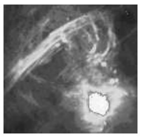
GCNEWS



The Newsletter of Galactic Center Research

Edited by Angela Cotera, Heino Falcke & Sera Markoff

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email: gcnews@mpifr-bonn.mpg.de **http://www.mpifr-bonn.mpg.de/gcnews/**

Chandra Surveys the Galactic Center

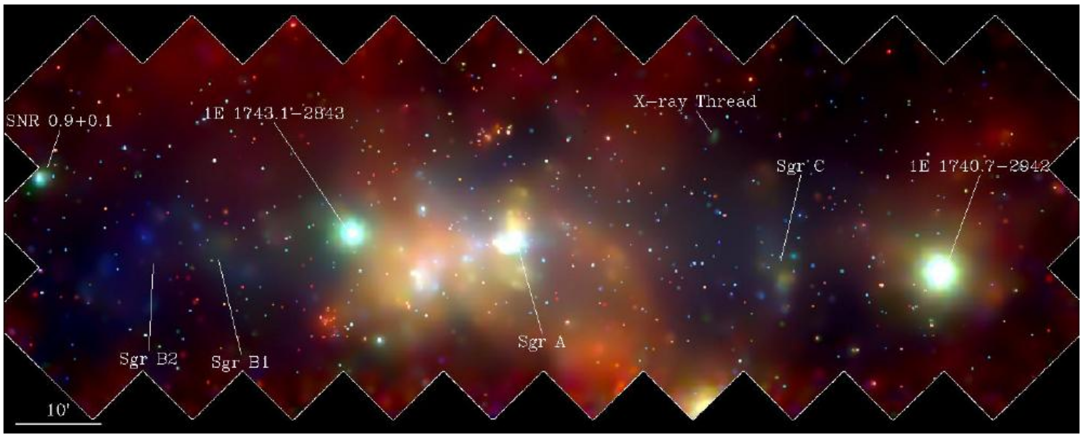

Figure 1: *Chandra* "true color" X-ray mosaic of the central $\sim 2 \times 0.8$ square degree band of the GC region. The three energy bands are $1-3$ keV (shown in red), $3-5$ keV (green), and $5-8$ keV (blue). The spatial resolution ranges from ~ 0.5" on-axis to ~ 5" at the near edge of the CCD and to ~ 10" at the diagonal edge. This image is adaptively smoothed with a signal-to-noise ratio of ~ 3 and is plotted logarithmically to emphasize low surface brightness emission. The saw-shaped boundaries of the map, plotted in Galactic coordinates, results from a specific roll angle of the observations.

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In the News

2002 GC Conference

Angela Cotera

Contracts are signed, the Scientific Organizing Committee has been assembled, the program is starting to come together, in short, we are off and running. There has been a change of venue since the last GCNEWS, to the Outrigger Keauhou Beach Resort, a few miles south of Kailua-Kona, Hawaii. During contract negotiations, we determined that the Keauhou Beach Resort would better meet our needs and the needs of the participants. Since our group will comprise a substantial portion of the hotel guests, we anticipate an improved level of service for all. The date remains the same, November 4-8, 2002. The conference fee will be $200 for early registration and the conference will be limited to about 100 participants.

We would like to thank all of our readers who participated in our online web poll, your input was greatly appreciated. The final tabulated results can be found in the *Announcements*, where you will also find the web address for the conference.

In addition to Tom Geballe (*Gemini Observatory*), your GCNEWS team (A. Cotera, S. Markoff, H. Falcke) will once again be Co-Chairs for the conference. On behalf of the Co-Chairs, I would like to express our appreciation for the members of our community who have agreed to serve on the SOC and who will decide on the final program of the conference:

Andreas Eckart (*Universität Köln*)
Rolf Kudritzki (*UH IfA*)
Mark Morris (*UCLA*
Ramesh Narayan (*CfA*)
Tomoharu Oka (*University of Tokyo*)
Mark Reid (*CfA*)
Francois Rigaut (*Gemini*)
Kris Sellgren (*University of Ohio*)
Farhad Yusef-Zadeh (*Northwestern*)

Finally, we would like to acknowledge the numerous institutes whose generous contributions will help make this an outstanding conference: Gemini Observatory, The University of Hawaii Institute for Astrophysics, WM Keck Observatory, Subaru Telescope, and the Joint Astronomy Centre.

The scope of the conference will be the central 300 parsecs – the scale of the fantastic *Chandra* results presented in this issue of GCNEWS! The region to be covered by the conference is also well illustrated in the 90 cm image of the GC by Namir Kassim et al., which can be found at http://rsd-www.nrl.navy.mil/7213/lazio/GC.

The wealth of theoretical research and observational advances at X-ray, infrared, submillimeter and radio wavelengths, during the past 3 years will undoubtably contribute to an interesting conference and lively discussions. We are once again planning to reserve significant amounts of time for discussion of results, so you may expect more spirited debates. The time reserved for discussion, in conjunction with an allotment of 15-20 minutes per talk and the anticipated number of participants, means that the conference poster sessions will likely be a significant portion of the conference.

We are in the process of creating the registration webpages, and will let you know when they are in place. The information will be sent by email to our subscribers and the people who filled out the survey form.

Deadlines have not yet been firmly established, but look for an abstract deadline in late August, early September – approximately coincident with the hotel registration deadline.

Now if we could just get Kilauea to erupt on November 9th....

GC Highlights from the January AAS

Susan Stolovy(SIRTF Science Center)

The most exciting Galactic Center (GC) news at the January 2002 AAS was unquestionably the spectacular Chandra observation (see article in this GCNEWS), revealed in a series of talks, posters, and press releases. In particular, a stunning panorama spanning the inner 2 × 1 degrees of the Galactic Plane was revealed by the UMASS/Columbia X-ray Survey of the Galactic Center (Q. Daniel Wang, Cornelia Lang, & Eric Gotthelf). See http://www.astro.umass.edu/∼wqd/gcs/index.htm for the press release and images and the article in this volume. This website also includes an enjoyable "News and Views" article written by Andreas Eckart for Nature, appearing in the same January 10 edition as the Wang, Gotthelf, and Lang article.

The group announced the detection of over 1000 X-ray point sources which are both spatially and spectrally distinguished from diffuse X-ray emission. The point sources, thought to originate from accretion of material from a normal star onto a compact companion (white dwarf, neutron star, or black hole), have a spectral line at 6.7 KeV from highly ionized Fe. The diffuse X-ray emission peaking at the GC can now be explained by emission from hot gas with typical temperatures of 10^7 K, a factor of 10 cooler than previously thought due to the poor spatial resolution of prior datasets. The diffuse gas that exhibits the 6.4KeV Fe fluorescent line could be excited by cosmic rays from supernovae or might even be literally a "reflection" of an earlier time in our Galaxy's history when possibly much more radiation emanated from the supermassive black hole at Sgr A*.

During the press conference Cornelia Lang gave a memorable quote: "The Galactic Center is dominated by very high pressures due to the hot gas component and the strong magnetic fields. It's a nice place to visit with a telescope, but I wouldn't want to live there." (*Remark: Not all of the editors would agree with the second half of that statement...*)

F. Yusef-Zadeh presented evidence for interaction of a molecular cloud with the nonthermal radio filaments from the spectrum and morphology of X-ray emission. An X-ray filament is seen adjacent to a nonthermal radio filament and diffuse X-ray gas fills a shell that appears to be confined by the radio filaments. (C. Lang showed that only one of the magnetic nonthermal radio filaments has X-ray emission COINCIDENT with it.).

D. Chuss presented a thesis talk on the sub-mm polarization measurements of magnetic fields in the GC, showing the magnetic field to be toroidal (due to galactic rotation) at large spatial scales (5 arcmin resolution) but complex and correlated with radio and mid-IR structures at smaller spatial scales (20″ resolution).

J. H. Zhao presented a history of Sgr A*'s variability at 1.3 and 0.87 mm showed two strong flare events over 7 months. Monitoring of Sgr A*'s variability at 7mm, 1.3 cm and 2.0 cm was also presented in a poster (G. Bower et al). A 20% flare of three hours has been seen at 15 GHz – similar to the time scale of the big Chandra flare.

S. Stolovy presented improved 0.2″ NICMOS images of the ionized gas (as imaged in Paschen alpha) near Sgr A* after removing residual point source artifacts from bright Pa-alpha emission stars such as the IRS16 cluster. This revealed an "arc" of ionized gas near Sgr A*.

