

News from the year 2006 Galactic Centre workshop

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Abstract. We summarize some of the new results from contributions made to Galactic Centre workshop that took place in Bad Honnef, Germany, on April 18-22 2006.

1. Introduction

One of the web definitions of “a center” reads: “A place of concentrated activity, influence, or importance” (<http://www.answers.com/topic/center>). Another adds, “a point of origin from which ideas or influences originate”. We believe this conference on the Galactic Center is a great illustration of these definitions for several important fields of research in modern Astrophysics. While it is very hard to summarize all the exciting work presented at this meeting, we shall try to give the reader a glimpse of the state of the art of the field as of April 2006. We shall cite the results by simply the name of the first author on the corresponding proceedings article, except for papers external to the proceedings.

2. The young massive stars in the central parsec

Young massive “He-I” stars dominate the power output of the central half-parsec [Krabbe et al. 1995] of our Galaxy. “Standard” models of star formation are not easily applicable here due to a huge tidal field of the central object at $R = 0.1$ pc distances from Sgr A*. The required gas density is $n_H > 10^{11} \text{cm}^{-3} (R/0.1 \text{pc})^{-3}$. In the last several years, a significant breakthrough in understanding of these stars has taken place. We now know that ...

- These young stars are not dynamically relaxed (Levin & Beloborodov 2003). They appear to form one (J. Lu, A. Ghez) or arguably two stellar disks (T. Paumard and also Genzel et al. 2003).
- There are inner and outer radii that seem to encompass most of the massive early type stars, $R \sim 0.03$ and $R \sim 0.5$ pc, respectively. (The “S” stars inside of 0.03 pc are discussed separately below.)
- This implies that the stars are very unlikely to have migrated from outside, thus suggesting an *in situ* star formation, despite the tidal shear produced by Sgr A*. The previous debate about whether the massive stars in the central parsec formed *in situ* or whether they are remnant of a tidally disrupted cluster brought into the Galactic center by dynamical friction is not entirely concluded, but the latter hypothesis seems very strongly constrained, requiring a rather heavy burden of extreme assumptions.
- The young stars surrounding Sgr A* are then likely to be the first observational evidence for star formation in massive gaseous disks in the inner parsecs of galactic nuclei (Levin,

Paumard). Recurring *in situ* star formation was suggested to occur in the GC due to a periodic inflow of gas from the Circumnuclear Disk (inner few parsecs) by Morris et al. (1999).

- The inner radius might be indicative of the minimum distance at which star formation can still occur, and is consistent with theoretical predictions (Levin, Nayakshin).
- NIR observations and X-ray constraints suggest that the IMF of young stars is very top-heavy (Paumard, Nayakshin). Such an IMF might be the result of inefficient cooling in the optically thick conditions in the disk (Nayakshin, Levin). The dynamically hot condition of the disk (*i.e.*, likely strong turbulence, as evidenced by the current circumnuclear disk), and the presumably strong magnetic field might also have this effect on the IMF (Morris 1993).
- The exact orbits of the stars in the stellar ring(s) remain a subject of debate. The acceleration limit (J. Lu) places lower limits on the eccentricities of some of the young stars, some of which are rather high. This spells trouble for the simplest version of the *in situ* model, *i.e.*, the model of a gaseous disk in a circular rotation about Sgr A*.
- Numerical simulations, however, show that stars may also form via gravitational fragmentation in an eccentric ring of gas (Sanders 1998; Nayakshin). Interestingly, an initially flat eccentric disk of stars becomes geometrically thick much faster than a flat circular disk (Nayakshin et al. 2006) due to orbital precession (Touma). Thus, the fact that the second feature in the stellar velocity distribution of young stars in the GC (the counter-clockwise “disk”) is more geometrically thick than the clockwise disk may be naturally explained by the different rates of orbital precession.
- New observations constrain stellar effective temperatures with increasing reliability. There appears to be no stars more massive than about $60 M_{\odot}$, which would be consistent with the age of the Sgr A* young star cluster (F. Martins).
- The star cluster IRS13E is a mysterious collection of several very massive young stars and perhaps a couple dozen lighter ones, so it may be the surviving core of a massive cluster which has been almost entirely tidally stripped (T. Paumard). Indeed, its dynamics place it in the counter-rotating stellar disk, so it may provide evidence that that disk has resulted from the disruption of a dense cluster. However, the visible mass of IRS13E is insufficient to bind it gravitationally. An alternative to the rather implausible explanation that the cluster core is only now making its first pass near the central black hole is that it is bound by an intermediate mass black hole. However, the X-ray evidence favors colliding stellar winds over black hole accretion. IRS13E-like objects are in fact not formed naturally in current *in situ* star formation simulations (Nayakshin). Understanding IRS13E is therefore crucial for understanding of the overall star formation event in the GC.
- Other co-moving groups of young stars might be present (R. Schoedel) in the inner parsec.
- IRS16SW appears to be an eclipsing contact binary with two $\sim 50 M_{\odot}$ stars orbiting with a period of about 18 days (T. Ott, M. Rafelski).

