Experimental Indicators of Accretion Processes in AGN (SMBHs)

Andreas Eckart

I.Physikalisches Institut der Universität zu Köln
Max-Planck-Institut für Radioastronomie, Bonn

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St. Petersburg Workshop 2016, Accretion Processes in Cosmic Sources

F. Peissker, M. Valencia-S., M. Parsa, M. Zajacek, B. Shahzamanian,
EU FP7-SPACE project: Strong Gravity
http://www.stronggravity.eu/
Experimental Indicators of Accretion Processes in AGN (SMBHs but not exclusively!)

i.e. observable activity indicators that allow to conclude on the nature of accretion

*biased and incomplete view*
*each topic is worth a dedicated talk*
Experimental Indicators of Accretion Processes in AGN

- Starformation and Black Hole Growth
- Relativistic radio jets
- NLR reverberation: response to long term variability
- BLR reverberation: short term response: BLR/size/map
- Variability and time lags: accretion disk size and structure

SgrA* as a special nearby case

- NIR polarization of SgrA* over the past ~10 years
- Radio/sub-mm single dish and VLBA monitoring
- Stability of the SgrA* system
- Monitoring the Dusty S-cluster Object: an accreting star (DSO alias G2) orbiting SgrA*
- DSO in NIR line emission as well as
- DSO in NIR continuum polarization
Overluminous host spheroids

- Large H2 luminosity
- Indications for a large reservoir of molecular gas
- Indications for strong starformation

but: bulge vs. pseudobulge discussion

Merging: AGN accretion phases

- Micic et al., 2016, MNRAS 461, 3322

AGN accretion phases for field galaxies peak between $z=1$ and 2
Jet speed vs. redshift: MOJAVE program

274 AGN with 5 temporally separate measurements.

Lister et al. AJ 152, 12, 2016
Swerling Jets: The case of 1308+326

Britzen et al. 2016 submitted

Precessing jets: variable geometry of accretion disk or environment
Jet Mode change in 0735+178

Mode changes jets: variable geometry of accretion disk or environment

VLBI jet-morphology and kinematics are correlated and switch between two modes (static – left and straight right).

Jet-Modes may be linked to accretion/acceleration modes.

Candidates for double black holes?

Britzen et al., AN 336, 471, 2015
Swerling Jets: The case of 1308+326

Possible magnetic field line structure

Blandford-Rees vs. Blandford–Znajek process for field i.e jet origin (production)

To give a better impression of the nature of components in 1308+326 we provide a schematic illustration.

Britzen et al. 2016 submitted
Reverberation allows us to study the activity and structure of the central region.
Evidence from QSO spectra

Variability & spectrum: disk properties

**BBB**

Line variability & spectrum accretion properties

**NLR/BLR**

SED of a spectroscopically identified QSO from COSMOS. Lusso et al. (2011).

Mean QSO (Francis et al. 1991; courtesy of P. J. Francis and C. B. Foltz)
method to map BLR or at least to determine its size.

time delay:

\[ \tau = (1 + \cos \vartheta) r / c \quad \longrightarrow \quad d\tau = -r / c \sin(\vartheta) d\vartheta \]

response function:

\[ \Psi(\tau) d\vartheta = 2\pi \zeta \ r^2 \sin \vartheta d\vartheta \]

\[ \Psi(\tau) d\tau = \Psi(\vartheta) \left| \frac{d\vartheta}{d\tau} \right| d\tau = 2\pi \zeta r c d\tau \]

10-100 light-days
Disk size from opt./UV/X-ray time lags

NGC5548

UV/opt lag 1-2 days:

\[ \tau \propto \lambda^{4/3} \]

X-ray/UV lags less pronounced

large disk size

0.35+-0.05 lt-days

(approximately consistent with steady state accretion disk theory)

Line and continuum variability in active galaxies


18 sources; two to three epochs, with time intervals of 5 to 10 yr.

Figure 3. Results from the [Fe\textsc{ii}] emission subtraction. The first plot shows the spectrum of J034740.18+010514.0 together with a fit of the [Fe\textsc{ii}] emission (yellow). The second plot shows the spectrum after subtraction of the [Fe\textsc{ii}] emission.