A. Cotera et al. presented subarcsecond resolution maps of the mid-IR dust temperature and opacity in the central parsec of the Galaxy from Keck. The temperature peaks at the embedded sources. Even more striking is a large gradient towards the central cluster.

R. McGary presented NH3 maps from the VLA of the inner 10 pc of the galaxy. These maps showed new elongated features that spatially and kinematically link giant molecular clouds to warmer molecular material closer to the GC.

S. Hyman reported a new radio transient source with no known counterpart 1.1 degrees north of the GC.

And finally...a little story involving the 2nd human to walk on the Moon... At one point late Wednesday afternoon, I was surprised to see Buzz Aldrin strolling by with some NASA administrators. When shown the beautiful color "panorama" Chandra image of the GC displayed in the poster area, Buzz asked where the black hole was, so I pointed it out to him and he went on his way....of course I assumed he meant the supermassive one at the very center–it's likely that there are many solar mass-black holes associated with the newly detected discrete X-ray sources.

Chandra Surveys the Central 300 parsec of the Galaxy

Cornelia C. Lang (University of Massachusetts)

Abstract

I report on the results from the recent, high-resolution X-ray survey of the central 2 x 0.8 square degrees of the Galactic Center using the *Chandra X-ray Observatory.* We find that this region is rich in high-energy sources, both point-like and diffuse, and for the first time we can cleanly separate these components. Approximately 1000 point-like sources have been detected, of which less than 20 have been previously identified or have known counterparts. The extended, diffuse emission is the dominant component of X-ray emission in this region and appears to correspond to energetic massive star forming activities in the GC.

Introduction

The unique morphology and distribution of radio and infrared features in the Galactic Center (GC) suggest that this region is a site of extremely energetic activities, however, the highest energy phenomena in the GC have not been well-characterized. X-ray emission is considered to be the best tracer of high energy astrophysical phenomena, yet differential interstellar absorption in the Galactic plane affects the surface brightness of the X-ray emission, especially for energies below 2 keV. Nearly all previous X-ray missions (EINSTEIN, GINGA, ROSAT, ASCA, BeppoSAX) have surveyed the GC region; however, the resolutions and energy bands have not been ideal for a complete study, in particular since the interstellar X-ray absorption prevents accurate determination of the intrinsic X-ray fluxes and morphologies of many sources. Observations of the GC using even the highest energy band of ROSAT PSPC ($1.1-2$ keV) suffered from absorption problems.

GINGA and ASCA opened up a new spectral window for observations of the GC, although with relatively low spatial resolution (Koyama et al. 1989, 1996). These observations illustrated for the first time that the GC was filled with a hot ($\sim 10^8$ K) tenuous gas showing prominent emission in spectral lines between $6-7$ keV (e.g., 6.4-keV fluorescence and 6.7-keV Fe XXV Kα). However, this hard X-ray emission was not resolved due to the $3'$ spatial resolution. Several recent studies of the brightest point-like sources (using BeppoSaX and ROSAT PSPC) have revealed more than 50 bright X-ray sources this region, a number of which are well known X-ray binaries (Sidoli et al. 1999, 2001).

With the advent of the *Chandra X-ray Observatory*, operating in the energy window of 0.1-12 keV, it has now become possible to make X-ray images of the GC with spatial resolutions as high as $0.5-1''$, for the first time comparable to the best near-infrared and radio observations of this region. The first *Chandra* observations at GC positions such as SgrA* (Baganoff et al. 2001), SgrB2 (Murakami et al. 2001) and the Radio Arc (Yusef-Zadeh et al. 2002) have revealed a wealth of point-like and diffuse emission sources. However, in order to comprehensively study the nature of the high-energy phenomena in this unique region of the Galaxy, we have imaged a large swath of the GC region using *Chandra* (Wang, Gotthelf & Lang 2002).

The *Chandra* Galactic Center Survey

In July of 2001, 30 separate positions in the GC region were observed with the front-illuminated chips of the Advanced CCD Imaging Spectrometer (ACIS-I) on *Chandra.* The standard imaging calibration and exposure-correction have been applied to all data. These images were mosaicked together and cover the central 2 x 0.8 square degrees along the Galactic plane. Figure 1 shows the "three color" X-ray image of this region, which has been adaptively smoothed and displayed in a logarithmic scale to emphasize the diffuse emission. The image is centered roughly on SgrA* and is shown in Galactic coordinates. It is clear that this region is rich in high energy sources, with much of the activity concentrated in the central 50-100 pc in and around the familiar Radio Arc and SgrA complexes.

Our initial source-detection analysis reveals 1000 discrete X-ray sources above 3σ, of which only a small number (less than 20) have been previously identified. The strongest identified X-ray point-like emitters include the bright X-ray binaries 1E 1740.7-2942 and 1E 1743.1-2843, the nearby star HD316314, AX J1744.3-2940, and the Arches stellar cluster. We estimate that half of the detected point sources may be extragalactic background sources, based on a comparison with the density of sources in a relatively blank region of the Galactic plane (Ebisawa et al. 2001).

Most of the sources are detected in the 2−10 keV energy band, with X-ray luminosities corresponding to $10^{32}-10^{35}$ erg s^{-1} at the distance of the GC. The combined spectral signature of the point sources is shown in Figure 2 (lower spectrum) and provides some insight as to the nature of these sources. The presence of strong He-like Fe Kα line emission at 6.7 keV in this spectrum indicates that these sources are likely to be accreting binary systems (white dwarf, neutron star, or black hole) (Barret et al. 2000). However, determining the true nature of these X-ray sources requires identification of their counterparts at other wavelengths and several follow up studies in the radio are currently underway. The fraction and distribution of these binary systems can provide important clues to the history of star formation activities in this region.

In addition to the X-ray point sources, we detect a significant amount of diffuse X-ray emission in the GC, concentrated in and around the region $\sim 10'$ offset from SgrA complex (to the lower left in Figure 1). Figure 2 also shows the combined spectral signature from the diffuse emission (upper spectrum). The shape and line features of the two spectra are significantly different. The lack of strong 6.7 keV line emission in the diffuse spectrum and the presence of prominent ionized lines (e.g., Si XIII Kα and S XV Kα) are characteristic of a plasma with temperature of 10^7 K. This temperature is consistent with an origin in young supernova renmants and massive star forming activities. Previous spectral analysis of the diffuse component with ASCA indicated that the diffuse emission had a temperature of $\sim 10^8$ K, which is much harder to explain physically and to gravitationally confine to the GC region (Koyama et al. 1996).

The spectrum of the diffuse emission also shows a prominent 6.4-keV iron fluorescence emission, and much of this 6.4 keV line emission appears to be associated with the dense molecular clouds in SgrA, B, and C as well as the Radio Arc region. However, the illuminating sources have not yet been identified and may arise from hard X-ray sources internal or external to the molecular clouds. Therefore, careful examination of the distribution of 6.4-keV emission, molecular gas and hard X-ray sources over large scales will help to resolve the source of this fluorescence emission.

Figure 3 shows a multi-wavelength view of the GC at radio (90 cm; LaRosa et al. 2000), mid-infrared (25 μm; Price et al. 2001) and our X-ray (2-10 keV) data. The X-ray emission appears to be generally correlated with the massive star forming regions in the Radio Arc (the Arches and Quintuplet cluster regions) and the SgrA and SgrB2 complexes. This correlation suggests that the mechanical energy release from massive stars, in the form of supernova explosions and stellar winds, is at least partly responsible for the diffuse X-ray emission in the GC. The lack of correspondance between X-ray emission and non-thermal radio and mid-infrared sources indicates that non-thermal processes, such as inverse Compton scattering of the CMB or of the interstellar infrared radiation field do not contribute significantly to the observed diffuse X-ray emission.

One exception to this anti-correlation between non-thermal radio and X-ray features is the extended X-ray counterpart ($\sim 1'$ or 2.5 pc in length) of the magnetic radio filament G359.54+0.18 (Yusef-Zadeh et al. 1997), which may provide new insight into the physical mechanism responsible for the acceleration of particles in these enigmatic filaments. On even larger scales (100 pc−1 kpc), correlations between diffuse X-ray emission and magnetic field structures in this region are crucial for understanding the history of energetic events in this active region. Our images suggest that the diffuse emission may extend beyond the region surveyed. It is thought that previous energetic activities in the GC may explain the large X-ray emission features detected in soft ROSAT X-ray images and may be related to the large, polarized plumes of radio continuum emission (Sofue 200). Vertical outflows of magnetized materials as is seen in nearby galaxies such as NGC4631 (Wang et al. 2001) have a profound impact on the mass, energy and metalicity balance in the galactic ISM.

