Motion of hot spots in the magnetosphere of the Galactic centre supermassive black hole (Sgr A*)

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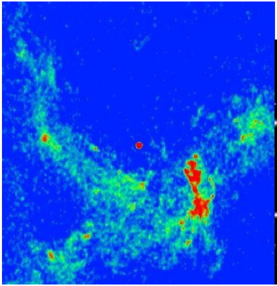
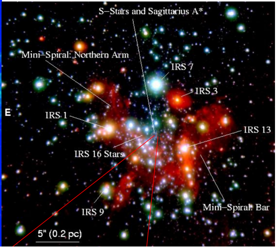
Compact radio source Sgr A*

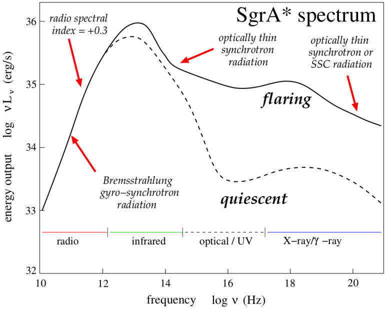
- discovered as a very compact radio source by Robert Brown and Bruce Balick on February 13, 1974
- at radio frequencies - optically thick, inverted source
- at wavelengths shortward of millimeter - optically thin and faint source
- radio image (Reid+99,03) vs. infrared image (Eckart+19):





Compact radio source Sgr A*

- very faint $L_{\mathrm{bol}} \approx 10^{36}\,\mathrm{erg\,s^{-1}} \ll L_{\mathrm{Edd}} = 5 \times 10^{44}\,\mathrm{erg\,s^{-1}}$ (Narayan+98,08)
- in the optically thin synchrotron/synchrotron self-Compton part of the spectrum (infrared, X-ray), Sgr A* is highly variable by an order of magnitude on the timescale of **one hour**
- X-ray flares (1 per day) always accompanied by infrared flares (2-3 per day) and not vice versa!!



Flares modelled as orbiting hot spots

- some of the NIR flares show substructures with the timescale of 20 min (Genzel+03)
- **orbiting hot spot model - emitting test particle in Kerr spacetime**

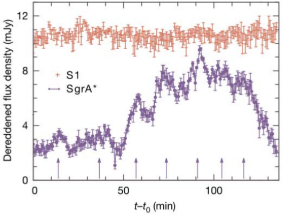
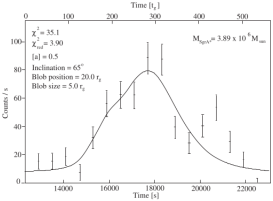


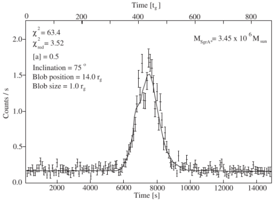
Figure: First NIR flare: Genzel+03,Gillessen+10

Flares modelled as orbiting hot spots

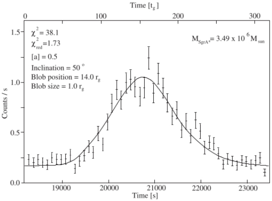
- bright X-ray flares have a double-peak structure (Karssen+17)
- **orbiting hot spot model - emitting test particle in Kerr spacetime**



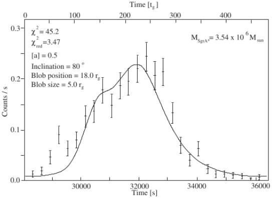
Best fit for the flare reported by Baganoffet al. (2001).



Best fit of the flare published in Porquet et al. (2003).



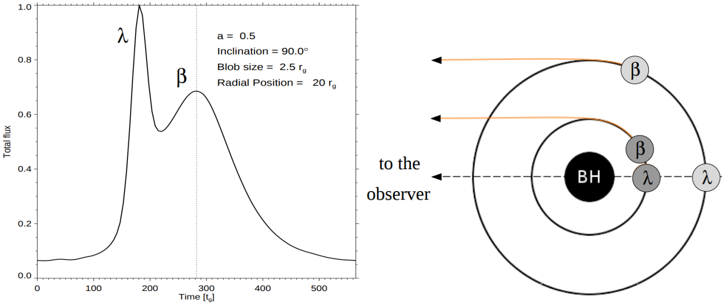
Best fit of the flare of Porquet et al. (2008).



Best fit of the models to the flare published in Nowak et al. (2012).

