Constraining the charge of the Galactic centre black hole

FISIPAC 18

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Zajaček+18, MNRAS, 480, 4408 (arXiv: 1808.07327)

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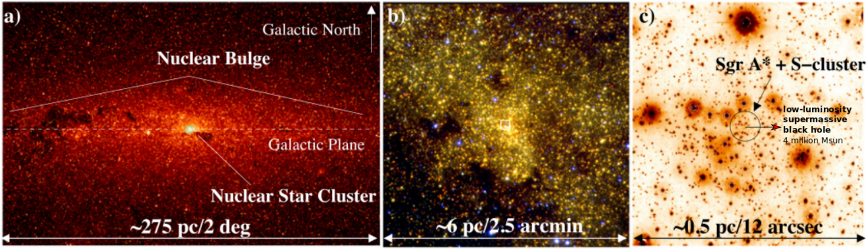
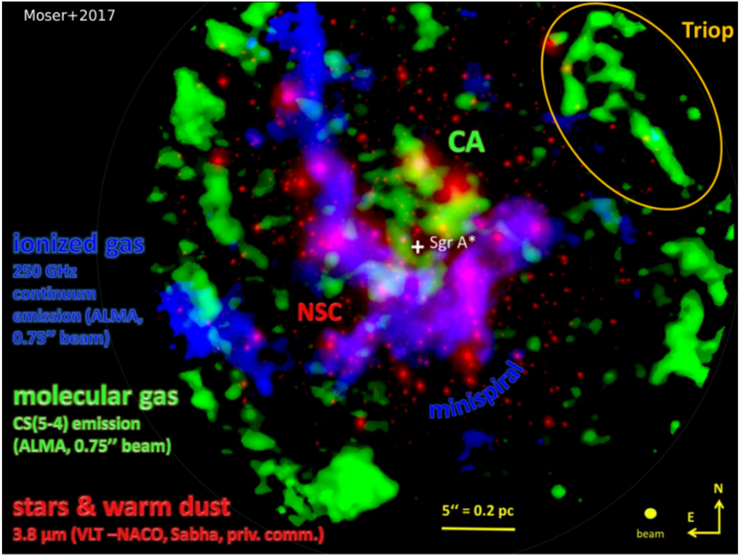
Approaching the Galactic center



- zoom-in towards the compact radio source (Sgr A*) – NIR wavelengths (Schödel+14): (a) Spitzer/IRAC, (b) ISAAC multicolor, (c) NACO/VLT
- **Nuclear Star Cluster**: one of the densest clusters in the Galaxy $\Longleftrightarrow$ **(super)massive black hole (SMBH)** of $4 \times 10^6\,M_\odot$ (Eckart+17, Genzel+10)
- enables monitoring individual objects as well as study cluster properties as a whole

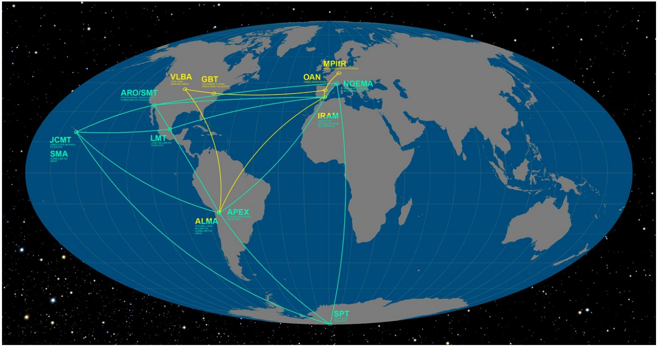
Approaching the Galactic center – a unique laboratory



