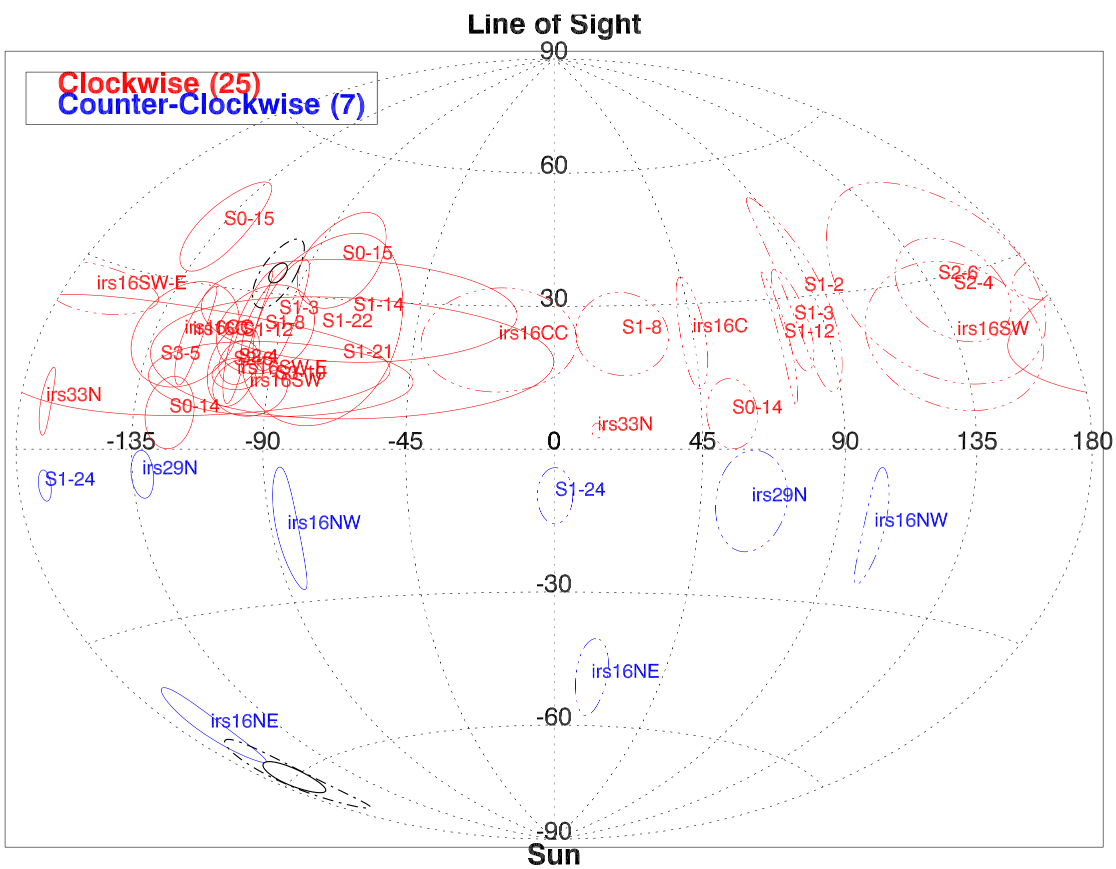

Figure 1 The distribution of orbital planes as determined from individual stellar orbits. The normal vector for each star's orbital plane, plus the associated uncertainty in that vector, describes a cone in 3D space. This cone can be projected as an elliptical region onto a celestial sphere centered on the black hole. The projected 3 sigma region of the normal vectors are plotted on an Aitoff projection of this celestial sphere with clockwise rotators in red and counter-clockwise in blue. See article for more details. Image credit: J. Lu & collaborators.

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In the News

Cornelia Lang & Rainer Schödel

Happy Holidays to all! We are pleased to end 2006 with a final issue of Galactic Center News. In this issue, we are back to having our regular feature article. This issue we present an invited review by Jessica Lu (UCLA) and collaborators featuring their results on high-precision measurements on stellar dynamics within 3"/0.11 pc of Sgr A*. They derive tight constraints on the orbital parameters of 33 young stars. From the orientation of the stellar orbits, they confirm the existence of a clockwise rotating disk of stars. Lu et al. have derived robust lower limits on the eccentricities of the young stars. They derive eccentricities > 0.4 for several stars in the clockwise disk, which is challenging to scenarios that propose that the young stars have formed in an accretion disk. The presented results provide important new constraints on models that intend to explain star formation mechanisms in the inner half-parsec, in immediate vicinity to the super-massive black hole and its intense tidal field.

The editorial board is happy to announce the arrival of two new members: welcome to Dr. Feng Yuan from the Shanghai Astronomical Observatory (SHAO) in China and Dr. Masaaki Sakano from University of Leicester in the UK (also by way of Japan). Each of them has contributed a report for this issue on current international efforts in Galactic Center research.

Joseph Lazio also reports on a successful session on Galactic Center results at the IAU General Assembly this past August. He is now the chair of a new IAU Working Group on the GC and GCs in other galaxies under the auspices of the Galactic System Division (VII). Thanks to Joe and to Patricia Whitelock of the South African Astronomical Observatory (the President of the IAU Division VII (The Galactic System)) for organizing and running this session and generating interest in GC research!

Finally, we have 27 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 astroph).

International GC Research & Meetings

Galactic Center Research in China

contributed by Feng Yuan (SHAO)

In China, recently, the Shanghai Astronomical Observatory (SHAO) has become a center for research on the Galactic center (GC). There are also faculty interested in this research area at the Institute of High Energy Physics (IHEP) and at Shanghai Jiaotong University. Both SHAO and IHEP belong to the Chinese Academy of Sciences (CAS), a national organization composed of over eighty institutes, aiming at conducting research in basic and technological sciences (similar to the Max-Planck Society in Germany). At SHAO, the three faculty working on GC research are Dr. Tao An, Dr. Feng Yuan, and Dr. Zhiqiang Shen.

The following are highlights of Galactic Center research in China:

• Broadband Multi-wavelength Campaign of SgrA*: 90 cm to 3.8 μm

Dr. Tao An observed the simultaneous multiwavelength continuum of Sgr A*. He and his collaborators (including Dr. Jun-Hui Zhao of the Harvard-Smithsonian Center for Astrophysics and Dr. Zhi-qiang Shen) observed Sgr A* using the Very Large Array (VLA) and the Giant Metrewave Radio Telescope (GMRT) in Pune, India, at multiple centimeter and millimeter wavelengths on 2003 June 17 when a strong outburst was occurring. The measured flux densities of Sgr A*, together with those obtained from the Submillimeter Array (SMA) and the Keck II 10 m telescope on the same date, are used to construct a simultaneous spectrum of Sgr A* from 90 cm to 3.8 μm, which seems to be so far the broadest spectrum measured on the same date. Perhaps more interestingly, they detected a significant low-frequency cutoff at about 100 cm. Compared with the detection obtained 28 years ago, the cutoff wavelength has increased by a factor of 3. They interpreted that the variation of the long wavelength cutoff is due to the change of column density of cool ionized gas in the free-free absorption screen in front of Sgr A* (An et al. 2005).

• Kinematics of the "Mini-Spiral"

Currently Dr. Tao An is involved in a project studying the kinematics of the ionized gas associated with the GC 'mini-spiral' using cm- and mm-wavelength data. The observations and data reduction have been finished.