3. S-stars in the central ~ 0.03 parsec

The so-called “S-stars” are the stars observed in the inner arcsecond in projection from Sgr A*, *i.e.*, in the inner region that excludes the He-I stars discussed above. These stars are now spectroscopically resolved to be less massive but nonetheless still quite young B-type stars. The paradox of youth is orders of magnitude more severe for these stars than for the He-I stars. Furthermore, the orientations of the orbits of these stars appear to be consistent with isotropic, so they do not point to any organized formation mechanism such as a disk. A large fraction of the S stars has relatively eccentric orbits, although this fraction is difficult to determine reliably

because of selection effects. There is also a strong selection effect toward studying only the brightest sources, although more stars are emerging all the time, so this situation is improving.

While there were many theoretical suggestions for the origin of these stars, there does not yet appear to be a clear winner among them. Gravitational instability of a massive accretion disk is not predicted to form stars closer in than about $1''$, and hence the in-situ star formation for S-stars is not favored. Some of the new ideas emerged from the meeting on the origin of these stars are:

- Massive perturbers, such as massive molecular clouds or star clusters, can significantly enhance the rate at which massive young binaries diffuse on nearly radial orbits (H. Perets). If these binaries are then disrupted, a population of stars similar to S-stars might be created.
- The population of remnants of disrupted binaries would have very large eccentricities ($e \approx 0.99$; Y. Levin). Ordinary N-body relaxation is too slow to evolve the orbits, which would then be a serious problem for the model, as several of the S-stars have moderated eccentricities ($e < 0.5$). Resonant relaxation (C. Hopman, T. Alexander), might however result in the orbital evolution that is rapid enough to explain those “rouge” S-stars.
- Although this was not discussed at the meeting, we note that the relatively young, ultra-high velocity stars now being found in the galactic halo, whose orbits are consistent with being purely radial, are widely seen to result from binary encounters either with the central black hole or with stellar mass black holes in a central cluster. Such process may be a promising way of producing the S stars as the former companions of the ultra-high velocity stars (O’Leary & Loeb 2006).
- Spectra of the S stars are consistent with those of normal B-type stars (F. Martins), possibly ruling out the model in which the S-stars are created by tidal disruption of giants on nearly radial orbits.

4. NIR/X-ray flares from Sgr A*

At the time of the last workshop on the Galactic center, Sgr A* had just been discovered at infrared wavelengths, and the first observations of X-ray flares had only recently been announced (Baganoff et al. 2001). (Millimeter-wavelength flares had been reported already at the 1998 Tucson workshop, and continued follow-up work on that was reported here by A. Miyazaki) Since that time, the characteristics of the emission have become clearer, and theories for the spectrum of Sgr A* have been elaborated to account for that (F. Yuan). However, this study is still at a very early stage, both observationally and theoretically, as the frequency, spectrum, location, and cause of the flares all remain widely debated. X-ray flares are well-defined events, rising above the feeble, marginally extended ($\sim 1.5''$) quiescent emission almost once per day. The near-infrared intensity variations of more than an order of magnitude appear to be essentially continuous red noise variations, rather than being well-defined “flares”. The common use of the term “flare” in the NIR typically refers to a broad intensity maximum in the continuous light curve.