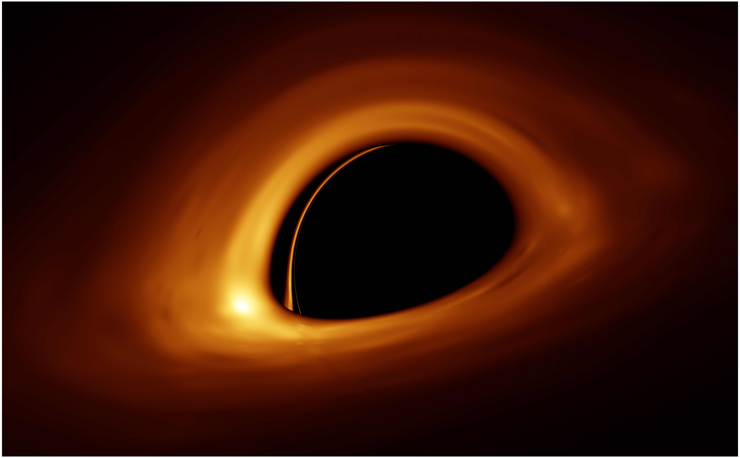
- the inner 1 pc: unique laboratory – a mutual interaction of stars, gas and dust in the potential of the SMBH

Approaching the Galactic center – a unique laboratory

- **Sgr A***: a very faint object (RIAFs) - **not an AGN**
- **no visible jet** – possibly low surface brightness
- black hole shadow?: not a clean observable (other compact configurations cannot be completely excluded)
- **stars in the vicinity of Sgr A*** (S-cluster; Eckart & Genzel 1996,1997) – We see them!
- even better: pulsar timing (not very plausible!!)



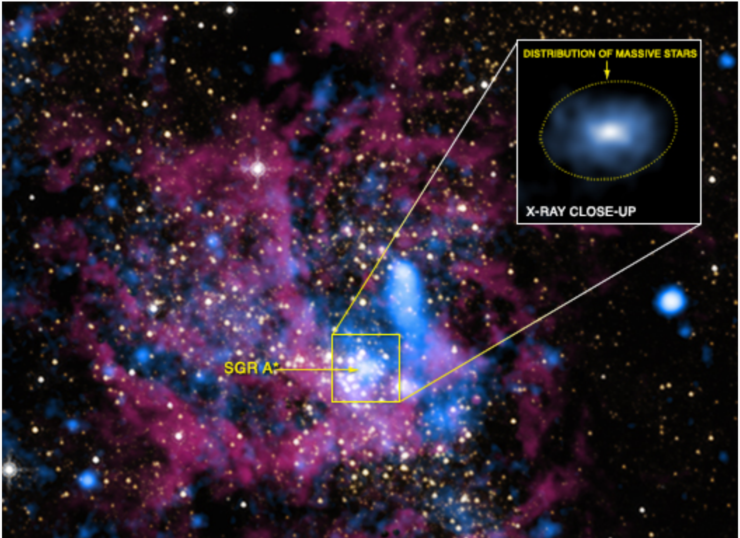
Approaching the Galactic center – Sgr A*



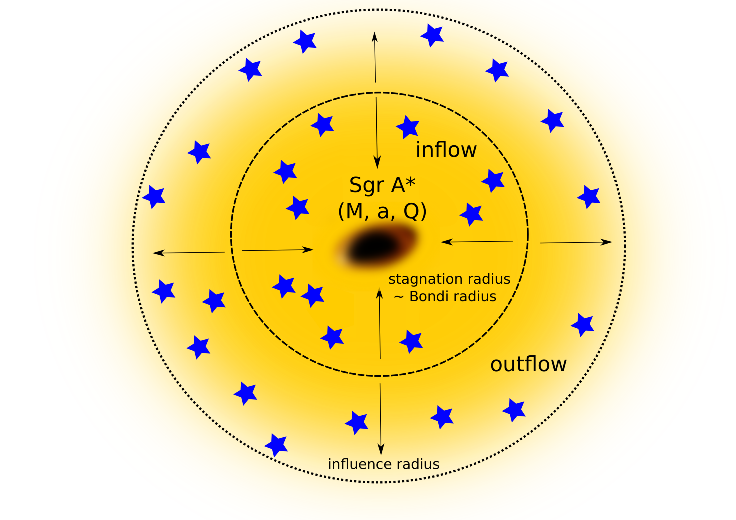
- Bursa+07: **Simulated image/emission** at the inclination of 80° with respect to the observer.