• SgrA*: Source Size & Structure

Dr. Zhi-qiang Shen is working on radio observations of the Galactic center, including the radio size measurement of Sgr A* and its radio variability. Last year, using VLBI, Dr. Shen and his collaborators (including Dr. Jun-Hui

Zhao of Harvard-Smithosian CfA) successfully obtained a radio image of Sgr A* at a wavelength of 3.5 mm, demonstrating that its size is ∼1AU (Shen et al. 2005). When combined with the lower limit on its mass, the lower limit on the mass density is $6.5 \times 10^{21} M_{\odot} \mathrm{pc}^{-3}$, which provides a strong evidence that Sgr A* is a supermassive black hole.

Furthermore, Dr. Shen and his collaborators detected larger apparent source sizes in one epoch of 7 mm VLBA observation. This indicates a temporal variation in the structure of Sgr A*. The derived structure is relatively big and intrinsically symmetrical within the error bars. Assuming this was caused by an outburst, they estimated the location of such a flare to be about 40 Schwarzschild radii from the central supermassive black hole (Shen et al. 2006).

• Accretion Models for Sgr A*

Dr. Feng Yuan has been working on the accretion models of Sgr A*. In particular, Since Dr. Ramesh Narayan first applied the ADAF model to Sgr A* in 1995, much progress has been made on this type of model. Dr. Yuan and his collaborators have recently updated the original ADAF model for Sgr A* into something known as the Radiatively Inefficient Accretion Flow (or 'RIAF') model (e.g., Yuan, Quataert & Narayan 2003; 2004; see Yuan 2006 for a recent review). The recent size measurements of Sgr A* at 3.5 and 7 mm present an independent test to all theoretical models. Yuan, Shen & Huang (2006) calculated the predicted size of the RIAF model and found that the predicted sizes at 3.5 and 7 mm are in good agreement with the observations. This result supplies a strong support to the model.

•X-Ray Emission in the GC

In addition, Dr. Feng Yuan and Dr. Yadi Xu of Shanghai Jiaotong University and their collaborators have calculated the thermal X-ray iron line emission from the Sgr A* region inside 1.″5 of the center and out to 10″. (Xu et al. 2006). For reasonable choices of parameters, the calculated equivalent widths of H-like and He-like iron lines agree with Chandra's detection. The model predicts that the strongest iron line in both regions is He-like iron line, with the line energy being 6.7 keV. However, the observed line energy in the two regions are 6.61 keV and 6.5 keV, respectively, below the model predictions. The inconsistency may be due to the assumption of ionization equilibrium. It is quite possible that the heating timescale of the plasma is shorter than the ionization timescale thus the plasma is in a state of non-ionization equilibrium (Baganoff et al. 2003; and currently being explored by Dr. Feng Yuan and Dr. Q.D. Wang (UMass) and Dr. Ji Li (MIT)).

Dr. Fangjun Lu at IHEP and collaborators observed two elongated X-ray features, G359.89-0.08 and G359.54+0.18, in the Galactic center (GC) region using the Chandra X-Ray Observatory (Lu et al. 2003). The former is an elongated X-ray feature partially coincident with a slightly curved nonthermal radio source. It is best interpreted as the synchrotron emission from a ram pressure-confined pulsar wind nebula. The later is one of the most prominent radio nonthermal filaments in the GC region located ∼ 30′ in projection from Sgr A*. Dr. Fangjun Lu is now contributing most of his time to the HXMT (Hard X-ray Modulation Telescope) project in China (*http://www.hxmt.org*).

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Mini Workshop on the Galactic Center in Japan - July 2006

contributed by Mami Machida (NAOJ) and Masaaki Sakano (Leicester)

On July 6th, 2006, there was a Galactic center mini-workshop held at the National Astronomical Observatory of Japan (NAOJ). This meeting focused on the the arc-like and circular structures of molecular gas discovered in the Galactic center (GC).

Discovery of Molecular Loops in the GC

Molecular loops in the GC by FUKUI, Yasuo (Nagoya Univ.) Molecular loops were discovered in the Galactic center by the NANTEN telescope. They presented a magnetic floatation model in which the loops are formed due to the magnetic buoyancy caused by the Parker instability.

Molecular loops in the GC by KUDO, Natsuko (Nagoya Univ.) They discussed the fourth quadrant loops known as loop 1 and loop 2. The kinetic energy involved in a loop is estimated to be 10^{51} erg for a velocity dispersion of 30 km $^{-1}$. The position-velocity diagram showed that the loop foot points have a large velocity span and are connected by a bridge.

Molecular loops in the Galactic center - comparison with CO and HI by TORII, Kazufumi (Nagoya Univ.) They compared the distribution of CO with HI gas in loop 1 and loop 2. They found a good correlation between CO and HI.

Observations of the GC Molecular Loops in Other Wavelengths

Vertical structure in the edge-on galaxy NGC891 by HANDA, Toshihiro (Univ. of Tokyo) These authors 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.

Distribution of high excitation molecular gas in CMZ by OKA, Tomoharu (Univ. of Tokyo) 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.

Magnetic field structure of SNRs with hard X-ray observation by BAMBA, Aya (RIKEN) 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.

Magnetic field structure observed with infrared by NAKAGAWA, Takao (JAXA) According to the infrared observations, the magnetic field in the Galaxy is aligned with the galactic plane. In CMZ, the magnetic field strength is estimated to be milli-Gauss.

Theories and Numerical simulations of the Parker instability and Phenomena in the GC and the Galactic Disk

The origin of molecular loop structures by MATSUMOTO, Ryoji (Chiba Univ.) Here, these authors considered that molecular loop structures are created by the Parker instability. If the strength of the magnetic field is about 100 μGauss, the molecular gas sliding down along the magnetic fields can generate a velocity dispersion of as high as 50 km s^{-1} in the molecular gas.

Local two-dimensional simulations of galactic loops by NOZAWA, Satoshi (Ibaraki Univ.) This work reports on two-dimensional MHD simulations of the Parker instability. It successfully reproduced the two loop-like structures observed in the Galactic center region.

Lobal three-dimensional simulations of galactic disks by MACHIDA, Mami (NAOJ) They carried out three-dimensional MHD simulations of galactic gas disks. They showed that the magnetic flux buoyantly rise from the disk.

Magnetic field amplification by Magneto-rotational instability Speaker: SANO, Takayoshi (Osaka Univ.) Due to Galactic rotation, the Galactic gas disk is subject to a magneto-rotational instability and and becomes turbulent. When the gas is isothermal, magnetic flux tubes can be created.

Formation of molecular gas cloud by KOYAMA, Hiroshi (Kobe Univ.) These authors studied the conditions for molecular cloud formation by the Parker instability.

The mechanism of particle acceleration inside the Galaxy by ASANO, Katsuaki (NAOJ) These authors investigated whether a 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 detected inside the Galaxy. They conclud from the rough estimation that the Parker instability is likely to be the origin of cosmic-ray acceleration.

IAU 2006 –– New Results on the Galactic Center

contributed by Joseph Lazio (Naval Research Lab)

At the General Assembly XXVI of the International Astronomical Union, a session entitled "New Results on the Galactic Centre" was held under the auspices of Division VII (Galactic Systems). The meeting had two purposes. The first was to summarize recent work on the Galactic center to the larger IAU audience. Invited talks highlighted a number of the recent observational advances, such as in the very high energy and infrared, or theoretical puzzles, such as the existence of young stars and a stellar disk (or two!) in the central parsec. There was also an effort made to place the center of the Milky Way into a larger context with respect to galactic centers in general.