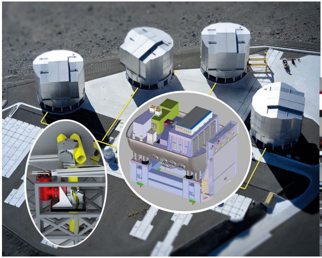
Flares modelled as orbiting hot spots

- bright X-ray flares have a double-peak structure (Karssen+17)
- **orbiting hot spot model - emitting test particle in Kerr spacetime**

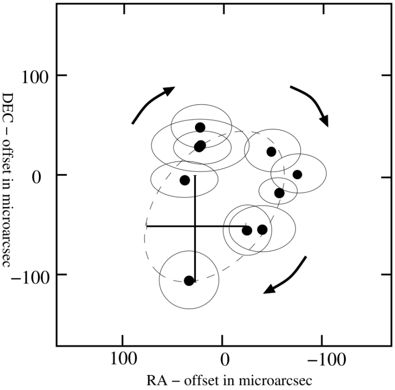


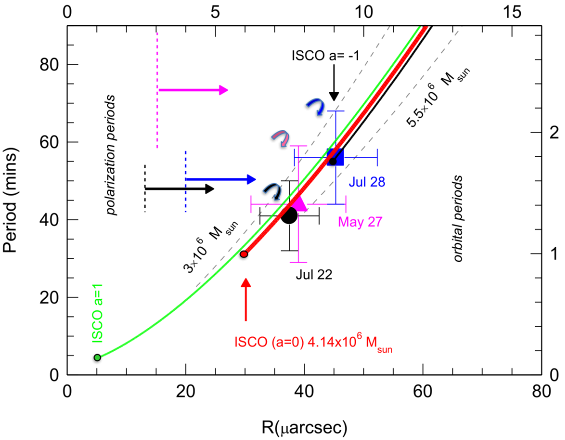
Towards hot spot observations

- ISCO of Sgr A* has a projected scale of ~ 60 microarcsec
- with 8-10m class telescopes it is not enough to resolve these structures, $\theta \sim 57\,\mathrm{mas}$
- EHT telescope does not have enough temporal resolution (integration of several hours)
- Very Large Telescope Interferometer GRAVITY combines angular and temporal resolution (astrometry with the angular resolution of the order of few 10 to 100 microarcsec)




Hot-spot orbiting SgrA*

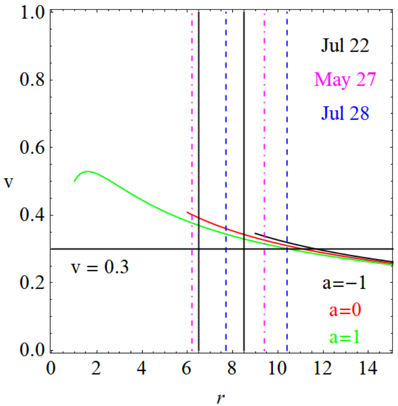


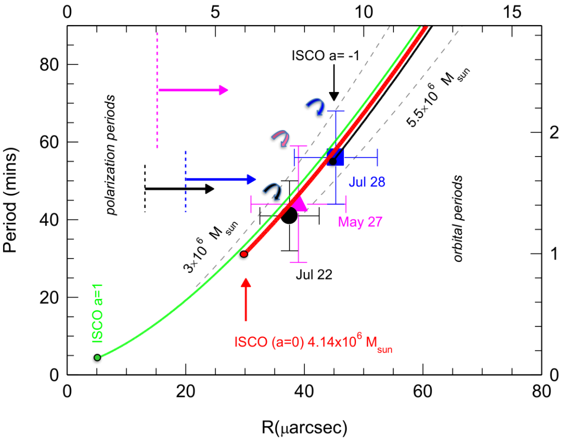


Left: Sky projected orbit of the flare emitting source component at 30% of light speed
Right: The dependence of the orbital period on the orbital radial distance for three flare events in which orbital motion was detected.

- GRAVITY Collaboration (A&A 618, 2018) **NIR**

Hot-spot orbiting SgrA*





Left: Velocity-distance plot for various spins fitted for 3 flares. Reported speed is 0.3*c*

Right: The dependence of the orbital period on the orbital radial distance for three flare events in which orbital motion was detected.

- GRAVITY Collaboration (A&A 618, 2018) **NIR**

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Astronomy & Astrophysics

Letter to the Editor

Detection of orbital motions near the last stable circular orbit of the massive black hole SgrA*⋆

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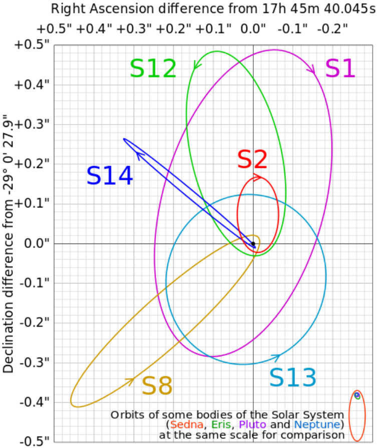
ABSTRACT

We report the detection of continuous positional and polarization changes of the compact source SgrA* in high states ("flares") of its variable near-infrared emission with the near-infrared GRAVITY-Very Large Telescope Interferometer (VLTI) beam-combining instrument. In three prominent bright flares, the position centroids exhibit clockwise looped motion on the sky, on scales of typically 150 μas over a few tens of minutes, corresponding to about 30% the speed of light. At the same time, the flares exhibit continuous rotation of the polarization angle, with about the same 45($\pm$15) min period as that of the centroid motions. Modelling with relativistic ray tracing shows that these findings are all consistent with a near face-on, circular orbit of a compact polarized "hot spot" of infrared synchrotron emission at approximately six to ten times the gravitational radius of a black hole of 4 million solar masses. This corresponds to the region just outside the innermost, stable, prograde circular orbit (ISCO) of a Schwarzschild–Kerr black hole, or near the retrograde ISCO of a highly spun-up Kerr hole. The polarization signature is consistent with orbital motion in a strong poloidal magnetic field.