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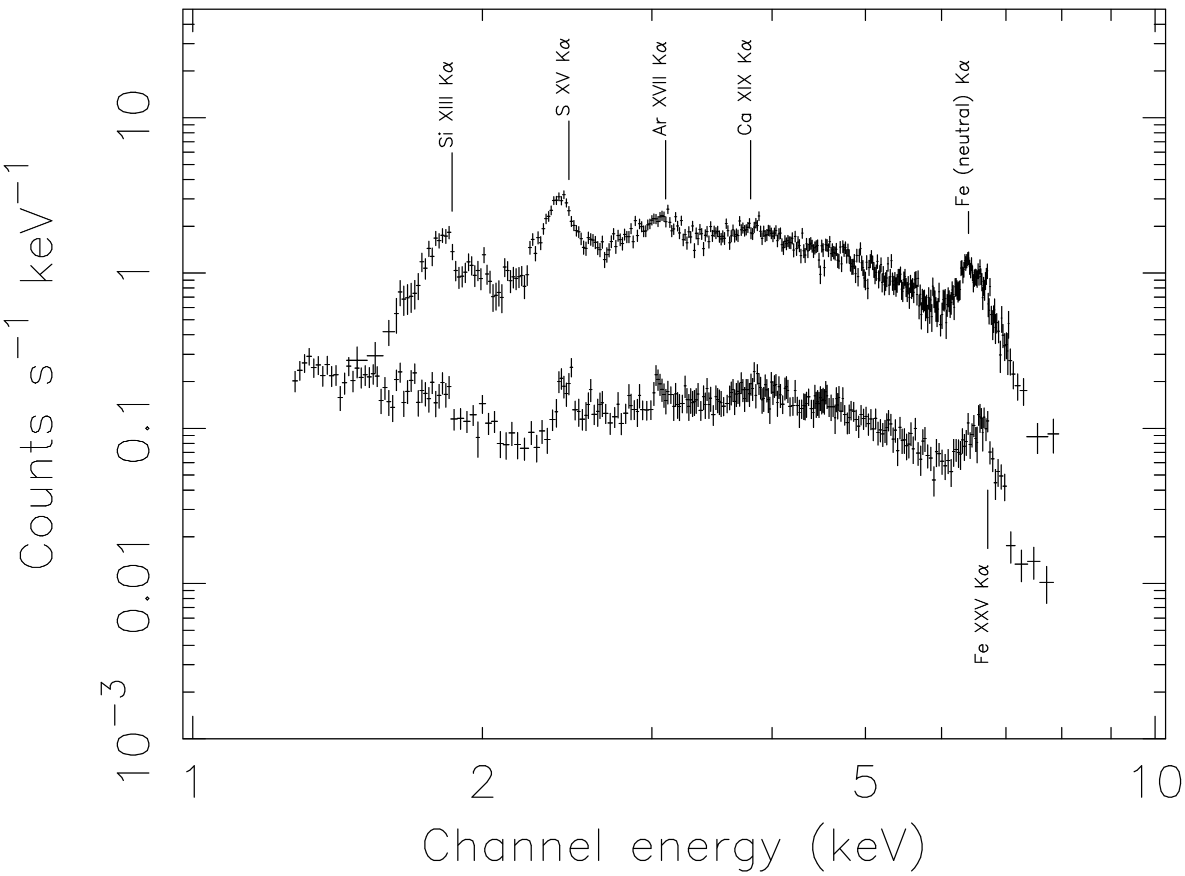

Figure 2: Spectra of total enhanced diffuse emission and total point sources. The discrete source and enhanced diffuse emission spectra were extracted from an ellipse (with the major and minor axis equal to $50'$ and $12'$), centered at the Sgr A* and oriented along the Galactic plane. For each spectrum, we derive an average auxiliary response, weighted by an image of selected events in the detector coordinates. A diffuse background, obtained in the outer field and normalized in both exposure and area, was subtracted from the two spectra.

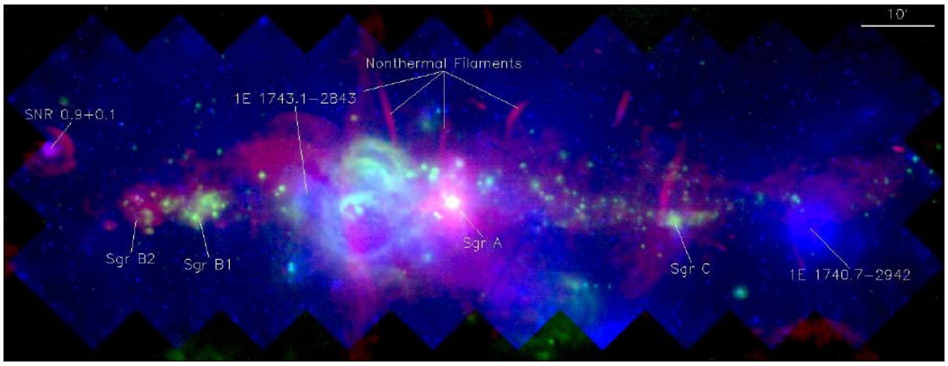

Figure 3: A three-color image of the GC region across the spectrum: red: radio 90 cm (VLA; LaRosa et al. 2001); green: mid-infrared (MSX; Price et al. 2001); blue: X-ray (1–8 keV; Fig. 1)

K. R. Anantharamaiah 1952–2001

W. Miller Goss & Cornelia C. Lang

Figure 4: Anantha at his farewell party in Socorro, 1989 (photo: W.M. Goss)

Our colleague Anantharamaiah (Anantha) died on October 29, 2001 in Bangalore India. He had been diagnosed with lung cancer in mid 2001. Anantha is survived by his wife Dr. Jyotsna Anantharamaiah and his son, Avinash.

Anantha joined the Raman Research Institute (RRI) in Bangalore in 1974 after a B.Sc. and M.Sc. in Physics from the University of Mysore. His Ph.D thesis from RRI and Bangalore University was obtained in 1985 based on Ooty Radio Telescope observations. In 2000, Anantha became the chair of the Astronomy and Astrophysics Division of RRI. He had become a professor at RRI in 1997.

Anantha was well known at the VLA/VLBA having spent five of the last 15 years there. Anantha was a Jansky Fellow from 1986-1989, active in VLA radio recombination line research (with Farhad Yusef-Zadeh, Alan Pedlar, Peter Dewdney and Miller Goss) and solar scattering of radio sources (with Tim Cornwell and Ramesh Narayan). Tim Cornwell has pointed out the breadth of Anantha's interests, understanding, and enthusiasm from their work on various forms of scattering. It will come as no surprise to those who knew Anantha that this work started with conversations between Anantha and Tim when returning from a ski trip to Santa Fe. The work itself centered around an experiment with the VLA to confirm coherences in the speckles of scattering of sources near the Sun but it led to continuing work with others on astrophysical applications of scattering.

The new field of high resolution observations of the weak radio recombination lines from extra-galactic spiral galaxies was begun in this period with collaborators: Alan Pedlar, Jun-Hui Zhao, Francois Viallefond, Bikram Phookun and Goss. Anantha was the driving force for this innovative, difficult and exciting research. An additional groundbreaking research area in the 1980s was the confirmation of carbon recombination lines at low frequencies in the direction of Cas A by Anantha, Radhakrishnan, Bill Erickson and Harry Payne using the 140 foot telescope at Green Bank. This work importance of line broadening at low frequencies due to pressure or radiation broadening. In addition, Anantha et al. demonstrated the smooth transition of these carbon recombination lines from emission at higher frequencies due to stimulated emission to absorption at lower frequencies, in agreement with the behavior expected from dielectronic-like recombination in the CII gas. In the years 1997-1999, Anantha spent two productive years working in Socorro. One of Anantha's most enjoyable projects in this period was a VLA and IRAM study of the remarkable radio and mm recombination lines from the starburst galaxy Arp 220.