The second purpose was to gauge the interest in forming an IAU Working Group on the Galactic center. The aim of such a working group would be to enhance the visibility of Galactic center science within the IAU and to increase the interest in the Milky Way Galactic center as an exemplar for low-luminosity galactic nuclei.

There was significant interest in forming such a working group. An Organizing Committee is being identified, with Joseph Lazio as the chair.

Upcoming GC Meetings

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

June 12-15 2007, Kerastari, Greece

First announcement:

Exotic and transient astrophysical phenomena reveal the violent and capricious nature of the universe. Wide-field and all-sky monitoring in the X-ray, gamma-ray, and more recently optical, bands has already led to a wealth of discoveries such as magnetars and gamma-ray bursts which probe extreme realms of physics and yet were not anticipated prior to their discovery. Radio telescopes have a tradition of providing high angular resolution in narrow fields or large fields of view with limited time resolution. A notable exception to this approach led to the discovery of pulsars thirty years ago.

Several different routes to wide-field, or even all-sky, observations with high time resolution are now appearing, on the road to the Square Kilometre Array (SKA). Coupled with this, the past few years have seen the discovery of new classes of radio transient, such as the RRATs and the Galactic Centre Radio Transient. This workshop will, for the first time, combine the astrophysics of rapid radio variability with the techniques of wide-field transient searches, in anticipation of an exciting decade ahead of us.

Scientific topics will include all aspects of transient and rapidly variable radio phenomena, including theory of explosive events and particle acceleration, and observations of gamma ray bursts, microquasars, pulsars and RRATs, flare stars, exoplanets, scintillation and intra-day variability of Active Galactic Nuclei. There will be extensive discussion of the coming new generation of wide-field radio observatories (e.g. ATA, LOFAR, SKA prototypes), and programs to monitor the radio sky to search for known, unknown (i.e. serendipitous) and known unknown (e.g. SETI) phenomena.

The meeting will be held in the Peloponese region of Greece, in the village of Kerastari, nestled in the mountains of ancient Arcadia (close to the town of Tripolis), and we aim to schedule lots of time for discussion and interaction, as well as relaxation. Based on past experience, we will probably end the workshop with a large party involving the whole village.

Participation at the workshop will be limited to 80 people, and as a result some selection may be necessary. We encourage all those interested to pre-register via the simple form at the bottom of this message, as soon as possible.

Invited speakers include:

Mitch Begelman, Geoff Bower, Dave Jauncey, Shri Kulkarni, Maura McLaughlin, Rachel Osten, Sterl Phinney (tbc), Anatoly Spitkovsky, Jill Tarter

Scientific Organising Committee:

Rob Fender (chair), Stephane Corbel, Bryan Gaensler, John Kirk, Joe Lazio, Jean-Pierre Macquart, Sera Markoff, Dave Meier, Ralph Spencer, Tasso Tzioumis

The conference website can be found at:

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

Orbits and Origins of the Young Stars in the Central Parsec

Jessica R. Lu, [1], A. M. Ghez [1], S. D. Hornstein [1], M. Morris [1], K. Matthews [2], D.J. Thompson [3], and E. E. Becklin [1]

[1]UCLA Division of Astronomy [2]Caltech Optical Observatory [3]LBT Observatory, U Arizona

Introduction

One peculiar attribute of our Galactic center is the presence of a population of massive ($30 - 120\ M_\odot$), young ($\lesssim 10$ Myr) stars within the sphere of influence of the supermassive black hole (see e.g. (1; 2)). The origin of such young stars is puzzling given that the present-day gas density is orders of magnitude too low to overcome the extreme tidal forces and collapse to form stars (3; 4). Proposed resolutions to this "paradox of youth" include scenarios in which these young stars formed in a massive, self-gravitating accretion disk that was once present around the black hole (5) or alternatively, formed far from their current positions, outside the black hole's sphere of influence, as part of a massive star cluster which spiraled in via dynamical friction and deposited the most massive stars where we see them today (6). Both of the above possible formation scenarios predict that the stars should lie in a common orbital plane, which is supported by analyses using the stars' observed 3D velocities that show indirect evidence for two perpendicular, counter-rotating disks with inner disk radii of around 1 arcsec (5; 7). However, formation in a self-gravitating accretion disk tends to suggest circular orbits while in-falling cluster scenarios could give rise either to circular or eccentric orbits.

In this article, we present results on the stellar orbits for the young stars that lie in the candidate disks (8). These orbits are used to test for the existence of two stellar disks and measure the eccentricities of the stars in order to distinguish between the various formation scenarios.

New Young Star Orbits

This study uses 11 years of diffraction-limited, infrared images of the Galaxy's central stellar cluster taken using both speckle and laser guide star adaptive optics (LGSAO) observing techniques at the 10 m Keck telescopes. For a sample of 33 young stars between $0\farcs8$ and $3\farcs2$ from the SBH, astrometry is extracted from the Keck data and radial velocities are obtained from the literature (2). Velocities in the plane of the sky are derived from the astrometric measurements by fitting first-order polynomials to positions as a function of time, weighted by the positional uncertainties. The measured proper motion are as much as ten times more precise than our most recent work in (9) with typical absolute uncertainties of 1-2 km/s. This substantial improvement comes from removing a small amount of residual geometric distortion from the NIRC-speckle data sets. Although this distortion is negligible near the center of the images, where Sgr A* and the central arcsecond sources are located; the astrometric accuracy of stars at larger radii is dominated by this residual distortion term. Given the improved precision, accelerations in the plane of the sky are derived by fitting second-order polynomials and many of the stars show a significant lack of acceleration given their projected distances from the SBH. Figure 1 shows the resulting acceleration limits for all the young stars in the sample as compared to the theoretical curve of acceleration as a function of radius.

For the sample of 33 young stars, we compute orbits for each star, assuming a Keplerian orbit model in which the gravitational potential arises from a single dominant point mass situated at the photometric centroid of Sgr A*. The mass and the distance to Sgr A* are fixed at values set by S0-2's orbit with $M_\bullet = 3.69\times10^6\ M_\odot$ and $R_\circ = 7.36$ kpc ((10)). For each star, there are then six free parameters: period (P), eccentricity (e), time of periapse passage ($T_\circ$), inclination (i), position angle of the ascending node (Ω), and the longitude of periapse. Not all of these parameters can be well constrained given that the stars have significant measurements of the 2D positions, 3D velocities, while there are only upper limits to the acceleration in the plane of the sky for the majority of the stars. Orbit fitting is carried out by minimizing the χ^2 value between the data and the model using the Thiele-Innes method (11). Uncertainties in the fits are characterized by fully exploring orbital parameter space and empirically determining those orbital solutions with $\chi^2 < \chi^2_{min} + 1$ for 1σ errors.

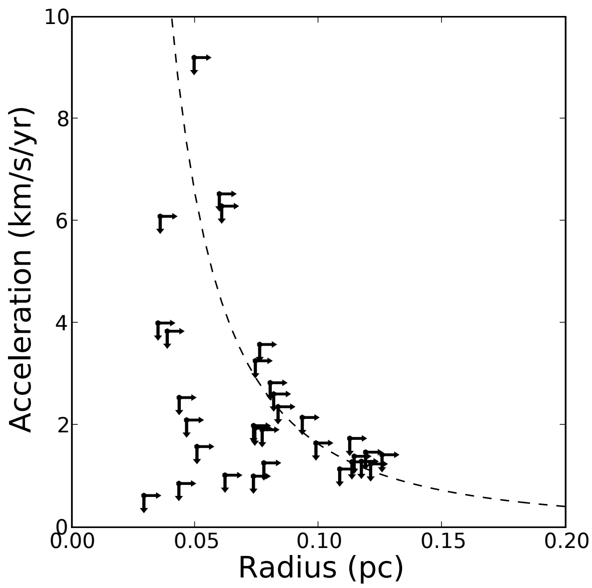

Figure 1 Acceleration limits for the sample of 33 young stars. The theoretical curve for acceleration as a function of total distance is plotted (dashed), as is each star's 3σ acceleration upper limit from orbit fitting (vertical arrow) and radius lower limit from the observed projected distance from the black hole (horizontal arrow).