Figure 4. The fit of the H\textbeta\ and [O\textsc{iii}] emission line complex with multiple Gaussian functions for J0347.
For otherwise constant accretion rate the total line variability reverberates in a similar way to the continuum variability with

Rashed et al. 2015, MNRAS 454, 291
**NLR** Reverberation

*NLR is large but very compact i.e. brightness centrally peaked*

**continuum radiation**

\[
L_{\text{cont}} \propto M \frac{dM}{dt}
\]

\[
\Delta L_{\text{cont}} \propto \Delta M \frac{dM}{dt} \propto \frac{dM}{dt}
\]

Typically:

several 10 lyr

10-20 yrs

**line radiation**

\[
L_{\text{line}} \propto \sqrt{M} \left( \frac{dM}{dt} \right)^{3/2}
\]

\[
\Delta L_{\text{line}} \propto \frac{1}{2} M^{-\frac{1}{2}} \Delta M \left( \frac{dM}{dt} \right)^{3/2} + M^{\frac{1}{2}} \frac{3}{2} \left( \frac{dM}{dt} \right)^{1/2} \left( \Delta \frac{dM}{dt} \right)
\]

\[
\Delta L_{\text{line}} \propto \Delta M \left( \frac{dM}{dt} \right)^{3/2} \propto \left( \frac{dM}{dt} \right)^{3/2}
\]

Typically:

NLR large but very centrally peaked

Rashed et al. 2015, MNRAS 454, 291
NLR  Reverberation

continuum radiation

\[ L_{\text{cont}} \propto M \frac{dM}{dt} \]

\[ \Delta L_{\text{cont}} \propto \Delta M \frac{dM}{dt} + M \Delta \frac{dM}{dt} \]

\[ \Delta L_{\text{cont}} \propto \Delta M \frac{dM}{dt} \propto \frac{dM}{dt} \]

line radiation

\[ L_{\text{line}} \propto \sqrt{M} \left( \frac{dM}{dt} \right)^{3/2} \]

\[ \Delta L_{\text{line}} \propto \frac{1}{2} M^{-1/2} \Delta M \left( \frac{dM}{dt} \right)^{3/2} + M^{1/2} \frac{3}{2} \left( \frac{dM}{dt} \right)^{1/2} \left( \Delta \frac{dM}{dt} \right) \]

\[ \Delta L_{\text{line}} \propto \Delta M \left( \frac{dM}{dt} \right)^{3/2} \propto \left( \frac{dM}{dt} \right)^{3/2} \]

\[ \Delta L_{\text{line}} \propto \left( \Delta L_{\text{cont}} \right)^{3/2} \]
CASE 1: low accretion rate
high opacity

\[ \frac{\dot{M}}{\dot{M}_E} \lesssim 0.1 \]

thin accretion disk compared to diameter efficiency: \( \eta \approx 0.1 \)

plus advection dominated accretion for LLAGN
\[ \dot{M} \ll \dot{M}_E \]

X-ray UV

CASE 2: high accretion rate
radiation heats disk
disk inflates and cools at larger radii, i.e.
radiation becomes inefficient.

\[ \frac{\dot{M}}{\dot{M}_E} \gg 1 \]

looks like a 10**4 K young star

Suzaku data
**SgrA* as an extreme LLAGN Nucleus**

**Ho 2008**: Fundamental plane correlation among core radio luminosity, X-ray luminosity, and BH mass. (a) luminosity, and BH mass. (b) Deviations from the fundamental plane as a function of Eddington ratio.

SgrA* is accreting in an advection dominated mode, else its luminosity would be than $10^7$ times higher.
SgrA* as a special nearby case

- NIR polarization of SgrA* over the past ~10 years
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- DSO in NIR continuum polarization
SgrA* and its Environment

Orbits of High Velocity Stars in the Central Arcsecond

Eckart & Genzel 1996/1997 (first proper motions)
Eckart+2002 (S2 is bound; first elements)
Schödel+ 2002, 2003 (first detailed elements)
Ghez+ 2003 (detailed elements)
Eisenhauer+ 2005, Gillessen+ 2009 (improving orbital elements)
Rubilar & Eckart 2001, Sabha+ 2012, Zucker+2006 (exploring the relativistic character of orbits)

~4 million solar masses at a distance of ~8+-0.3 kpc
SgrA* - Stable Geometry and Accretion

SgrA* is a stable system

- Range of NIR polarization angles
- Possible direction of X-ray jet?
- Possible wind direction
- Mini-Cavity
- IRS 7
- IRS 3
- IRS 10E
- IRS 6E
- IRS 9
- IRS 12N
- 5 arcsec

Graphs showing:
- Rel. freq. density [mJy]^{-1}
- Log_{10}(Pol. Flux density/[mJy])
- Flux density [mJy]

Scaling: $\alpha \sim 4$
SgrA* 345GHz/100GHz variability

Fig. 1. A single measurement map of the GC from 2009-05-17T04:19:58, the extended submm emission from the surroundings of Sgr A* (CNR and Minispiral) dominate the data.

Fig. 2. A single measurement map of the GC from 2009-05-17T04:19:58 with subtracted background. The remaining point-like source represents the submm emission from Sgr A* itself.