- The locations of NIR flares are offset from the dynamical center of the Sgr A* star cluster by no more than $2 \text{ mas} \sim 2 \times 10^{14} \text{ cm}$. This implies they do originate from Sgr A* (S. Trippe).
- There is a dusty clump of gas very near the line of sight to Sgr A*, which may influence the mid-infrared fluxes of Sgr A* during flares (Ghez et al. 2005; A. Eckart).
- There is not yet universal agreement about whether the spectral index observed during flares is correlated with the flare luminosity, but much recent effort has gone into measuring the NIR spectrum and its relationship to the X-ray emission properties (S. Hornstein; S.

Gillessen; A. Krabbe; A. Eckart). Hornstein finds no variability of the NIR spectral index of Sgr A* from 1.6 to 4.6 μm .

- Simultaneous observations of Sgr A* at infrared, radio and X-ray wavelengths have been attempted since 2002, and a few events have been captured in multiple bands (A. Eckart; Yusef-Zadeh et al. 2006). The present indications are that X-ray flares are accompanied by NIR maxima, although the statistics on this can only be improved. This strengthens theories in which the same population of electrons is responsible for both the NIR and X-ray events, but probably by virtue of different processes (synchrotron and synchrotron self-Compton, respectively).
- A breakthrough has occurred with the first measurements of the polarization of the NIR emission from Sgr A* and of its variability (A. Eckart). The polarization shows much more time structure than the total intensity, suggesting that it is affected by the varying direction of motion of the nonthermally emitting gas. A similar phenomenon is also evidenced at submillimeter wavelengths (D. Marrone). Polarization variability time scales of ~ 20 minutes are particularly intriguing in view of the occasional periodicities that have been claimed for the total IR (Genzel et al. 2003) and X-ray intensities (G. Belanger), and in view of the coincidence of this time scale with the period of the innermost stable circular orbit around a rotating black hole of $3.6 \times 10^6 M_{\odot}$. Theoretical models suggest that polarised emission of a rotating blob near Sgr A* could produce characteristic signatures that would allow observers to constrain the spin of Sgr A* (L. Meyer; A. Broderick).
- A compelling 22-minute periodicity was inferred from the data on one rather long X-ray flare observed with XMM (G. Belanger). The duration of the entire flare was only about 7 times this period, so the analysis of the statistics of this event is an important and delicate issue. The ~ 15 other flares seen with Chandra and XMM have not yet shown any significant periodicity, so any such modulation of the X-ray flare signal is apparently uncommon.

5. New X-ray results on the GC

- The *Suzaku* telescope, formerly known as *AstroE2*, can now distinguish between rather closely lying X-ray lines. K. Koyama reported *Suzaku* results on the Fe K- α line at ~ 6.7 keV in the GC diffuse emission. It is found that the centroid energy is 6.680 keV, which favors the thermal collisional origin of that line, rather than its being due to charge exchange with cosmic rays (in which the line energy would be 6.666 keV). The ratio of X-ray line intensities shows that plasma emitting the diffuse emission is in near ionization equilibrium. Also, the emitting medium does not have a large bulk motion with respect to Sgr A*.
- The diffuse X-ray emission presented a puzzle for many years, as the plasma emitting it would be too hot to be confined by the gravity of the GC, and would require an enormous energy source to maintain (R. Belmont). R. Warwick suggests that the diffuse X-ray emission is produced by a population of cataclysmic variables (CVs) rather than by a hot diffuse plasma. This parallels the recent results of Revnivtsev et al. (2006) on the larger scale Galactic ridge X-ray emission, but conflicts with the conclusions of Munro et al. (2004) and Koyama et al. (2006).
- Association of the “neutral” 6.4 keV Fe K- α line with the 4.5 – 6 keV continuum emission argues for origin of most of that emission in local cosmic ray ionization (R. Warwick), rather than photo-ionization.
- Sgr B2 cloud’s 6.4 keV Fe K- α X-ray emission, and that in the newly found “X-ray reflection nebula”, are however the results of photo-ionization (K. Koyama).
- *Chandra* observations show that low mass stars $M \lesssim 1 - 2 M_{\odot}$ seem to be deficient by a factor of up to ten in both the central star cluster (S. Nayakshin) and the Arches star cluster

(D. Wang). The extent to which the apparent top-heavy MF of the Arches cluster is owed to the preferential tidal stripping of its original low mass stars is not yet clear.