Basic set-up of the Galactic centre

Composite image (X-ray and infrared): Sgr A* embedded in a plasma cloud (Wang+13)



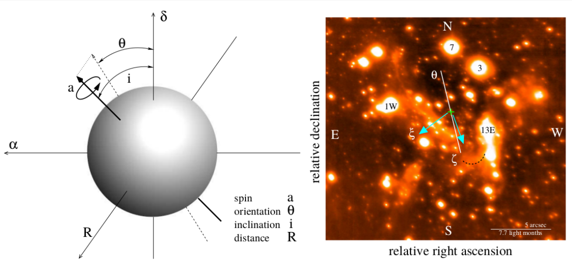
Basic set-up of the Galactic centre



- Hot, diluted plasma of $10^7\,\mathrm{K}$ emits thermal bremsstrahlung in the soft X-ray domain (a few keV; Baganoff+03, Wang+13)

Parameters of Sgr A*

- positional vector r, velocity vector v
- **no-hair theorem:**
  (a) **mass**: $M_\bullet = (4.3 \pm 0.3) \times 10^6\, M_\odot$ (Eckart+17; Parsa+17, Gravity Collaboration 18)
  (b) **spin**: $a_\bullet \geq 0.4$ (Meyer+06; Kato+10; Witzel+18)
  (c) **charge**: $Q_\bullet = ?$, usually $Q_\bullet \equiv 0 \leftarrow$ due to quick discharge in plasma, BUT the combination of black-hole rotation in a magnetic field is known to lead to non-zero values of **Wald charge** (Wald, R. M. 1974)



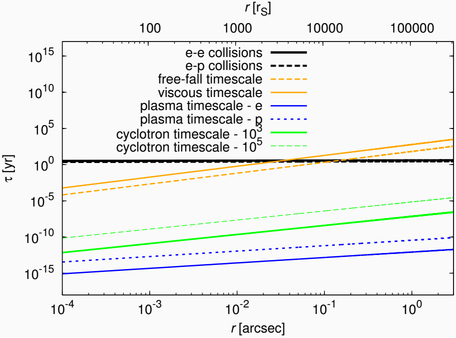
Plasma properties close to Sgr A*

Very weakly coupled plasma inside the Bondi radius

$$R_{\rm B} \approx 0.125 \left(\frac{M_\bullet}{4\times 10^6\, M_\odot}\right)\left(\frac{T_{\rm e}}{10^7\,{\rm K}}\right)^{-1}\left(\frac{\mu_{\rm HII}}{0.5}\right)\,{\rm pc}\,, \quad (1)$$

may be expressed as:

$$R_{\rm c} = \frac{E_{\rm p}}{E_{\rm k}} \sim \frac{e^2(L_{\rm i}4\pi\epsilon_0)^{-1}}{k_{\rm B}\,T_{\rm e}} = \frac{e^2 n_{\rm p}^{1/3}(4\pi\epsilon_0)^{-1}}{k_{\rm B}\,T_{\rm e}} \simeq 10^{-10}\,, \quad (2)$$



Theoretical predictions for the charge: I. Classical approach

- in hot atmospheres of stars and Sgr A*, lighter electrons tend to separate from heavier protons
- separation stopped by an induced charge $Q_{\rm eq}$

$$Q_{\rm eq} = \frac{2\pi\epsilon_0 G(m_{\rm p} - m_{\rm e})}{e} M_{\bullet} \approx 3.1 \times 10^8 \left(\frac{M_{\bullet}}{4 \times 10^6 \, M_{\odot}}\right) C \, . \tag{3}$$

- already derived by Eddington (1926)
- generalized by Bally & Harrison (1978): “Electrically polarized Universe”

Theoretical predictions for the charge: II. Relativistic approach

- the most general is Kerr-Newman solution (1965) for the Galactic centre black hole
- the extremal Kerr-Newman black hole has a single event horizon and has a charge of