Young Star Disk

Constrained orbital parameters include the angle to the ascending node (Ω) and the inclination (i), which can be combined to determine the orientation of each star's orbital plane. Figure 2 shows the orientation for all the stars' orbital planes. Some stars have two possible orbital solutions since the star's unknown line of sight distance from the SBH can either be positive or negative (behind or in front of the plane of the SBH). One of the solutions for the clockwise (red) stars' normal vectors cluster around a common point indicating that these stars may lie on a common orbital plane. The counter-clockwise stars, plotted in blue, do not appear to cluster around any single point, suggesting that they do not lie on a common orbital plane. Over plotted in black are the candidate orbital planes proposed by (5) and (7) with updated values from (2) for the candidate plane normal vectors (solid black) and disk thickness (dashed black). Although the proposed counter-clockwise disk is not supported by the sample of young stars in this work (all within $\sim 3''$ of Sgr A*), our current observations cannot definitively rule out the existence of a 2nd disk until we expand our study to include more young stars at larger radii.

Determining the existence of a second disk is critical to understanding the formation scenarios of the young stars within the central parsec. For the self-gravitating accretion disk scenario, it is unlikely that two gas disks could exist simultaneously at the same radii since the disks would collide. Since the clockwise and counter-clockwise populations appear to have similar ages of $\sim$6 million years old to within $\sim$1 million years of each other (2), the existence of two stellar disks at the present epoch would mean that a second gas disk must have formed, become massive enough to collapse under self-gravity, and fragmented to form stars within, at most, 1 million years of the first gas disk. Likewise, for the in-falling cluster scenario, two nearly perpendicular disks of stars most likely cannot be formed by the infall of a single star cluster. The existence of two stellar disks would arise from two clusters spiraling in within 6 million years of each other, as set by the clusters' ages, and would thus give an estimate of the frequency of such cluster infall events.

On the other hand, if there is only one disk plus a randomly scattered population, then it may be possible to explain all the stars within the central parsec with a single formation scenario with scattering events giving rise to out-of-the-plane members. This scenario has a difficulty in that IRS 13 appears to be a large cluster of young stars; which either does not lie on the common orbital plane or is counter-rotating within this plane. There is no obvious

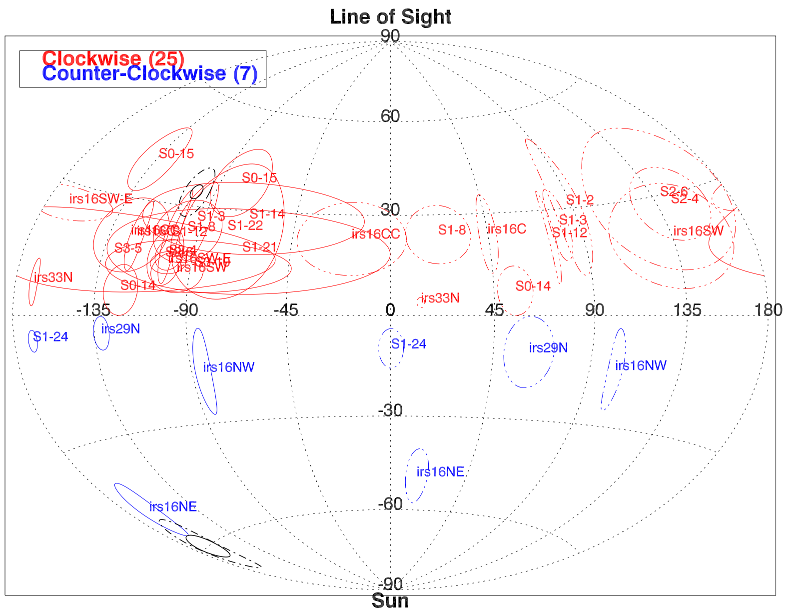

Figure 2 The distribution of orbital planes as determined from individual stellar orbits. The normal vector for each star's orbital plane, plus the associated uncertainty in that vector, describes a cone in 3D space. This cone can be projected as an elliptical region onto a celestial sphere centered on the black hole. The projected 3 sigma region of the normal vectors are plotted on an Aitoff projection of this celestial sphere with clockwise rotators in red and counter-clockwise in blue. For reference, those stellar orbits with normal vectors pointing toward or away from the Sun have face-on orbits as seen from Earth. Stars having two possible orbital solutions as a result of a degeneracy in the orbital parameter Ω (angle to the ascending node) have one solution drawn with a solid line and the other with a dashed line.

mechanism for drastically changing the orbit of the highest density portion of the young star disk.

Young Star Eccentricities

Stars in both disks show evidence for eccentric orbits. Of the 26 stars that may be in the clockwise disk, 10 of the stars have 3σ lower limits to their eccentricities of >0.2. Figure 3 shows the 3σ limit on eccentricities for all the stars in the sample. These eccentricity limits are robust as there is a sharp lower limit in chi-squared vs. eccentricity space. Eccentricities of $\gtrsim 0.4$ may be difficult to explain with a self-gravitating accretion disk formation scenario. Results from Nayakshin & Cuadra (12) indicate that stars born in a circular accretion disk would retain their nearly circular orbits well past the present epoch. If the disk mass is built up from many small cloud-infall events, then the disk may circularize prior to becoming massive enough to form stars from self-gravity ($> 10^4\ M_\odot$); however, for a single massive cloud infall or a cloud-cloud collision event, it remains to be determined if star formation can occur rapidly enough that the cloud's initial eccentricity is imparted to the subsequently formed stars before circularizing.

High eccentricity orbits may be more naturally explained in the in-falling star cluster formation scenario. Stars that are stripped from a cluster as it spirals in should have a similar inclination, semi-major axis, and eccentricity as the cluster itself. Therefore, an in-falling cluster with an initially eccentric orbit will produce a thin disk of stars with similarly eccentric orbits (13). However, this formation scenario has its own share of unresolved issues including (1) the required high initial cluster mass ($> 10^5 - 10^6\ M_\odot$, (14; 15)); (2) the required high central density, possibly even the presence of an intermediate mass black hole (16; 14); and (3) the lack of observational evidence for tidally stripped stars at larger radii or X-ray emission from pre-main sequence low-mass stars within the central parsec (17).