6. The central molecular zone and star formation

- Gas in the CMZ is particularly warm, dense, and turbulent, with temperatures ranging up to several hundred degrees K (N. Rodriguez-Fernandez). About 10-30% of the column density of the CMZ can be attributed to a hot (~ 150 K) photodissociation region. It is not yet possible to decide definitively among the possible heating mechanisms proposed for the rest of the gas, or even whether the right mechanism has yet been proposed. Observations of an unusually high relative abundance of SiO in CMZ clouds imply that shocks affect the chemical abundances there.
- The study of the CMZ is a mature field, with many surveys done in past decades. Therefore, it was remarkable to see in a recent CO survey some altogether new morphological features: very large molecular loops rising far above the Galactic plane (Y. Fukui). The shapes and velocity fields of these features are reasonably interpreted as having been produced by the Parker instability, although it remains unclear why the loop-like magnetic structures resulting from that instability would have a molecular form.
- The Spitzer/IRAC survey has provided a wealth of detail that will be mined for a long time to come (S. Stolovy). Hot dust and PAH emission are ubiquitous throughout the inner few hundred parsecs, pointing the way to sites of star formation activity. The close correspondence between the IRAC images and the radio images of HII regions – notably near the Quintuplet Cluster – illustrate the strong interaction between the luminous, hot stars and gas in the CMZ (A. Coter).
- Star formation in the CMZ is a currently active process that has been ongoing quasi-continuously since the formation of the Galaxy (Figer 2007). It has been punctuated recently, and very likely at a steady rate in the past, by the formation of massive, compact clusters, three of which have formed within the past 10^7 years. Inevitable tidal dissolution makes it very difficult to identify older clusters than that. One of the important outstanding problems in Galactic center research is to identify the mechanism for the formation of such massive clusters as the Arches and Quintuplet.

7. The Galactic center magnetic field

Two important puzzles that emerge from this workshop are the strength and the dispersion of the magnetic field in the central 100 parsecs (M. Morris). The paradigm suggested some time ago by the presence of numerous, vertically-oriented, nonthermal radio filaments was a pervasive milligauss field having a relatively small dispersion in both strength and direction. The field was hypothesized to be highlighted by synchrotron radiation only at the places where relativistic electrons have been injected. The pervasive milligauss field has been called into question based on recent studies of low-frequency synchrotron radiation (T. LaRosa), and using the minimum energy assumption, which may be inapplicable to this situation. The debate about the field strength hinges also on the relatively short synchrotron lifetime of the emitting electrons in the strong field case, and therefore whether there exists a reacceleration mechanism. Others have argued that the radio filaments represent local concentrations of the field caused by turbulence or by some transitory current structure. However, these proposals encounter difficulties with time scales or geometry. Additional constraints on the magnetic field can perhaps be supplied by the high energy results from INTEGRAL (G. Belanger) and HESS (J. Hinton). What is now needed is a direct measurement of the magnetic field; submillimeter measurements of polarized line and continuum emission may settle this issue before the next workshop. Also, current theoretical efforts to model cosmic rays and their synchrotron emission will soon be informing this debate.

It is an important issue to settle, because a strong magnetic field could play a vital role in many of the phenomena observed in the Galactic center.