Fig. 3. All light curves obtained between 2004 and 2014. This plot contains both the LABOCA data (blue markers) and the literature data (other colors).

Borkar et al. MNRAS 2016
Subroweit et al. 2016
SgrA* 345GHz/100GHz variability

Borkar et al. MNRAS 2016
Subroweit et al. 2016

345 GHz LABOCA

100 GHz ATCA

\[ S(100 \text{ GHz}, t) \sim S(\nu_0 = 100 \text{ GHz}, t) + S_{\text{adiab}}(\nu_0 > 100 \text{ GHz}, t) \]
Adiabatic Expansion in SgrA*

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<th>100 GHz</th>
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<td>c)</td>
<td>flares peaking hypothetically at 350 GHz or above</td>
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Subroweit et al. 2016 submitted
SgrA* 345GHz/100GHz variability

Borkar et al. MNRAS 2016
Subroweit et al. 2016

SgrA* peaks around 350 GHz

345 GHz LABOCA

\[ S(100 \text{ GHz}, t) \sim S(\nu_0 = 100 \text{ GHz}, t) + S_{\text{adiab}}(\nu_0 > 100 \text{ GHz}, t) \]
Adiabatic Expansion in SgrA*

\[ \nu_m = \nu_{m0} \left( \frac{R(t)}{R_0} \right)^{-\frac{(4p+6)}{(p+4)}} \]

\[ R(t) = v_{\text{exp}} t + R_0 \]

\[ p = 1 - 2\alpha_{\text{sync}} \sim 2.4 \]

\[ \frac{R(t)}{R_0} \sim \left( \frac{\nu_m}{\nu_{m0}} \right)^{-1/2.44} \sim \left( \frac{100 \text{ GHz}}{350 \text{ GHz}} \right)^{-1/2.44} \approx 1.67 \]

starting at \( \sim 1 \) Rs

\[ v_{\text{exp}} \times 0.5 \text{ h} \sim 0.67 R_S \]

\[ v_{\text{exp}} \sim 0.01 c \]

Subroweit et al. 2016 submitted
Jet vs. Core Luminosity in SgrA*

**Fig. 8.** Intrinsic image, scatter-broadened image, and visibility amplitude distribution for model 24 at $\lambda = 1.3$ mm. Images are time-averaged (over $\Delta t \approx 3$ h) and the color intensity indicates the intensity of radiation normalized to unity (linear scale). The visibility amplitudes are in units of Jansky. The visibility $u - v$ tracks are from Fish et al. (2011).
Jet vs. Core Luminosity in SgrA*

\[ \left( \frac{T_e}{T_p} \right)_{\text{disk}}, \Theta_{c,jet} \]


\[ \frac{k_b T_c}{m_c c^2} = \Theta_{c,j} = \text{const.} \]

Disk: proton e-Temp. ratio

\[ \frac{k_b T_c}{m_c c^2} = \left( \frac{k_b T_p}{\mu m_p} \right) \left( \frac{m_p}{m_c} \right) \left( \frac{1}{(T_p/T_c)_{\text{disk}}} \right) \]

Moscibrodzka et al., A&A 570, A7, 2014
Fig. 5: 2 hour LCP maps of Sgr A* observed on May 17 2012. (a) May 17 6-8h. (b) May 17 7-9h. (c) May 17 8-10h. (d) May 17 9-11h. (e) May 17 10-12h. Summarized map parameters can be found in table 2.
Central component of 1.55 Jy
secondary component of 0.02 Jy
at 1.5 mas and 140 deg. E-N
with a 4 hour delay relative to the
NIR flare

Rauch et al. 2016

See also 'Asymmetric structure in SgrA* ...'
'speckle transfer function?'
Monitoring the Orbit of the DSO

Eckart, A., et al., 2014 ATel
Eckart et al. 2013, A&A 551, 18
Peissker et al. 2016 in prep

Accretion of matter (from ist shell or disk [or companion]?) onto a Galactic Center star?!
Dusty S-cluster Object (DSO/G2)


GC in L-Band. Courtesy: N. Sabha/Uni. of Cologne
DSO/G2 Approaching SgrA*

Gillessen et al. 2012/13
Burkert et al. 2012,
Schartmann et al. 2012
DSO/G2 has survived its closest approach to SgrA*

Valencia-S. et al. 2015, in agreement with Witzel et al. 2014

Peissker et al. (tbs)
Br\textsubscript{\gamma} line maps of the DSO

During periapse the source is seen at its full size.

Both Br\textsubscript{\gamma} and L-band continuum originate from a <20mas compact source.