In summary, we have retroactively improved our 11 year astrometric data set used for monitoring stellar orbits in the Galactic center. This has resulted in improved proper motions with uncertainties of only ~1-2 km/s. We have attempted the first orbit fitting of the young stars proposed to lie in stellar disks orbiting the supermassive black hole. The individual orbits for the young stars confirm a disk of young stars at a high inclination rotating in a clockwise

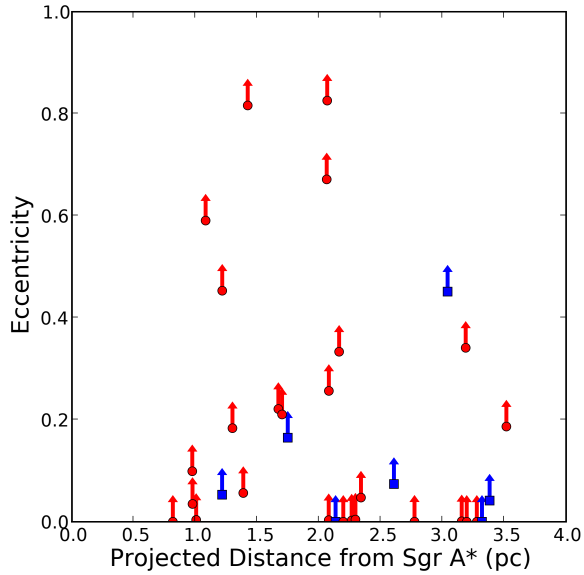

Figure 3 Lower limits to the eccentricities as determined from individual stellar orbits. Stars rotating with a clockwise orientation are plotted as red circles and counter-clockwise stars are plotted as blue squares.

sense. The counter-clockwise rotating stars do not appear to be consistent with the previously proposed second disk. Stars within the well-defined, clockwise disk also appear to have high eccentricities, which is challenging to current accretion disk formation scenarios and provides a new observational constraint for models of star formation in the Galactic center.

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Abstracts

A RIAF Interpretation for the Past Higher Activity of the Galactic Center Black Hole and the 511 keV Annihilation Emission

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There are several lines of evidence that the super-massive black hole at the Galactic center had higher activities in the past than directly observed at present. Here I show that these lines of evidence can quantitatively and consistently be explained if the mean accretion rate during the past $\sim 10^7$ yrs has been $\sim 10^{3-4}$ times higher than the current rate, by the picture of radiatively inefficient accretion flow (RIAF) and associated outflow that has been successfully applied to Sgr A*. I argue that this increased rate and its duration are theoretically reasonable in the Galactic center environment, while the accretion rate suddenly dropped about 300 years ago most likely because of the shell passage of the supernova remnant Sgr A East. Then I show that a significant amount of positrons should have been created around the event horizon during the higher activity phase, and injected into interstellar medium by the outflow. The predicted positron production rate and propagation distance are close to those required to explain the observed 511 keV annihilation line emission from the Galactic bulge, giving a natural explanation for the large bulge-to-disk ratio of the emission. The expected injection energy is $\sim$ MeV, which is also favorable as an explanation of the 511 keV line emission.

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Inverse Compton Scenarios for the TeV Gamma-Ray Emission of the Galactic Centre

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The intense Compton cooling of ultra-relativistic electrons in the Klein-Nishina regime in radiation dominated environments, such as that found in the Galactic Centre, may result in radically different electron spectra than those produced by Synchrotron cooling. We explore these effects and their impact on the X-ray and γ-ray spectra produced in electron accelerators in this region in comparison to elsewhere in our galaxy. We discuss the broad-band emission expected from the newly discovered pulsar wind nebula G 359.95−0.04 and the possible relationship of this X-ray source to the central TeV γ-ray source HESS J1745−290. Finally we discuss the possible relationship of the Galactic Centre INTEGRAL source IGR J1745.6−2901 to the TeV emission.

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The Intrinsic Size of Sagittarius A* from 0.35 cm to 6 cm

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We present new high-resolution observations of Sagittarius A* at wavelengths of 17.4 to 23.8 cm with the Very Large Array in A configuration with the Pie Town Very Long Baseline Array antenna. We use the measured sizes to calibrate the interstellar scattering law and find that the major axis size of the scattering law is smaller by $\sim 6\%$ than previous estimates. Using the new scattering law, we are able to determine the intrinsic size of Sgr A* at wavelengths from 0.35 cm to 6 cm using existing results from the VLBA. The new law increases the intrinsic

size at 0.7 cm by $\sim 20\%$ and $< 5\%$ at 0.35 cm. The intrinsic size is 13^{+7}_{-3} Schwarzschild radii at 0.35 cm and is proportional to λ^{γ}, where γ is in the range 1.3 to 1.7.

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Email: gbower@astro.berkeley.edu
Eprint: astro-ph/0608004

GCIRS16SW: a massive eclipsing binary in the Galactic Center

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We report on the spectroscopic monitoring of GCIRS16SW, an Ofpe/WN9 star and LBV candidate in the central parsec of the Galaxy. SINFONI observations show strong daily spectroscopic changes in the K band. Radial velocities are derived from the He I 2.112μm line complex and vary regularly with a period of 19.45 days, indicating that the star is most likely an eclipsing binary. Under various assumptions, we are able to derive a mass of $\sim 50\ M_{\odot}$ for each component.

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Email: martins@mpe.mpg.de
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Correlation between Flux and Spectral Index during Flares in Sagittarius A*

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Flares in Sagittarius A* are produced by hot plasmas within a few Schwarzschild radii of the supermassive black hole at the Galactic center. The recent detection of a correlation between the spectral index and flux during a near infrared (NIR) flare provides a means to conduct detailed investigations of the plasma heating and radiation processes. We study the evolution of the electron distribution function under the influence of a turbulent magnetic field in a hot collisionless plasma. The magnetic field, presumably generated through instabilities in the accretion flow, can both heat the plasma via resonant wave-particle coupling and cool the electrons via radiation. The electron distribution can generally be approximated as relativistic Maxwellian. To account for the observed correlation, we find that the magnetic field needs to be anti-correlated with the electron "temperature". NIR and X-ray light curves are produced for a cooling and a heating phase. The model predicts simultaneous flare activity in the NIR and X-ray bands, which can be compared with observations. These results can be applied to MHD simulations to study the radiative characteristics of collisionless plasmas, especially accretion flows in low-luminosity AGNs.

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Stringent Constraint on Galactic Positron Production

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The intense 0.511 MeV gamma-ray line emission from the Galactic Center observed by INTEGRAL requires a large annihilation rate of nonrelativistic positrons. If these positrons are injected at even mildly relativistic energies, higher-energy gamma rays will also be produced. We calculate the gamma-ray spectrum due to inflight annihilation and compare to the observed diffuse Galactic gamma-ray data. Even in a simplified but conservative treatment, we find that the positron injection energies must be $\lesssim 3$ MeV, which strongly constrains models for Galactic positron production.

Ref.: PRL, Aug 2006, in press
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Eprint: astro-ph/0512411

Pinwheels in the Quintuplet Cluster

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The five enigmatic "Cocoon stars" after which the Quintuplet cluster was christened have puzzled astronomers since their discovery. Their extraordinary cool, featureless thermal spectra have been attributed to various stellar types from young to

highly evolved, while their absolute luminosities places them among the supergiants. We present diffraction-limited images from the Keck 1 telescope which resolves this debate with the discovery of rotating spiral plumes characteristic of colliding-wind binary "pinwheel" nebulae. Such elegant spiral structures, found around high-luminosity Wolf-Rayet stars, have recently been implicated in the behavior of supernovae lightcurves in the radio and optical.