8. Other interesting results

- Adaptive optics near-infrared observations of the Arches cluster also suggest that its IMF is top-heavy (A. Stolte, S. Kim). The IMF is mass-segregated as a function of the projected distance from the center of the cluster.
- The prominent mid-infrared source AFGL 5376 appears to have resulted from a strong, ~ 100 -pc shock between two vertically oriented molecular systems. The association of this structure with magnetic radio filaments (J. Staguhn) raises the possibility that the shock is associated with a region of strongly compressed magnetic field.
- The Sgr A East supernova remnant, which encircles the GC in projection, and is probably not very far behind Sgr A* is impacting the dense molecular material surrounding it, giving rise to 1720 MHz OH maser emission (L. Sjouwerman) and to shocked H₂ line emission (S. Lee) at several points around its periphery. The impact upon the 50 km s⁻¹ cloud gives rise to a compressed ridge (M. Tsuboi). The energetics and the age of this supernova are still under discussion. While some consider it to be a normal Type II supernova, Others suggest that it may have resulted from a much more energetic hypernova. Similarly, age estimates for the remnant now range between 1700 and 10,000 years.
- The mass of the Circumnuclear Disk (CND), which orbits Sgr A* and has an inner radius of ~ 1 pc, has been debated for some time, with estimates ranging from 10^4 to a few $\times 10^5 M_{\odot}$. With the SMA results of M. Montero-Castano on J = 4-3 HCN emission, it now appears that, while hot gas is characteristic of the CND, the density is not uniformly as high as had previously been estimated (Christopher et al. 2005). Consequently, the CND mass may lie near the lower end of the above range. The CND is a likely reservoir for future accretion activity onto SgrA*, so this result has important implications for the long-term accretion rate. The CND also serves as a test case for the clumpy medium model of T. Beckert for dusty tori in low-luminosity AGNs.
- There appears to be a low extinction channel along the Galactic plane, from NE to SW which points to the minicavity (R. Schödel). If ascribed to an outflow from Sgr A* it agrees with the model of K. Muzic for the proper motions of mid-IR filaments, and with the orientation of the polarization vector found by A. Eckart.
- The GC distance determined using the orbital fits to the proper motions of the S stars, in concert with measurements of their radial velocities, could be as small as 7.4 kiloparsec (T. Ott), although ongoing efforts are warranted to eliminate astrometric biases occurring near periape and during close passages by other stars.
- Sophisticated Monte-Carlo modeling of dynamical mass segregation in the GC predicts about 20 thousand stellar-mass black holes in the inner parsec (M. Freitag).
- Horizontal branch/Red clump stars, i.e. stars with $M \lesssim 2 M_{\odot}$ and older than 10^9 years, seem to be missing in the inner 9", possibly due to their expulsion from that region by stellar mass black holes (T. Alexander).
- Numerical models of stellar wind accretion onto Sgr A* predict a strong variability of the accretion rate (J. Cuadra) on time scales of tens to hundreds of years. The implications of these results for the structure of the inner radiatively inefficient accretion flow (F. Yuan) are at the moment not clear. Radio evidence gathered over a long term with the VLA indicates that there has been a secular change in the low-frequency turnover frequency (T. An), suggesting a variable mass flux in the stellar winds which feed into the accretion flow. These variations would modulate the opacity of the local absorbing medium.

- Moving toward higher frequencies so that the λ^2 dependence of the size of the elliptical scattering disk is minimized, several VLBI groups are reporting an intrinsic size of for the radio source, as well as its variation with wavelength (G. Bower, Z-Q. Shen, T. Krichbaum). The intrinsic size at 3mm is ~ 15 Schwarzschild radii, consistent with equating the dominant variability time scales reported at that wavelength with the dynamical time at that radius (Mauerhan et al. 2005). There is still some discrepancy between the suggested wavelength-dependences of the intrinsic source size: $\lambda^{1.1}$ (Shen) to $\lambda^{1.6}$ (Bower). There is enthusiasm in this community for the future use of VLBI techniques at submillimeter wavelengths, where the scattering disk will presumably be substantially smaller than the source. In one of the next few meetings, we can perhaps expect to witness images of the shadow of the black hole's event horizon. As A. Broderick shows, the theorists are ready for that.

Acknowledgments

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