Over the years, Anantha was interested in GC research and was an active contributor. Anantha collaborated in a large VLA study of the GC at 20 and 90 cm with Jacqueline van Gorkom, Ulrich Schwarz, Pedlar, Ron Ekers, and Goss. The nature of Sgr A West, East, and the spectral properties of the nonthermal filaments (NTFs) was a theme of this research. Farhad Yusef-Zadeh remembers the detailed recombination line observations of the GC which he and Anantha carried out using the 140 foot telescope at Green Bank in 1987. These were difficult observations, but Anantha's understanding of single dish, recombination line observations led them to success. Subsequently, Yusef-Zadeh and Anantha presented their results at the IAU symposium in Los Angeles in 1988. Farhad points out that their conference proceeding perhaps has the longest two names on any astronomical publication (32), including 9 A's!

Anantha's presence in Socorro from 1997-1999 revived a lot of the ongoing GC research there. Anantha revisited some of his VLA 20 and 90 cm radio recombination line observations (with Pedlar and Goss) of the ionized gas in the SgrA Complex (from 1987 and 1996) and presented a comprehensive paper at the Tucson GC workshop in the fall of 1998. In addition, he began a lasting collaboration with Cornelia Lang (then a NRAO predoc from UCLA) exploring the GC magnetic filaments. The discovery of the "Pelican" filament (the only one parallel to the Galactic plane) was made during this time in collaboration with Namir Kassim and Joe Lazio. The early VLA 74 MHz observations of the GC (under the leadership of Kassim) were painstakingly reduced by Anantha, and are now being continued in the PhD thesis (University of New Mexico) of Michael Nord.

At the Tucson GC workshop Anantha played a major role in many of the discussions and sparked many suggestions for ways to extend Galactic Center work into his familiar low frequency domain. He encouraged people to use the GMRT in India, and subsequently, a number of GC astronomers from that workshop ended up visiting Anantha in Bangalore and Pune during the IAU Symposium on Low Frequency Radio Astronomy in late 1999. Anantha was also the prime instigator and a loyal member of the "Galactic Center Club" which became a Socorro institution in 1998-1999, meeting Fridays after work at the Capitol Bar.The Tucson meeting "Central Parsecs" caps were mandatory uniform!

While Anantha was recognized as the world expert in radio recombination lines, his research interests were diverse and he made significant contributions in many areas, including interstellar and interplanetary scattering, the cosmic deuterium abundance, and the understanding of noise in radio interferometric imaging. Anantha was also one of the last of the rare breed of instrumental astrophysicists who was as comfortable with correlator boards and low noise amplifiers as he was with the physics of the interstellar medium.

But it was not only Anantha's incredible insightfulness into all areas of astronomy for which he will be missed. Anantha was also well known and loved for his intense humor, warm personality and thoughtfulness which permeated all aspects of life. For these reasons, he has enriched both the Galactic Center astronomy and the world wide astronomy communities.

Abstracts

A New System of Parallel Isolated Nonthermal Filaments Near the Galactic Center: Evidence for a Local Magnetic Field Gradient

T. N. LaRosa[1] *T. Joseph W. Lazio, Namir E. Kassim*

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We report the discovery of a system of isolated nonthermal filaments approximately 0.5° northwest (75 pc in projection) of Sgr A. Unlike other isolated nonthermal filaments which show subfilamentation, braiding of subfilaments, and flaring at their ends, these filaments are simple linear structures and more closely resemble the parallel bundled filaments in the Galactic center radio arc. However, the most unusual feature of these filaments is that the 20/90 cm spectral index uniformly decreases as a function of length, in contrast to all other nonthermal filaments in the Galactic center. This spectral gradient may not be due to simple particle aging but could be explained by a curved electron energy spectrum embedded in a diverging magnetic field. If so, the scale of the magnetic gradient is not consistent with a large scale magnetic field centered on Sgr A* suggesting that this filament system is tracing a local magnetic field.

Ref.: ApJ, 2001 December 10, in press
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Eprint: astro-ph/0108360

The stability of the Circumnuclear Disk clouds in the Galactic Centre

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The influence of rotation and magnetic fields on the physical properties of isothermal gas clouds is discussed. The presence of rotation and/or magnetic fields results in an increase of the critical cloud mass with respect to gravitational instability for clouds of a given temperature and external pressure. Rotating clouds have higher densities. Consequently, they are more stable against tidal shear than non-rotating clouds. They can approach the Galactic Centre up to a radius of ~2 pc without being disrupted by the tidal shear due to the gravitational potential. For smaller radii the clouds either collapse or become tidally disrupted. We suggest that this mechanism is responsible for the formation of the inner

Ref.: A&A, Aug 2001, in press
Email: bvollmer@sun184.mpifr-bonn.mpg.de
Eprint: astro-ph/0108354

Detection of X-ray Emission from the Arches Cluster Near the Galactic Center

F. Yusef-Zadeh, C. Law, M. Wardle, Q. D. Wang, A. Fruscione, C.C. Lang, A. Cotera

The Arches cluster is an extraordinarily compact massive star cluster with a core radius of about 10″ (~0.4 pc) and consisting of more than 150 O star candidates with initial stellar masses greater than 20 $M_{\odot}$ near G0.12-0.02. X-ray observations of the radio Arc near the Galactic center at l~ 0.2^0 which contains the Arches cluster have been carried out with the Advanced CCD Imaging Spectrometer (ACIS) on board Chandra X-ray Observatory. We report the detection of two X-ray sources from the Arches cluster embedded within a bath of diffuse X-ray emission extending beyond the edge of the cluster to at least 90″ × 60″ (3.6 pc × 2.4 pc). The brightest component of the X-ray emission coincides with the core of the cluster and can be fitted with two-temperature thermal spectrum with a soft and hard component of 0.8 and 6.4 keV, respectively. The core of the cluster coincides with several ionized stellar wind sources that have previously been detected at radio wavelengths, suggesting that the X-ray emission from the core arises from stellar wind sources. The diffuse emission beyond the boundary of the cluster is discussed in the context of combined shocked stellar winds escaping from the cluster. We argue that the expelled gas from young clusters such as the Arches cluster may be responsible for the hot and extended X-ray emitting gas detected throughout the inner degree of the Galactic center.

Ref.: ApJ, in press
Email: zadeh@oort.astro.nwu.edu

Eprint: astro-ph/0108174

ASCA X-ray source catalogue in the Galactic Center region

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The ASCA satellite made 107 pointing observations on a 5×5 deg^2 region around the center of our Milky Way Galaxy (the Galactic Center) from 1993 to 1999. In the X-ray images of the 0.7–3 keV or 3–10 keV bands, we found 52 point sources and a dozen diffuse sources. All the point sources are uniformly fitted with an absorbed power-law model. For selected bright sources, Sgr A*, AX J1745.6−2901, A 1742−294, SLX 1744−300, GRO J1744−28, SLX 1737−282, GRS 1734−292, AX J1749.2−2725, KS 1741−293, GRS 1741.9−2853, and an unusual flare source XTE J1739−302, we present further detailed spectral and timing analyses, and discuss on their nature. A dozen extended X-ray sources comprise radio supernova remnants, giant molecular clouds, and those new discoveries. Most show emission lines from either highly ionized atoms or low-ionized irons. The X-ray spectra were fitted with either a thin thermal or power-law model. This paper summarizes the results and provides the ASCA X-ray source catalogue in the Galactic Center region.

Ref.: ApJS, 2001, in press
Email: mas@star.le.ac.uk
Eprint: astro-ph/0108376
http://www.star.le.ac.uk/~mas/research/paper/Sakano2001apjs.pdf.gz

Rapid X-ray flaring from the direction of the supermassive black hole at the Galactic Centre

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Most galactic nuclei are now believed to harbour supermassive black holes. Studies of stellar motions in the central few light-years of our Milky Way Galaxy indicate the presence of a dark object with a mass of about 2.6 million solar masses. This object is spatially coincident with Sagittarius A* (Sgr A*), the unique compact radio source located at the dynamical centre of our Galaxy. By analogy with distant quasars and nearby active galactic nuclei (AGN), Sgr A* is thought to be powered by the gravitational potential energy released by matter as it accretes onto a supermassive black hole. However, Sgr A* is much fainter than expected in all wavebands, especially in X-rays, casting some doubt on this model. Recently, we reported the first strong evidence of X-ray emission from Sgr A*. Here we report the discovery of rapid X-ray flaring from the direction of Sgr A*. These data provide compelling evidence that the X-ray emission is coming from accretion onto a supermassive black hole at the Galactic Centre, and the nature of the variations provides strong constraints on the astrophysical processes near the event horizon of the black hole.