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Email: angelle.tanner@jpl.nasa.gov
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Production of Hypervelocity Stars through Encounters with Stellar-Mass Black Holes in the Galactic Centre

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Stars within 0.1 pc of the supermassive black hole Sgr A* at the Galactic centre are expected to encounter a cluster of stellar-mass black holes (BHs) that have segregated to that region. Some of these stars will scatter off an orbiting BH and be kicked out of the Galactic centre with velocities up to $\sim 2000\,\mathrm{km\ s^{-1}}$. We calculate the resulting ejection rate of hypervelocity stars (HVSs) by this process under a variety of assumptions, and find it to be comparable to the tidal disruption rate of binary stars by Sgr A*, first discussed by Hills (1988). Under some conditions, this novel process is sufficient to account for all the B-type HVSs observed in the halo, and to dominate the production rate of all HVSs with lifetimes much less than the relaxation time-scale at a distance ~ 2 pc from Sgr A* ($\gtrsim 2$ Gyr). Since HVSs are produced by at least two unavoidable processes, the statistics of HVSs could reveal bimodal velocity and mass distributions, and can constrain the distribution of BHs and stars in the innermost 0.1 pc around Sgr A*.

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Email: roleary@cfa.harvard.edu
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Hypervelocity Collisions of Binary Stars at the Galactic Centre

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Recent surveys have identified seven hypervelocity stars (HVSs) in the halo of the Milky Way. Most of these stars may have originated from the breakup of binary star systems by the nuclear black hole SgrA*. In some instances, the breakup of the binary may lead to a collision between its member stars. We examine the dynamical properties of these collisions by simulating thousands of different binary orbits around SgrA* with a direct N-body integration code. For some orbital parameters, the two stars collide with an impact velocity lower than their escape velocity and may therefore coalesce. Some of the massive S-stars near Sgr A* might be the merger remnants of binary systems.

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Iron and Nickel Line Diagnostics for the Galactic Center Diffuse Emission

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We have observed the diffuse X-ray emission from the Galactic center (GC) using the X-ray Imaging Spectrometer (XIS) on Suzaku. The high-energy resolution and the low-background orbit provide excellent spectra of the GC diffuse X-rays (GCDX). The XIS found many emission lines in the GCDX near the energy of K-shell transitions of iron and nickel.

The most pronounced features are Fe I Kα at 6.4 keV and K-shell absorption edge at 7.1 keV, which are from neutral and/or low ionization states of iron, and the K-shell lines at 6.7 keV and 6.9 keV from He-like (Fe XXV Kα) and hydrogenic (Fe XXVI Lyα) ions of iron. In addition, Kα lines from neutral or low ionization nickel (Ni I Kα) and He-like nickel (Ni XXVII Kα), and Fe I Kβ, Fe XXV Kβ, Fe XXVI Lyβ, Fe XXV Kγ and Fe XXVI Lyγ are detected for the first time. The line center energies and widths of Fe XXV Kα and Fe XXVI Lyα favor a collisional excitation (CE) plasma for the origin of the GCDX. The electron temperature determined from the line flux ratio of Fe XXV-Kα/ Fe XXV-Kβ is similar to the ionization temperature determined from that of Fe XXV-Kα/Fe XXVI-Lyα. Thus it would appear that the GCDX plasma is close to ionization equilibrium. The 6.7 keV flux and temperature distribution to the galactic longitude is smooth and monotonic, in contrast to the integrated point source flux distribution. These facts support the hypothesis that the GCDX is truly diffuse emission rather than the integration of the outputs of a large number of unresolved point sources. In addition, our results demonstrate that the chemical composition of Fe in the interstellar gas near the GC is constrained to be about 3.5 times solar.

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Constraints on the Stellar Mass Function from Stellar Dynamics at the Galactic Center

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We consider the dynamical evolution of a disk of stars orbiting a central black hole. In particular, we focus on the effect of the stellar mass function on the evolution of the disk, using both analytic arguments and numerical simulations. We apply our model to the ring of massive stars at 0.1pc from the Galactic Center, assuming that the stars formed in a cold, circular disk, and find that our model requires the presence of a significant population of massive (¿100Msun) stars in order to explain the the observed eccentricities of 0.2-0.3. Moreover, in order to limit the damping of the heavier stars' eccentricities, we also require fewer low-mass stars than expected from a Salpeter mass function, giving strong evidence for a significantly "top-heavy" mass function in the rings of stars seen near to the Galactic Center. We also note that the maximum possible eccentricities attainable from circular initial conditions at ages of ¡10Myr are around 0.4-0.5, and suggest that any rings of stars found with higher eccentricities were probably not formed from circular disks.

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Polarimetry of Near-Infrared Flares from Sgr A*

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We report new polarization measurements of the variable near-infrared emission of the SgrA* counterpart associated with the massive 3–4$\times 10^6 M_\odot$ Black Hole at the Galactic Center. We investigate the physical processes responsible for the variable emission from SgrA*. The observations have been carried out using the NACO adaptive optics (AO) instrument at the European Southern Observatory's Very Large Telescope. We find that the variable NIR emission of SgrA* is highly polarized and consists of a contribution of a non- or weakly polarized main flare with highly polarized sub-flares. The flare activity shows a possible quasi-periodicity of 20$\pm$3 minutes consistent with previous observations. The highly variable and polarized emission supports that the NIR emission is non-thermal. The observations can be interpreted in a jet or temporary disk model. In the disk model the quasi-periodic flux density variations can be explained due to spots on relativistic orbits around the central MBH. Alternative explanations for the high central mass concentration involving boson or fermion balls are increasingly unlikely.

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Near-infrared polarimetry setting constraints on the orbiting spot model for Sgr A* flares

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Recent near-infrared polarization measurements of Sgr A* show that its emission is significantly polarized during flares and consists of a non- or weakly polarized main flare with highly polarized sub-flares. The flare activity suggests a quasi-periodicity of $\sim$20 minutes in agreement with previous observations. By simultaneous fitting of the lightcurve fluctuations and the time-variable polarization angle, we address the question of whether these changes are consistent with a simple hot spot/ring model, in which the interplay of relativistic effects plays the major role, or whether some more complex dependency of the intrinsic emissivity is required. We discuss the significance of the 20 min peak in the periodogram of a flare from 2003. We consider all general relativistic effects that imprint on the polarization degree and angle and fit the recent polarimetric data, assuming that the synchrotron mechanism is responsible for the intrinsic polarization and considering two different magnetic field configurations. Within the quality of the available data, we think that the model of a single spot in addition to an underlying ring is favoured. In this model the broad near-infrared flares of Sgr A* are due to a sound wave that travels around the MBH once while the sub-flares, superimposed on the broad flare, are due to transiently heated and accelerated electrons which can be modeled as a plasma blob. Within this model it turns out that a strong statement about the spin parameter is difficult to achieve, while the inclination can be constrained to values $\gtrsim 35°$ on a 3σ level.

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K-band polarimetry of an Sgr A* flare with a clear sub-flare structure

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The supermassive black hole at the Galactic center, Sgr A*, shows frequent radiation outbursts, often called 'flares'. In the near-infrared some of these flares were reported as showing intrinsic quasi-periodicities. The flux peaks associated with the quasi-periodic behavior were found to be highly polarized. The aim of this work is to present new evidence to support previous findings of the properties of the polarized radiation from Sgr A* and to again provide strong support for the quasi-periodicity of $\sim 18 \pm 3$ min reported earlier. Observations were carried out at the European Southern Observatory's Very Large Telescope on Paranal, Chile. We used the NAOS/CONICA adaptive optics/near-infrared camera instrument. By fitting the polarimetric lightcurves with a hot-spot model, we addressed the question of whether the data are consistent with this model. To fit the observed data we used a general relativistic ray-tracing code in combination with a simple hot-spot/ring model. We report on new polarization measurements of a K-band flare from the supermassive black hole at the Galactic center. The data provide very strong support for a quasi-periodicity of 15.5 ± 2 min. The mean polarization of the flare is consistent with the direction of the electric field vector that was reported in previous observations. The data can be modeled successfully with a combined blob/ring model. The inclination i of the blob orbit must be $i > 20°$ on a 3σ level, and the dimensionless spin parameter of the black hole is derived to be $a_\star > 0.5$.