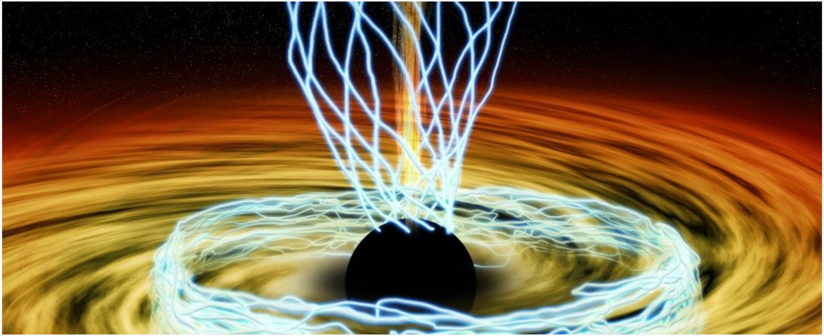
$$Q_{\rm max}^{\rm rot} = 2M_{\bullet}\sqrt{\pi\epsilon_0 G(1-\tilde{a}_{\bullet}^2)}\,. \tag{4}$$

which for non-rotating cases may be simply evaluated as

$$Q_{\rm max}^{\rm norot} = 2\sqrt{\pi\epsilon_0 G}M_{\bullet} = 6.86\times 10^{26}\left(\frac{M_{\bullet}}{4\times 10^6\,M_{\odot}}\right)\,C\,. \tag{5}$$

Theoretical predictions for the charge: II. Relativistic approach

- supermassive black holes are not located in vacccum
- Sgr A* embedded in hot plasma and threaded by magnetic field



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Theoretical predictions for the charge: II. Relativistic approach

- electric field is induced by a rotating black hole immersed in the circumnuclear magnetic field with a poloidal component
- in the vicinity of Sgr A*, magnetic field of $\sim 10\,\mathrm{G}$ is present (Eckart+12)
- this magnetic field is expected to share the properties of the background space-time metric: axial symmetry and stationarity
- Then, the four-vector potential may be expressed, $A^{\alpha} = k_1 \xi^{\alpha}_{(t)} + k_2 \xi^{\alpha}_{(\phi)}$
- the solution of Maxwell equations for A^{α} (Wald 1974):

$$A_t = \frac{B}{2}\left(g_{t\phi} + 2a g_{tt}\right), \quad A_{\phi} = \frac{B}{2}\left(g_{\phi\phi} + 2a g_{t\phi}\right). \qquad (6)$$

- the black hole rotation leads to the Faraday induction: A_t represents the induced electric field
- the potential difference between the horizon and infinity is:

$$\Delta\phi = \phi_{\mathrm{H}} - \phi_{\infty} = \frac{Q - 2aMB}{2M}. \qquad (7)$$

which leads to the selective accretion of charges from plasma

Theoretical predictions for the charge: II. Relativistic approach

- the black hole accretes charges until the potential difference is zero, i.e. the maximum net charge is $Q_\bullet = 2a_\bullet M_\bullet B_{\rm ext}$
- the upper boundary for the induced charge is given by (for the maximum rotation of $a_\bullet \leq M_\bullet$),

$$Q_{\bullet\rm ind}^{\rm max} = 2.32 \times 10^{15} \left(\frac{M_\bullet}{4 \times 10^6 M_\odot}\right)^2 \left(\frac{B_{\rm ext}}{10{\rm G}}\right)\ {\rm C}, \qquad (8)$$

- the presence of charge associated with Sgr A* is supported by the presence of highly ordered non-negligible magnetic field (Morris 2015) + the black hole spin is most likely non-zero and higher than $a_\bullet \simeq 0.4$

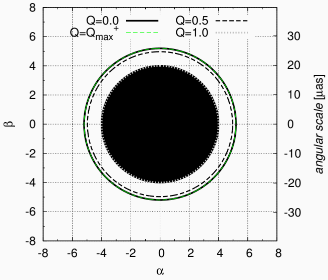
Summary of charge constraints for Sgr A*

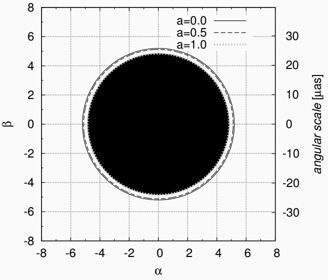
Summary of the constraints on the electric charge of the SMBH at the Galactic centre