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The Nature of the 10 Kilosecond X-ray Flare in Sgr A*

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The X-ray mission Chandra has observed a dramatic X-ray flare – a brightening by a factor of 50 for only three hours – from Sgr A*, the Galactic Center supermassive black hole. Sgr A* has never shown variability of this amplitude in the radio and we therefore argue that a jump of this order in the accretion rate does not seem the likely cause. Based on our model for jet-dominated emission in the quiescent state of Sgr A*, we suggest that the flare is a consequence of extra electron heating near the black hole. This can either lead to bulk heating of thermal electrons to $T_e \sim 6 \cdot 10^{11}$ K and significantly increased synchrotron-self Compton emission, or result from non-thermal particle acceleration with increased synchrotron radiation and electron Lorentz factors up to $\gamma_e \gtrsim 10^5$. While the former scenario is currently favored by the data, simultaneous VLBI, submm, mid-infrared and X-ray observations should ultimately be able to distinguish between the two cases.

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Unusual diffuse X-ray source in the Galactic center region

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We report the *ASCA* and *Chandra* discovery of a diffuse X-ray source in the Galactic center region. The X-ray spectrum is fitted with a non-equilibrium ionization (NEI) plasma model of about 6-keV temperature. The model requires higher than solar metal abundances, a young plasma age of $\simeq$ 100 years and a large $N_{\rm H}$ value of about 10^{23} cm^{-2}. The $N_{\rm H}$ value constrains the source position to be in the Galactic center region at about 8.5 kpc distance. The high resolution X-ray image with the *Chandra* ACIS shows a ring of $10''$ radius which corresponds to 0.4 pc at the Galactic center, and a tail-like structure. Although the morphology is peculiar, the other X-ray features are likely to be a very young supernova remnant, possibly in a free expansion phase.

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Low-Frequency Radio Transients in the Galactic Center

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We report the detection of a new radio transient source, GCRT J1746-2757, located only 1°.1 north of the Galactic center. Consistent with other radio transients toward the Galactic center, this source brightened and faded on a time scale of a few months. No X-ray counterpart was detected. We also report new 0.33 GHz measurements of the radio counterpart to the X-ray transient source, XTE J1748-288, previously detected and monitored at higher radio frequencies. We show that the spectrum of XTE J1748-288 steepened considerably during a period of a few months after its peak. We also discuss the need for a more efficient means of finding additional radio transients.

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SiO Maser Survey in the Galactic Center Region with a Multi-Beam Receiver

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We have made a wide-field survey of SiO masers in the $7' \times 13'$ area around the Galactic center with the Nobeyama 45-m radio telescope using a 2×3 multi-beam SIS mixer receiver at 43 GHz. We detected 9 SiO maser sources (6 of them are new); newly detected 6 sources have been identified with Miras or OH 1612 MHz maser sources. The source surface number density, $\sim$ 360 per square degree, found in this survey is slightly smaller than the number density of OH 1612 MHz sources in the same area. A least-squares analysis of the radial velocities of the detected sources has revealed a rapid rotation of the stars around the Galactic center. This implies that most of the objects detected in this survey belong to the nuclear disk near the Galactic center.

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Mass Spectrum of the Galactic Center Molecular Clouds

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We have observed three molecular clumps in the Galactic center region in the CS J=2–1 line with the Nobeyama Millimeter Array. We have determined the mass spectrum and other statistical relations for the Galactic center cloud cores. The derived mass spectrum is somewhat steeper than for galactic cloud cores based on molecular line observations. In addition, the spectrum is steeper than that of the large scale Galactic center clumps.

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Polarization of X–ray emission from the Sgr B2 cloud

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The Sgr B2 giant molecular cloud is claimed to be an "X–ray reflection nebula" – the reprocessing site of a powerful flare of the Sgr A* source, occurred few hundred years ago. The shape of the X–ray spectrum and the strength of the iron fluorescent line support this hypothesis. We argue that the most clean test of the origin of X–rays from Sgr B2 would be a detection of polarized emission from this source.

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Using Pulsars to Detect Massive Black Hole Binaries via Gravitational Radiation: Sagittarius A* and Nearby Galaxies

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Pulsar timing measurements can be used to detect gravitational radiation from massive black hole binaries. The ~106d quasi-periodic flux variations in Sagittarius A* (Sgr A*) at radio wavelengths reported by Zhao 2001 may be due to binarity of the massive black hole that is presumed to be responsible for the radio emission. A 106d equal-mass binary black hole is unlikely based on its short inspiral lifetime and other arguments. Nevertheless the reported quasi-periodicity has led us to consider whether the long-wavelength gravitational waves from a conjectured binary might be detected in present or future precision timing of millisecond pulsars. While present timing cannot reach the level expected for an equal-mass binary, we estimate that future efforts could. This inquiry has led us to further consider the detection of binarity in the massive black holes now being found in nearby galaxies. For orbital periods of ~2000d where the pulsar timing measurements are most precise, we place upper limits on the mass ratio of binaries as small as 0.06.

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Interstellar gas in the Galaxy and the X-ray luminosity of Sgr A* in the recent past

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Information about the X-ray luminosity of the supermassive black hole located at the Galactic center (GC), Sgr A*, and its temporal variations in the past is imprinted in the scattered emission observed today in the direction towards giant molecular clouds (GMCs) located in our Galaxy. Due to light travel time effects these clouds probe the activity of Sgr A* at different times in the past depending on their position relative to the GC and the observer. In this paper we combine results of recent *ASCA* observations along the Galactic plane, providing upper limits for the scattered flux in the 4-10 keV range produced in a given direction, with data from CO surveys of the same regions. These CO surveys map the position and mass of the molecular gas which the GMCs are made up of. Demanding the scattered flux to be not larger than the observed one, this data enables us to derive upper limits for the 4-10 keV luminosity of Sgr A* at certain times during the last 40 000 years down to about $8\times10^{40}\,\mathrm{erg\,s^{-1}}$. At other times the limits are less tight, of the order of $10^{41} - 10^{42}\,\mathrm{erg\,s^{-1}}$. For two periods of time of about 2000 and 4000 years duration 8000 and 14 000 years ago the currently available CO data is insensitive to any enhanced activity of the GC. Flares lasting longer than 3000 years fill these time gaps and therefore can be excluded to have occured during the last 40 000 years with a luminosity larger than a few $10^{42}\,\mathrm{erg\,s^{-1}}$. The more extended and continuous HI distribution in the Galactic disk, which also scatters the radiation emitted by Sgr A*, allows us to extend the time coverage further into the past, back to about 110 000 years, albeit the limits are becoming less tight. We thereby can rule out a long term X-ray activity phase of Sgr A* at one per cent of its Eddington level ending less than about 80 000 years ago. The limits presented in this paper can be improved by observations of emission in the fluorescent iron K_α-line. We study the feasibility of these methods to investigate past nuclear activity in other spiral galaxies observed with the angular resolution of X-ray telescopes like *Chandra* and *XMM-Newton*.

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Production of neutrons, neutrinos and gamma-rays by a very fast pulsar in the Galactic Center region

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We consider the possibility that the excess of cosmic rays near $\sim 10^{18}$ eV, reported by the AGASA and SUGAR groups from the direction of the Galactic Center, is caused by a young, very fast pulsar in the high density medium. The pulsar accelerates iron nuclei to energies $\sim 10^{20}$ eV, as postulated by the Galactic models for the origin of the highest energy cosmic rays. The iron nuclei, after about 1 yr since pulsar formation, leave the supernova envelope without energy losses and diffuse through the dense central region of the Galaxy. Some of them collide with the background matter creating neutrons (from desintegration of Fe), neutrinos and gamma-rays (in inelastic collisions). We suggest that neutrons produced at a specific time after the pulsar formation are responsible for the observed excess of cosmic rays at $\sim 10^{18}$ eV. From normalization of the calculated neutron flux to the one observed in the cosmic ray excess, we predict the neutrino and gamma-ray fluxes. It has been found that the 1 km^2 neutrino detector of the IceCube type should detect from a few up to several events per year from the Galactic Center, depending on the parameters of the considered model. Also future systems of Cherenkov telescopes (CANGAROO III, HESS, VERITAS) should be able to observe 1 - 10 TeV γ-rays from the Galactic Center if the pulsar was created inside a huge molecular cloud about $3 - 10 \times 10^3$ yrs ago.