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The detection of the (J, K)=(18,18) line of NH_3

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A study of the metastable (J, K)=(18,18) line of ammonia (NH_3) is presented aiming at better defining the physical properties of molecular gas in extreme environments. The spectra were collected with the Effelsberg 100-m telescope and are analyzed in combination with other data using a rotation diagram (Boltzmann plot). The first astronomical detection of the metastable $(J, K) = (18,18)$ line of NH_3 is reported. This is the NH_3 line with by far the highest energy, 3130 K above the ground state, detected in interstellar space. It is observed in absorption toward the galactic center star forming region Sgr B2. There is a clear detection toward Sgr B2 (M) and a likely one toward Sgr B2 (N). An upper limit for emission is determined for Orion KL. If we combine the (18,18) line results from Sgr B2 (M) with the previously measured (12,12) absorption line, we find a rotation temperature, T_{rot}, of >1300 K for the absorbing cloud. This is at least a factor of two higher than previously derived values from less highly excited ammonia lines. T_{rot} gives a lower limit to the kinetic temperature. There is a hot low density gas component in the envelope of Sgr B2. It is possible that the (18,18) line arises in this region. The radial velocity of the low density, hot envelope is the same as that of the dense hot cores, so the (18,18) line could also arise in the dense hot cores where non-metastable (J>K) absorption lines from energy levels of up to ∼1350 K above the ground state have been observed. A discussion of scenarios is presented.

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H.E.S.S. observations of the Galactic Center region and their possible dark matter interpretation

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The detection of γ-rays from the source HESS J1745−290 in the Galactic Center (GC) region with the HESS array of Cherenkov telescopes in 2004 is presented. After subtraction of the diffuse γ-ray emission from the GC ridge, the source is compatible with a point-source with spatial extent less than 1.2′(stat.) (95% CL). The measured energy spectrum above 160 GeV is compatible with a power-law with photon index of 2.25 ± 0.04(stat.) $\pm$ 0.10(syst.) and no significant flux variation is detected. These measurements are discussed in the framework of dark matter annihilation. It is found that the bulk of the VHE emission must have non-dark-matter origin. Loose constraints on the velocity-weighted annihilation cross section $< \sigma \times v >$ are derived assuming the presence of an astrophysical non-dark-matter γ-ray contribution.

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New Galactic Wolf-Rayet stars, and candidates. An annex to The VIIth Catalogue of Galactic Wolf-Rayet Stars

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This paper gathers, from the literature and private communication, 72 new Galactic Population I Wolf-Rayet stars and 17 candidate WCLd stars, recognized and/or discovered after the publication of The VIIth Catalogue of Galactic Wolf-Rayet Stars. This brings the total number of known Galactic Wolf-Rayet stars to 298, of which 24 (8%) are in open cluster Westerlund 1, and 60 (20%) are in open clusters near the Galactic Center.

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Email: K.A.van.der.Hucht@sron.nl
Eprint: astro-ph/0609008, ftp://ftp.sron.nl/pub/karelh/UPLOADS/papers.dir/New-WR-Annex.pdf

Galactic Centre X-ray Sources

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We report on a campaign to identify the counterparts to the population of X-ray sources discovered at the centre of our Galaxy by Wang et al. (2002) using *Chandra*. We have used deep, near infrared images obtained on VLT/ISAAC to identify candidate counterparts as astrometric matches to the X-ray positions. Follow up Ks-band spectroscopic observations of the candidate counterparts are used to search for accretions signatures in the spectrum, namely the Brackett-γ emission line (Bandyopadhyay et al.1997). From our small initial sample, it appears that only a small percentage, $\sim 2-3\%$ of the $\sim$ 1000 X-ray sources are high mass X-ray binaries or wind accreting neutron stars, and that the vast majority will be shown to be canonical low mass X-ray binaries and cataclysmic variables.

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Eprint: astro-ph/0611177

The Nature of the Variable Galactic Center Source GCIRS 16SW Revisited: A Massive Eclipsing Binary

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We present a re-analysis of our H- and K-band photometry and light-curves for GCIRS 16SW, a regular periodic source near the Galactic center. These data include those presented by DePoy et al. (2004); we correct a sign error in their reduction, finding GCIRS 16SW to be an eclipsing binary with no color variations. We find the system to be an equal mass overcontact binary (both stars overfilling their Roche lobes) in a circular orbit with a period P=19.4513 days, an inclination angle i=71 degrees. This confirms and strengthens the findings of Martins et al. (2006) that GCIRS 16SW is an eclipsing binary composed of two 50Msun stars, further supporting evidence of recent star formation very close to the Galactic center. Finally, the calculated luminosity of each component is close to the Eddington luminosity, implying that the temperature of 24400 K given by Najarro et al. (1997) might be overestimated for these evolved stars.

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The Origin of Diffuse X-ray and γ-ray Emission from the Galactic Center Region: Cosmic Ray Particles

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The inner couple hundred pcs of our Galaxy is characterized by significant amount of synchrotron-emitting gas, which appears to co-exist with a large reservoir of molecular gas. Many of the best studied sources in this region exhibit a mixture of 6.4 keV Fe Kα emission, molecular line emission and nonthermal radio continuum radiation. The spatial correlation between fluorescent Fe K-α line emission at 6.4 keV and molecular line emission from Galactic center molecular clouds has been explained as reflected X-rays from a past outburst of Sgr A*. Here we present multi-wavelength study of a representative Galactic center cloud Sgr C using Chandra, VLA and FCRAO. We note a correlation between the nonthermal radio filaments in Sgr C and the X-ray features, suggesting that the two are related. This correlation, when combined with the distribution of molecular gas suggests against the irradiation of Sgr C by Sgr A*. Instead, we account for this distribution in terms of the impact of the relativistic particles from local (nonthermal filaments) and extended sources with diffuse neutral gas producing both a nonthermal bremsstrahlung X-ray continuum emission, as well as diffuse 6.4 keV line emission. The production rate of Fe Kα photons associated with the injection of electrons into a cloud as a function of column density is calculated. The required energy density of low-energy cosmic rays associated with the synchrotron emitting radio filaments or extended features is estimated to be in the range between 20 and $\sim 10^3$ eV cm^{-3} for Sgr C, Sgr B1, Sgr B2, and "the 45 and -30 km s^{-1}" clouds. We also generalize this idea to explain the cosmic-ray heating of molecular gas, the interstellar cosmic ray ionization, the pervasive production of diffuse Kα line and TeV emission from the Galactic center molecular clouds. In particular, we suggest that Inverse Compton scattering of the sub-millimeter radiation from dust by relativistic electrons may contribute substantially to the large-scale diffuse TeV emission observed towards the central regions of the Galaxy.

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The Stellar Mass Spectrum in Warm and Dusty Gas: Deviations from Salpeter in the Galactic Centre and in Circum-Nuclear Starburst Regions

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Understanding the origin of stellar masses is a key problem in astrophysics. In the solar neighborhood, the mass distribution of stars follows a seemingly universal pattern. In the centre of the Milky Way, however, there are indications for strong deviations and the same may be true for the nuclei of distant starburst galaxies. Here we present the first numerical hydrodynamical calculations of stars formed in a molecular region with chemical and thermodynamic properties similar to those of warm and dusty circum-nuclear starburst regions. The resulting IMF is top-heavy with a peak at 15 solar masses, a sharp turn-down below 7 solar masses, and a power-law decline at high masses. We find a natural explanation for our results in terms of the temperature dependence of the Jeans mass, with collapse occuring at a temperature of 100 K and an H_2 density of a few * $10^5 cm^{-3}$, and discuss possible implications for galaxy formation and evolution.