Orbital projection effects: Top: The evolution of the projected separation between two neighboring points of arbitrary 0.5 units in 2011. Bottom: Foreshortening factor of any structure along the orbital extent as a function of time.

DSO/G2 emits K-band continuum

2006-2015 recentered at the DSO position and combined

Eckart et al. 2013
DSO/G2 orbit

Meyer et al. 2014a,b
Valencia-S et al. 2015
Peissker et al. (tbs)

$e=0.976$

Pericenter distance: 163 AU

in agreement with Pfuhl et al. 2015;
Phifer et al. 2013; Meyer et al. 2014b
Discovery of a new faint Dusty S-cluster member: OS1
OS1 does not follow the DSO trajectory

Peissker, Eckart, Valencia-S et al. (tbs)
OS1 does not follow the DSO trajectory

Periapse distance: 750 AU

Peissker, Eckart, Valencia-S et al. (tbs)
Potential reasons for having a large line width

Plus interaction with ambient medium

The radial structure of protostellar accretion disks
C. Combet and J. Ferreira
Pre-main sequence stars with large line widths

Edwards et al. 2013
M0V; T Tauri; around 2 solar masses
600-700 km/s in Brγ

Eisner et al. 2007
Herczeg & Hillenbrand 2014
K8.5; 0.68 solar masses
800 km/s in Brγ
**DSO/G2 as a young stellar object**

**Brγ production mechanisms:**
Ionized winds, accretion funnel flows, the jet base, bow shock layer

**Brγ broadening:**
Inclination of the system magnetospheric accretion model (200-700 km/s)


Zajacek, Karas, Eckart 2014
The DSO is polarized in the NIR

Fig. 1. The final $K_s$-band deconvolved median images of the central arcsecond at the GC in polarimetry mode (left: $0^\circ$, right: $90^\circ$) in the years 2008 (top) and 2012 (bottom). The arrow points to the position of the DSO and the asterix indicates Sgr A* position. In all the images North is up and East is left.

Fig. 2. NIR $K_s$-band light curve of the DSO observed in polarimetry mode in different years of 2008, 2009, 2011, and 2012.

Shahzamanian et al. 2016
The DSO is polarized in the NIR

Fig. 3. Sketch of the DSO polarization angle variation when it moves on its eccentric orbit around Sgr A* position for four different years. This part will change: The orange shaded areas show the range of possible values of polarization angle based on our observation and simulation results.

Shahzamanian et al. 2016
The DSO is polarized in the NIR

Shahzamanian et al. 2016
DSO model: shocked stellar wind

Fig. 9. The RGB image of the source model of the DSO. The explanation is in the text.

Fig. 8. The emission map of scattered light in $K_s$ band, the distribution of the polarization degree and the angle in the left, middle, and the right panels, respectively for three different configurations of the star–outflow system: $\delta = 0^\circ, 45^\circ, 90^\circ$ from the top to the bottom panels.

Shahzamanian et al. 2016
General Summary

Experimental Indicators of Accretion Processes in AGN

Starformation and Black Hole Growth jet formation as well as NLR and BLR reverberation indicate compactness and activity of the region around the Black Hole

SgrA* as a special nearby case

NIR polarization of SgrA* over the past ~10 years, as well as radio monitoring indicate that SgrA* is a stably accreting system

Monitoring the Dusty S-cluster Object
1. DSO/G2 line emission remains compact through the years. DSO/G2 emits K-band continuum emission (18 mag) and has survived the closest approach to SgrA*.
2. DSO/G2 PV diagrams can also capture emission from the fore/background and other line-emitting sources.
3. Discovery of OS1 → Existence of a population of faint, dusty objects.
4. The NIR continuum of the DSO is polarized
   • DSO might be a YSO (T Tauri M=0.8-2.0M☉, ~0.1Myr)
The Galactic Center is a unique laboratory in which one can study signatures of strong gravity with GRAVITY.

- **ESO**
  - ESO E-ELT
  - Hardware delivery from Cologne 2015

- **LBT**
  - Hardware delivery from Cologne 2015

- **NIR Beam Combiner**
  - Universitity of Cologne
  - MPIA, Heidelberg
  - Osservatorio Astrofisico di Arcetri
  - MPIfR Bonn

- **ESO, E-ELT**
  - NL leads Euro-Team
  - Universitity of Cologne studies for
  - METIS @ E-ELT

- **MPE, MPIA, Paris, SIM**
  - Universitity of Cologne participation
  - GRAVITY @ VLTI

- **Cologne**
  - contribution to MIRI on JWST

- **JWST**
  - Hardware delivery from Cologne 2013
Cologne built Fringe Tracking Spectrometer for GRAVITY
End