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The Galactic Centre Source IRS 13E: a Post-LBV Wolf-Rayet Colliding Wind Binary?

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IRS 13E is an infrared, mm and X-ray source in the Galactic Centre. We present the first *Chandra* X-ray spectrum for IRS 13E and show that it is consistent with a luminous and highly absorbed X-ray binary system. Since the X-ray luminosity is too large for a solitary star, our interpretation is that of an early-type long-period binary with strong colliding winds emission. This naturally explains the observed X-ray spectrum and count rate as well as its lack of significant short term variability. Due to the short lifetime of any nebula 0.2 pc from the putative central super-massive black-hole, we argue that the primary of IRS 13E has exited the LBV phase in the last few thousand years.

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Unified description of dark matter at the center and in the halo of the Galaxy

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We consider a self-gravitating ideal fermion gas at nonzero temperature as a model for the Galactic halo. The Galactic halo of mass $\sim 2 \times 10^{12} M_\odot$ enclosed within a radius of ~ 200 kpc implies the existence of a supermassive compact dark object at the Galactic center that is in hydrostatic and thermal equilibrium with the halo. The central object has a maximal mass of $\sim 2.3 \times 10^6 M_\odot$ within a minimal radius of ~ 18 mpc for fermion masses ~ 15 keV.

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Filaments in the Galactic Center – with special reference to the "Snake"

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The nonthermal filaments in the Galactic Center constitute one of the great mysteries of this region of the Galaxy. We summarise the observational data on these filaments and critically review the various theories which currently outnumber the observed filaments. We summarise our theory for the longest of these filaments, the Snake, and discuss the relevance of this model for the other filaments in the Galactic Center region. The physics involved in our model for the Snake involves much of the physics that has dominated the career of Professor Don Melrose. In particular, the diffusion of relativistic electrons in the Snake is determined from the theory of resonant scattering by Alfvén waves.

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Circular Polarization of Radio Emission from Relativistic Jets

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In inhomogeneous optically thick synchrotron sources a substantial part of the electron population at low energies can be hidden by self-absorption and overpowered by high energy electrons in optically thin emission. These invisible electrons produce Faraday rotation and conversion, leaving their footprints in the linear and circular polarized radiation of the source. An important factor is also the magnetic field structure, which can be characterized in most cases by a global magnetic field and a turbulent component. We present the basic radiative transfer coefficients for polarized synchrotron radiation and apply them to the standard jet model for relativistic radio jets. The model can successfully explain the unusual circular and linear polarization of the Galactic Centre radio source Sgr A* and its sibling M81*. It also can account for the circular polarization found in jets of more luminous quasars and X-ray binaries. The high ratio of circular to linear polarization requires the presence of a significant fraction of hidden matter and low-energy electrons in these jets. The stable handedness of circular polarization requires stable global magnetic field components with non-vanishing magnetic flux along the jet, while the low degree of total polarization implies also a significant turbulent field. The most favoured magnetic field configuration is that of a helix, while a purely toroidal field is unable to produce significant circular polarization. If connected to the magnetosphere of the black hole, the circular polarization and the jet direction determine the magnetic poles of the system which is stable over long periods of time. This may also have implications for possible magnetic field configurations in accretion flows.

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Modeling the Galactic Center Nonthermal Filaments as Magnetized Wakes

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We simulate the Galactic Center nonthermal filaments as magnetized wakes formed dynamically from amplification of a weak (tens of μG) global magnetic field through the interaction of molecular clouds with a Galactic Center wind. One of the key issues in this *cometary model* is the stability of the filament against dynamical disruption. Here we show 2-dimensional MHD simulations for interstellar conditions that are appropriate for the Galactic Center. The structures eventually disrupt through a shear driven nonlinear instability but maintain coherence for lengths up to 100 times their width as observed. The final instability, which destroys the filament through shredding and plasmoid formation, grows quickly in space (and time) and leads to an abrupt end to the structure, in accord with observations. As a by-product, the simulation shows that emission should peak well downstream from the cloud-wind interaction site.

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Observations of SiO Maser Sources within a Few Parsecs from the Galactic Center

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Mapping and monitoring observations of the SiO maser sources near the Galactic center were made with the Nobeyama 45-m telescope at 43 GHz. Rectangular mapping an area of approximately $200'' \times 100''$ in a $30''$ grid, and triangular mapping in a $20''$ grid toward the Galactic center, resulted in 15 detections of SiO sources; positions of the sources were obtained with errors of 5–$10''$ except for a few weak sources. Three-year monitoring observations found that the component at $V_{lsr} = -27$ km s^{-1} of IRS 10 EE flared to about 1.5 Jy during 2000 March–May, which was a factor of more than 5 brighter than its normal intensity. Using the radial velocities and positions of the SiO sources, we identified 5 which are counterparts of the previously observed OH 1612 MHz sources. The other 10 SiO sources have no OH counterparts, but two were previously detected with VLA, and four are located close to the positions of large-amplitude variables observed at near-infrared wavelengths. A least-square fit to a plot of velocities versus Galactic longitudes gives a rather high speed for rotation of the star cluster around the Galactic center. The observed radial-velocity dispersion is roughly consistent with the value obtained before. It was found that all the SiO sources with OH 1612 MHz counterparts have periods of light variation longer than 450 days, while SiO sources without OH masers often have periods shorter than 450 days. This fact suggests that lower-mass AGB stars are more often detected in SiO masers than in the OH 1612 MHz line.

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A Jet-ADAF model for Sgr A*

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The recent Chandra observation of the radio source at the center of our Galaxy, Sgr A*, puts new constraints on its theoretical models. The spectrum is very soft, and the source is rapidly variable. We consider different models to explain the observations. We find that the features of the x-ray spectrum can be marginally explained with an advection-dominated accretion flow (ADAF) model while it does not well fit the radio spectrum. An ADAF with strong winds (ADIOS) model is not favored if we assume that the wind does not radiate. Alternatively, we propose a coupled jet plus accretion disk model to explain the observations for Sgr A*. The accretion flow is described as an ADAF fed by Bondi-Hoyle accretion of hot plasma in the Galactic Center region. A small fraction of the accretion flow is ejected near the black hole, forming a jet after passing through a shock. As a result, the electron temperature increases to $\sim 2 \times 10^{11}$K, which is about 10 times higher than the highest temperature attained in the ADAF. The model is self-consistent since the main jet parameters are determined by the underlying accretion disk at the inner edge. The emergent spectrum of Sgr A* is the sum of the emission from jet and underlying ADAF. The very strong Comptonization of synchrotron emission from the jet dominates the bremsstrahlung from the ADAF, therefore, a very short variability timescale is expected and the predicted X-ray slope and the radio spectrum is in very good agreement with the observations.

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Stellar Orbits Near Sagittarius A*

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The SHARP/NTT stellar proper motion data now cover an interval from 1992 to 2000 and allow us to determine orbital accelerations for some of the most central stars. We confirm the stellar acceleration measurements obtained by Ghez et al. (2000) with NIRC at the Keck telescope. Our analysis differs in 3 main points from that of Ghez et al.: 1) We combine the high precision but shorter time scale NIRC/Keck

data with the lower precision but longer time scale SHARP/NTT data set; 2) We statistically correct the observed accelerations for geometrical projection effects; 3) We exclude star S8 from the analysis of the amount and position of the central mass. From the combined SHARP/NTT and NIRC/Keck data sets we show that the stars S2, and most likely S1 and S8 as well, are on bound, fairly inclined ($60^o < i < 80^o$), and eccentric ($0.4 < e < 0.95$) orbits around a central dark mass. The combination of both data sets results in a position of this central mass of 48^{+54}_{-24} *mas* E and 18^{+42}_{-61} *mas* S of the nominal radio position of Sgr A*. The mean statistically corrected enclosed mass derived from accelerations is $M_{acc} = (5 \pm 3) \times 10^6$ $M_\odot$ with current radial separations of S1 and S2 from SgrA* of about $8 - 10$ *mpc*. This enclosed mass estimate is derived from *individual* stellar orbits as close to the massive black hole at the center of the Milky Way as currently possible. Although the uncertainties are large this estimate is fully consistent with the enclosed mass range of $(2.6 - 3.3) \times 10^6 M_\odot$ derived by Genzel et al. (2000) from radial and/or proper motion velocities of a homogenized sample of sources. Star S8 was excluded from the analysis, since for the current proper motion velocity and radial separation from the center we find that the measured acceleration requires orbital motion around a compact object with a mass in excess of $3 \times 10^6 M_\odot$. The data suggest that this star *either* was or is subject to a close interaction with a different object *or* that its position measurements are influenced by the emission of a different cluster star. Therefore, we base the analysis of the enclosed mass solely on the available data for S1 and S2. We also discuss two late type stars with projected separations from Sgr A* of about 0.5" and 1". In addition to proper motions these stars have known radial velocities. Orbit calculations indicate that those stars are very likely at larger physical distances from the center and part of the larger scale central stellar cluster with a core radius of approximately 0.3 *pc*.