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Discovery of Variable Iron Fluorescence from Reflection Nebulae in the Galactic Center

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Based on three years of deep observations of the Galactic center with the *Chandra* X-ray Observatory, we report the discovery of changes in the intensities and morphologies of two hard X-ray nebulosities. The nebulosities are dominated by fluorescent iron emission, and are coincident with molecular clouds. The morphological changes are manifest on parsec scales, which requires that these iron features are scattered X-rays from a 2 or 3-year-long outburst of a point source (either Sgr A* or an X-ray binary) with a luminosity of at least 10^{37} erg s^{-1}. The variability precludes the hypotheses that these nebulae either are produced by keV electrons bombarding molecular clouds, or are iron-rich ejecta from supernovae. Moreover, the morphologies of the reflection nebulae implies that the dense regions of the clouds are filamentary, with widths of $\approx$0.3 pc and lengths of $\approx$ 2 pc.

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A polarised infrared flare from Sagittarius A* and the signatures of orbiting plasma hotspots

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In this article we summarise and discuss the infrared, radio, and X-ray emission from the supermassive black hole in the Galactic Centre, SgrA*. We include new results from near-infrared polarimetric imaging observations obtained on May 31st, 2006. In that night, a strong flare in K_s band (2.08 μm) reaching top fluxes of $\sim$16 mJy could be observed. This flare was highly polarised (up to $\sim$40 %) and showed clear sub-structure on a time scale of 15 minutes, including a swing in the polarisation angle of about 70 degrees. For the first time we were able to observe both polarised flux and short-time variability, with high significance in the same flare event. This result adds decisive information to the puzzle of the SgrA* activity. The observed polarisation angle during the flare peak is the same as observed in two events in 2004 and 2005. Our observations strongly support the dynamical emission model of a decaying plasma hotspot orbiting SgrA* on a relativistic orbit. The observed polarisation parameters and their variability with time might allow to constrain the orientation of accretion disc and spin axis with respect to the Galaxy.

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An Unambiguous Detection of Faraday Rotation in Sagittarius A*

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The millimeter/submillimeter wavelength polarization of Sgr A* is known to be variable in both magnitude and position angle on time scales down to a few hours. The unstable polarization has prevented measurements made at different frequencies and different epochs from yielding convincing measurements of Faraday rotation in this source. Here we present observations made with the Submillimeter Array polarimeter at 227 and 343 GHz with sufficient sensitivity to determine the rotation measure at each band without comparing position angles measured at separate epochs. We find the 10-epoch mean rotation measure to be $(-5.6 \pm 0.7) \times 10^5$ rad m^{-2}; the measurements are consistent with a constant value. We conservatively assign a 3σ upper limit of 2×10^5 rad m^{-2} to rotation measure changes, which limits accretion rate fluctuations to 25%. This rotation measure detection limits the accretion rate to less than $2 \times 10^{-7}\ M_\circ$ yr^{-1} if the magnetic field is near equipartition, ordered, and largely radial, while a lower limit of $2 \times 10^{-9}\ M_\circ$ yr^{-1} holds even for a sub-equipartition, disordered, or toroidal field. The mean intrinsic position angle is $167^\circ \pm 7^\circ$ and we detect variations of 31^{+18}_{-9} degrees. These variations must originate in the submillimeter photosphere, rather than arising from rotation measure changes.

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Determining the nature of the faint X-ray source population near the Galactic Centre

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We present results of a multi-wavelength program to study the faint discrete X-ray source population discovered by Chandra in the Galactic Centre (GC). From IR imaging obtained with the VLT we identify candidate K-band counterparts to 75% of the X-ray sources in our sample. By combining follow-up VLT *K*-band spectroscopy of a subset of these candidate counterparts with the magnitude limits of our photometric survey, we suggest that only a small percentage of the sources are HMXBs, while the majority are likely to be canonical LMXBs and CVs at the distance of the GC. In addition, we present our discovery of highly structured small-scale (5-15″) extinction towards the Galactic Centre. This is the finest-scale extinction study of the Galactic Centre to date. Finally, from these VLT observations we are able to place constraints on the stellar counterpart to the "bursting pulsar" GRO J1744-28.

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The Position of Sagittarius A*: III. Motion of the Stellar Cusp

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In the first two papers of this series, we determined the position of Sgr A* on infrared images, by aligning the positions of red giant stars with positions measured at radio wavelengths for their circumstellar SiO masers. In this paper, we report detections of 5 new stellar SiO masers within 50" (2 pc) of Sgr A* and new and/or improved positions and proper motions of 15 stellar SiO masers. The current accuracies are ≈ 1 mas in position and ≈ 0.3 mas/yr in proper motion. We find that the proper motion of the central stellar cluster with respect to Sgr A* is less than 45 km/s. One star, IRS 9, has a three-dimensional speed of ≈ 370 km/s at a projected distance of 0.33 pc from Sgr A*. If IRS 9 is bound to the inner parsec, this requires an enclosed mass that exceeds current estimates of the sum of the mass of Sgr A* and luminous stars in the stellar cusp by $\approx 0.8 \times 10^6$ Msun. Possible explanations include i) that IRS 9 is not bound to the central parsec and has "fallen" from a radius greater than 9 pc, ii) that a cluster of dark stellar remnants accounts for some of the excess mass, and/or iii) that R_0 is considerably greater than 8 kpc.

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Gravitational wave bursts from the Galactic massive black hole

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The Galactic massive black hole (MBH), with a mass of M_{bh}=3.6×10^6 solar masses, is the closest known MBH, at a distance of only 8 kpc. The proximity of this MBH makes it possible to observe gravitational waves from stars with periapse in the observational frequency window of the *Laser Interferometer Space Antenna* (LISA). This is possible even if the orbit of the star is very eccentric, so that the orbital frequency is many orders of magnitude below the LISA frequency window, as suggested by Rubbo et al. (2006). Here we give an analytical estimate of the detection rate of such gravitational wave bursts. The burst rate is critically sensitive to the inner cut-off of the stellar density profile. Our model accounts for mass-segregation and for the physics determining the inner radius of the cusp, such as stellar collisions, energy dissipation by gravitational wave emission, and consequences of the finite number of stars. We find that stellar black holes have a burst rate of the order of 1 per year, while the rate is of order <0.1 per year for main sequence stars and white dwarfs. These analytical estimates are supported by a series of Monte Carlo samplings of the expected distribution of stars around the Galactic MBH, which yield the full probability distribution for the rates. We estimate that no burst will be observable from the Virgo cluster.

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Announcements

GC Workshop 2006 Proceedings Published Online

The Proceedings of the *Galactic Center Workshop 2006* (April 18-22, Bad Honnef, Germany, editors: R. Schdel, G. Bower, M. Muno, S. Nayakshin, T. Ott) have been published in Volume 54 of the Journal of Physics: Conference Series and can be found online at:

http://www.iop.org/EJ/toc/1742-6596/54/1

We will set a link on the conference web site. All participants of GC2006 will also obtain a hardcopy of the proceedings via surface mail.

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