Process	Limit	Notes
Mass difference between p and e	$Q_{\rm eq} = 3.1 \times 10^8 \left(\frac{M_\bullet}{4\times10^6\,M_\odot}\right)\,\mathrm{C}$	stable charge
Accretion of protons	$Q^{+}_{\rm max} = 6.16 \times 10^8 \left(\frac{M_\bullet}{4\times10^6\,M_\odot}\right)\,\mathrm{C}$	unstable charge
Accretion of electrons	$Q^{-}_{\rm max} = 3.36 \times 10^5 \left(\frac{M_\bullet}{4\times10^6\,M_\odot}\right)\,\mathrm{C}$	unstable charge
Magnetic field & SMBH rotation	$Q^{\rm max}_{\bullet\rm ind} \lesssim 10^{15} \left(\frac{M_\bullet}{4\times10^6 M_\odot}\right)^2 \left(\frac{B_{\rm ext}}{10\mathrm{G}}\right)\,\mathrm{C}$	stable charge
Extremal SMBH	$Q_{\rm max} = 6.86 \times 10^{26} \left(\frac{M_\bullet}{4\times10^6\,M_\odot}\right) \sqrt{1-\tilde{a}_\bullet^2}\,\mathrm{C}$	uppermost limit

Observational consequences: I. Black hole shadow

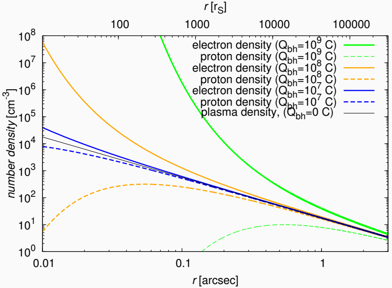
- effect only important for fractions of the extremal charge
- not a clean observable (charge/spin degeneracy)

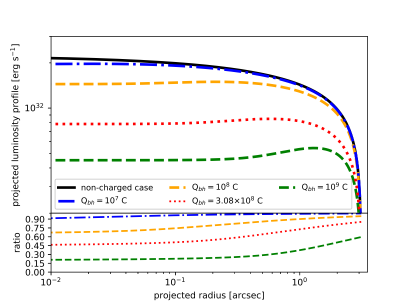




Observational consequences: II. Thermal bremsstrahlung

- unscreened charge leads to charge separations in the vicinity: e-e, p-p bremstrahlung much less efficient than for e-p pairs (mass imbalance)
- test suitable for small charge values
- comparison with X-ray observations puts an upper limit of $Q_\bullet \lesssim 10^8\,\mathrm{C}$



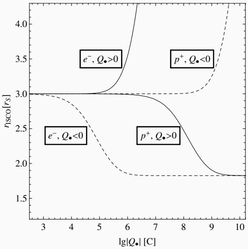


Observational consequences: III. ISCO shift

- the presence of the charge leads to the ISCO shift of orbiting particles, in a similar way as the black hole spin does (Pugliese+11)
- the effective potential for the charged particle around the charged, non-rotating black hole:

$$\frac{E_{\rm par}}{m_{\rm par}c^2} = \frac{k_1 q_{\rm par}\ Q_\bullet}{r} + \left[\left(1-\frac{1}{r}+\frac{k_2 Q_\bullet^2}{r^2}\right)\left(1+\frac{L_{\rm par}^2}{m_{\rm par}c^2 r^2}\right)\right]^{1/2}, \tag{9}$$

- for like charges, it can mimic the spin up to $a_\bullet = 0.64$



Conclusions

- previous claims that astrophysical black holes are uncharged are not supported
- however, **the black hole charge is small**, $Q_\bullet < 10^{15}\,\mathrm{C}$ (eleven orders of magnitude below the extremal value), hence the space-time metric is not effected
- however, **it can affect the dynamics of charged particles (shift of ISCO)** and is related essentially to energy extraction from black holes (Blandford-Znajek process)
- we propose an **observational test based on the flattening and eventually drop in the X-ray bremsstrahlung profile** $\rightarrow$ X-ray data are consistent with the flat to slightly rising profile (not decreasing), which limits the charge values for Sgr A* $Q_\bullet \lesssim 3 \times 10^8\,\mathrm{C}$