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Shocked molecular gas towards the SNR G359.1–0.5 and the Snake

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We have found a bar of shocked molecular hydrogen (H2) towards the OH(1720 MHz) maser located at the projected intersection of supernova remnant (SNR) G359.1–0.5 and the nonthermal radio filament, known as the Snake. The H2 bar is well aligned with the SNR shell and almost perpendicular to the Snake. The OH(1720 MHz) maser is located inside the sharp western edge of the H2 emission, which is consistent with the scenario in which the SNR drives a shock into a molecular cloud at that location. The spectral–line profiles of 12CO, HCO+, and CS towards the maser show broad–line absorption, which is absent in the 13C0 spectra and most probably originates from the pre–shock gas. A density gradient is present across the region and is consistent with the passage of the SNR shock while the H2 filament is located at the boundary between the pre–shocked and post-shock regions.

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Millisecond Pulsars as Probes of Mass Segregation in the Galactic Center

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We propose a simple test for the existence of a cluster of black hole remnants around Sgr A* that is based on a small sample of any type of Galactic Center objects, provided they are substantially less massive than the black holes and constitute part of an old ($\gtrsim$ 1 Gyr) population. The test relies on the fact that, under the presence of such a cluster of heavy remnants and because of energy equipartition, lower mass objects would be expelled from the central regions and settle into a distribution very different than the cusp expected to be induced by the supermassive black hole alone. We show that with a sample of just 50 objects and using only their angular positions on the sky relative to Sgr A* it is possible to clearly differentiate between a distribution consistent with the presence of the cluster of black holes and a power-law cusp distribution. We argue that millisecond pulsars might currently be the best candidate to perform this test, because of the large uncertainties involved in the age determination of less exotic objects. In addition, by measuring their

first and second period derivatives, millisecond pulsars offer the rare opportunity of determining the complete phase space information of the objects. We show that this extra information improves the detection of any mass segregation by about 30%.

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Diffuse X-rays in the Galactic center region — The zoo of iron line clumps, non-thermal filaments and hot plasmas

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This paper reports the diffuse X-ray features around the Galactic center observed with *Chandra*. We confirm the *ASCA* and *Ginga* discoveries of the large-scale thin-thermal plasma with strong lines in the Galactic center region. In addition, many small clumps of emission lines from neutral (6.4 keV line) to He-like (6.7 keV line) irons are discovered. The 6.4 keV line clumps would be reflection nebulae, while those of the 6.7 keV line are likely SNRs. We also find emission lines of intermediate energy between 6.5–6.7 keV, which are attributable to young SNRs in non equilibrium ionization. Non-thermal filaments or belts with X-ray spectra of no emission line are found, suggesting the Fermi acceleration site in a rapidly expanding shell. All these suggest that multiple-supernovae or extremely large explosion had occurred around the Galactic center region in the recent past.

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On the Nature of the X-ray Emission from the Galactic Center Region

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The origin of the X-ray emission from the central region of the Galaxy has remained a mystery, despite extensive study over the past two decades. A fundamental question is the relative contribution of the point-source and diffuse components of this emission, which is critical to understanding the high-energy phenomena and processes unique to this Galactic nuclear environment. Here, we report on results from a large-scale imaging survey of the Galactic center with sufficient spatial resolution to allow a clean separation of the two components. The He-like Fe Kα emission, previously attributed to the diffuse emission, is found largely due to the discrete X-ray source population. The number and spectrum of such sources indicate the presence of numerous accreting white dwarfs, neutron stars, and/or black holes in the region. The diffuse X-ray emission dominates over the contribution from the faint discrete sources and is shown to be associated with distinct interstellar structures observed at radio and mid-infrared wavelengths, suggesting that it arises from the recent formation of massive stars. We have also mapped out the 6.4-keV fluorescence line emission from neutral to moderately ionized irons. The ubiquitous association of the emission with molecular gas indicates that either the X-ray radiation from the Galactic center was substantially more intense in the past than at present or non-relativistic cosmic-rays are important in producing Fe K shell vacancies.

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The Spectrum and Variability of Circular Polarization in Sagittarius A* from 1.4 to 15 GHz

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We report here multi-epoch, multi-frequency observations of the circular polarization in Sagittarius A*, the compact radio source in the Galactic Center. Data taken from the VLA archive indicate that the fractional circular polarization at 4.8 GHz was −0.31% with an rms scatter of 0.13% from 1981 to 1998, in spite of a factor of 2 change in the total intensity. The sign remained negative over the entire time range, indicating a stable magnetic field polarity. In the Summer of 1999 we obtained 13 epochs of VLA A-array observations at 1.4, 4.8, 8.4 and 15 GHz. These observations employ a new technique that produces an error of 0.05% at 1.4, 4.8 and 8.4 GHz and 0.1% at 14.9 GHz. In May, September and October of 1999 we obtained 11 epochs of Australia Telescope Compact Array observations at 4.8 and 8.5 GHz. In all three of the data sets, we find no evidence for linear polarization greater than 0.1% in spite of strong circular polarization detections. Both VLA and ATCA data sets support three conclusions regarding the fractional circular polarization: the average spectrum is inverted with a spectral index $\alpha \approx 0.5 \pm 0.2$; the degree of variability is roughly constant on timescales of days to years; and, the degree of variability increases with frequency. We also observed that the largest increase in fractional circular polarization was coincident with the brightest flare in total intensity. Significant variability in the total intensity and fractional circular polarization on a timescale of 1 hour was observed during this flare, indicating an upper limit to the intrinsic size during outburst of 70 AU at 15 GHz. The fractional circular polarization at 15 GHz reached -1.1% and the spectral index is strongly inverted ($\alpha \sim 1.5$) during this flare. We tentatively conclude that the spectrum has two components that match the high and low frequency total intensity components.

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New Constraints on the Nature of Radio Emission in Sagittarius A*

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The mm to sub-mm spectrum of Sgr A* at the Galactic center, as well as its polarization characteristics, are consistent with the inner 10 Schwarzschild radii of a tight Keplerian emitting region of hot, magnetized, orbiting gas. This plasma may also be the source (through self-Comptonization) of the X-rays detected by *Chandra*. It has long been suspected that the circularization region between the quasi-spherical infall at large radii, and this inner zone, is responsible for producing the rest of Sgr A*'s spectrum. In this paper, we report the results of a detailed study of this region, with several important conclusions that will be highly relevant to upcoming coordinated multi-wavelength observations. First, the combination of existing cm and X-ray data preclude the possibility of producing the observed strong 1.36 GHz radio flux via thermal synchrotron within a bounded flow. If Sgr A*'s radio spectrum is produced by accreting gas, it appears that a non-thermal particle distribution is a necessity. This may not be surprising, given that the energy associated with the radial motion is probably dissipated by shocks before the gas circularizes, which can produce the required power-law distribution. Second, if this is the correct picture for how Sgr A*'s spectrum is produced, it appears that the *Chandra*-detected X-rays may originate *either* from self-Comptonization in the inner Keplerian region, or from optically-thin nonthermal synchrotron emission in the much larger, circularization zone, extending up to 500 Schwarzschild radii or more. This is a question that should be answered by upcoming broadband observations, since the mm-bump and X-rays are strongly correlated in the former case, whereas the X-rays are strongly correlated to the cm-radio flux in the latter. In addition, X-rays produced in the circularized gas could show periodic or quasi-periodic variations, but not those produced via nonthermal synchrotron emission much farther out.

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An Accretion-Induced X-ray Flare in Sgr A*

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The recent detection of a three-hour X-ray flare from Sgr A* by *Chandra* provides very strong evidence for a compact emitting region near this supermassive black hole at the Galactic center. Sgr A*'s mm/sub-mm spectrum and linear polarimetric properties, and its quiescent-state X-ray flux density, are consistent with a model in which low angular momentum gas captured at large radii circularizes to form a hot, magnetized Keplerian flow within tens of Schwarzschild radii of the black hole's event horizon. In Sgr A*'s quiescent state, the X-ray emission appears to be produced by self-Comptonization (SSC) of the mm/sub-mm synchrotron photons emitted in this region. In this paper, we show that the prominent X-ray flare seen in Sgr A* may be due to a sudden enhancement of accretion through the circularized flow. Depending on whether the associated response of the anomalous viscosity is to increase or decrease in tandem with this additional injection of mass, the X-ray photons during the outburst may be produced either via thermal bremsstrahlung (if the viscosity decreases), or via SSC (if the viscosity increases). However, the latter predicts a softer X-ray spectrum than was seen by *Chandra*, so it appears that a bremsstrahlung origin for the X-ray outburst is favored. A strong correlation is expected between the mm/sub-mm and X-ray fluxes when the flare X-rays are produced by SSC, while the correlated variability is strongest between the sub-mm/far-IR and X-rays when bremsstrahlung emission is dominant during the flare. In addition, we show that future coordinated multi-wavelength observations planned for the 2002 and 2003 cycles may be able to distinguish between the accretion and jet scenarios.

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Polarimetric Imaging of the Massive Black Hole at the Galactic Center

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The radio source Sgr A* in the Galactic center emits a polarized spectrum at millimeter and sub-millimeter wavelengths that is strongly suggestive of relativistic disk accretion onto a massive black hole. We use the well-constrained mass of Sgr A* and a magnetohydrodynamic model of the accretion flow to match both the total flux and polarization from this object. Our results demonstrate explicitly that the shift in the position angle of the polarization vector, seen at wavelengths near the peak of the mm to sub-mm emission from this source, is a signal of relativistic accretion flow in a strong gravitational field. We provide maps of the polarized emission to illustrate how the images of polarized intensity from the vicinity of the black hole would appear in upcoming observations with very long baseline radio interferometers (VLBI). Our results suggest that near-term VLBI observations will be able to directly image the polarized Keplerian portion of the flow near the horizon of the black hole.

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Measuring the Black Hole Spin in Sgr A*

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The polarized mm/sub-mm radiation from Sgr A* is apparently produced by a Keplerian structure whose peak emission occurs within several Schwarzschild radii ($r_S \equiv 2GM/c^2$) of the black hole. The *Chandra* X-ray counterpart, if confirmed, is presumably the self-Comptonized component from this region. In this paper, we suggest that sub-mm timing observations could yield a signal corresponding to the period P_0 of the marginally stable orbit, and therefore point directly to the black hole's spin a. Sgr A*'s mass is now known to be $(2.6 \pm 0.2) \times 10^6\, M_\odot$ (an unusually accurate value for supermassive black hole candidates), for which 2.7 min ¡ P_0 ¡ 36 min, depending on the value of a and whether the Keplerian flow is prograde or retrograde. A Schwarzschild black hole ($a = 0$) should have $P_0 \approx 20$ min. The identification of the orbital frequency with the innermost stable circular orbit is made feasible by the transition from optically thick to thin emission at sub-mm wavelengths. With stratification in the emitter, the peak of the sub-mm bump in Sgr A*'s spectrum is thus produced at the smallest radius. We caution, however, that theoretical uncertainties in the structure of the emission region may still produce some ambiguity in the timing signal. Given that Sgr A*'s flux at $\nu \sim 1$ mm is several Jy, these periods should lie within the temporal-resolving capability of sub-mm telescopes using bolometric detectors. A determination of P_0 should provide not only a value of a, but it should also define the angular momentum vector of the orbiting gas in relation to the black hole's spin axis. By analogy with low-mass X-ray binaries and Galactic black hole candidates, Sgr A* may also display quasi-periodic oscillations, which can reveal additional features in the geometry of the accreting gas. In addition, since the X-ray flux detected by *Chandra* appears to be the self-Comptonized mm to sub-mm component, these temporal fluctuations may also be evident in the X-ray signal.

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Sgr A* and Sgr A East: Intimate Life in the Galactic Center

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A hydrodynamic interaction between an old supernova remnant and a massive black hole is studied with the help of a high-resolution adaptive mesh refinement code. A series of multidimensional numerical models is obtained for a fixed distance between supernova explosion site and the black hole but different densities of the ambient medium. The interaction between the shell of the supernova remnant and the black hole results in a rapid increase of the emission from the vicinity of the black hole. Light curves of the gas heated by gravitational compression and hydrodynamical interactions are obtained assuming optically thin conditions. It is shown that the duration of the event and the peak luminosity critically depend on the density of the ambient medium. The model is applied to the data obtained by the Chandra satellite for the Galactic center.

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The Origin of X-ray Emission from a Galactic Center Molecular Cloud: Low Energy Cosmic Ray Electrons

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The Galactic center region near l$\approx 0.2^0$ hosts a mixture of nonthermal linear filaments and thermal radio continuum features associated with the radio Arc. Chandra observations of this region reveal an X-ray filament and diffuse emission with an extent of roughly $60'' \times 2''$ and $5' \times 3'$, respectively. The X-ray filament lies at the edge of the nonthermal radio filaments and a dense molecular shell G0.13-0.13 that has an unusually high kinetic temperature $\geq$70K. These observations demonstrate that the G0.13–0.13 molecular cloud and the nonthermal radio filaments of the Arc are interacting. The diffuse X-ray emission is correlated with the molecular shell and is fitted either by two-temperature (1 and 10 keV) thermal emission or by power-law and 1 keV thermal gas. Fluorescent 6.4 keV line emission is also detected throughout the molecular shell. This cloud coincides within the error circle of a steady unidentified EGRET source 3EGJ1746–2851. We argue that low-energy cosmic ray electrons (LECRe) produce the power-law continuum by bremsstrahlung and 6.4 keV line emission from the filament and the diffuse cloud with the implication on the origin of the Galactic ridge X-ray emission. The strong 6.4 keV Fe-line emission seen from other Galactic center clouds could be produced in a similar fashion rather than via fluorescent emission induced by a transient hard X-ray source in the Galactic center. In addition, heating by ionization induced by LECRe are also responsible for the high temperature of G0.13-0.13. The gamma-ray source is a result of brehmsstrahlung by the high-energy tail of the electron energy distribution.

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Announcements

GC 2002 — Conference Survey Results:

The number of responses for each question is given in brackets. Total number of respondents: 118

1. What is the probability that you will attend the conference?
   90% **(49)** 75% **(30)** 50% **(38)** Will not attend **(1)**
2. In terms of distance from Sgr A*, what should the scope of the conference be?
   10 pc **(21)** 100 pc **(21)** A few 100 pc **(37)** 1 kpc **(16)** The nuclei of galaxies **(22)**
3. What is the primary wavelength of your research?
   Radio/Submm **(39)** Infrared **(31)** X-ray **(13)** I am a theorist, so I want them all **(35)**
4. Would you be likely to bring your spouse, family, or significant other?
   Yes **(58)** No **(58)**
5. Would you be interested in going on a few hour snorkeling cruise on Wednesday afternoon at a price of $30-$40, depending on attendance?
   Yes **(80)** No **(31)**
6. The conference will end Friday afternoon, but we anticipate that many of you will stay until Sunday because of the reduction in fares. We are therefore thinking of offering an additional recreational program on Saturday. Would you be interested in:
   (26) A trip to Volcanos National Park
   (11) A trip up Mauna Kea
   (61) Either would interest me
   (15) I definitely would not be interested/will not stay through Saturday

GC 2002 — Conference Webpages:

Conference: http://www.gemini.edu/science/gc_conf/

Hotel: http://www.ohanahotels.com/details/property.asp?h_id=50

Snorkel Cruise: http://www.fair-wind.com/

Sgr A* Observing Campaign:

The Galactic Center and Sgr A*, will be the subject of an unprecedented, simultaneous multiwavelength observing campaign during the period 23–30 May 2002. Participating observatories include Chandra, Keck-I, VLT-UT1, Magellan-Baade, SMA, OVRO, VLBA, ATCA, and VLA. Contact Fred Baganoff or Mark Morris for more details. Good luck to all –may your skies be clear and Sgr A* flare!

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