Key words. Galaxy: center – black hole physics – gravitation – relativistic processes

The Milky Way's SgrA* as SMBH

- **Best known candidate for SMBH at 8 kpc**
- **Mass is** $\sim 4 \times 10^6 M_\odot$ based on different methods:
  - the orbits of S stars (Parsa et al. 2017)
  - modelling of the NSC (Do et al. 2013)
  - fits to double peaked X-ray flares (Karssen et al. 2017)
- **Spin is loosely constrained**
  - has no Newtonian effect
  - regime of strong gravity is needed
  - spin can be determined based on the modelling of e.g. the light curves of a hot spot or a jet base.



- **Magnetic field** ~ 10 Gauss (10^{-3} Tesla)
  - Modeling, e.g. SSC model (Eckart et al. 2012, 2017)
  - Faraday rotation (Eathough et al. 2013)
  - MF is ordered even at ISCO scales (GRAVITY 2018, Johnson et al. 2015)
  - MF is weak – satisfies to no-hear theorem: $B \ll 10^{12}$ Gauss
  - However, even weak magnetic field can completely change the dynamics of elementary particles

$$\frac{F_{\rm Lorentz}}{F_{\rm grav}} = \frac{eGM_{\rm bh}B\,v}{m_p\,c^5} \sim 10^6 \left(\frac{B}{10{\rm G}}\right)\left(\frac{M}{4\times 10^6 M_\odot}\right).$$

  - but BH is surrounded by plasma, not individual particles

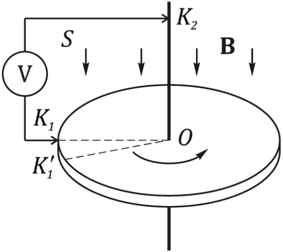
Charge separation in a magnetized plasma

- **Is a plasma surrounding BH always neutral?**
  - In ordinary plasma YES!
  - In relativistic and magnetized – NOT!
- **What supports the charge separation?**
  - Relativistic motion of a plasma induces electric field

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B},$$

  - For the motion around BH with $\mathbf{v} = \boldsymbol{\Omega} \times \mathbf{R}$. this leads to the net charge density

$$\rho_q = \frac{1}{4\pi c} \frac{\Omega B_\perp}{|e|},$$

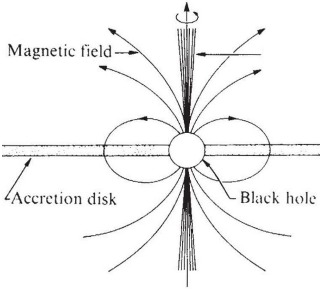


$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

- **Where are the extra charged particles?**
  - In a similar way, rotation of BH in MF induces EF and BH with the magnetosphere acts as dynamo!

$$A_t = \frac{B}{2}(g_{t\phi} + 2ag_{tt}), \qquad A_\phi = \frac{B}{2}(g_{\phi\phi} + 2ag_{t\phi}).$$

$$\Delta\varphi = \varphi_{\mathrm{H}} - \varphi_\infty = \frac{Q - 2aMB}{2M}.$$



Neglected charge - electrically polarized Universe!

- Arthur Eddington (1926) – stars are positively charge to prevent e & p from further separation in stellar atmosphere. For Sun the charge is 77 C.
- Goldreich & Julian (1969) – NS induce electric field while rotating in magnetic field.
- Wald (1974) – BH immersed into MF induce electric charge – vacuum solution.
- Ruffini & Wilson (1975) – charge separation in a plasma – both BH and magnetosphere are charged.
- Bally & Harrison (1978) – any macroscopic body is positively charged with **~100C** per Solar mass.
- Zajacek et al. (2018) – electric charge of Galactic centre SMBH SgrA* is $10^8 - 10^{15}$C

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

Parameters of the flare components

Flare strength: 0.4 of S2 in NIR K-band (136THz) or 5.2 mJy.

Flare luminosity: 10^{33} erg s^{-1} in X-ray.

Number density: $10^6 - 10^8 cm^{-3}$ (synchrotron, radio Faraday or SSC model)

SSC model: electrons upscatter synchrotron photons to higher energies.

Adiabatic expansion model ($v \sim 0.01c$) gives constraints on the flare's size:

$$R_{\rm hs} \sim \frac{GM_\bullet}{c^2} \approx 10^{12} \left(\frac{M_\bullet}{4 \times 10^6 M_\odot} \right) {\rm cm}.$$

Masses: $10^{17} - 10^{20}$g assuming spherical source.

Period at ISCO scales ~ 45 min. If MF (10G) is orthogonal to the orbital plane, charge is

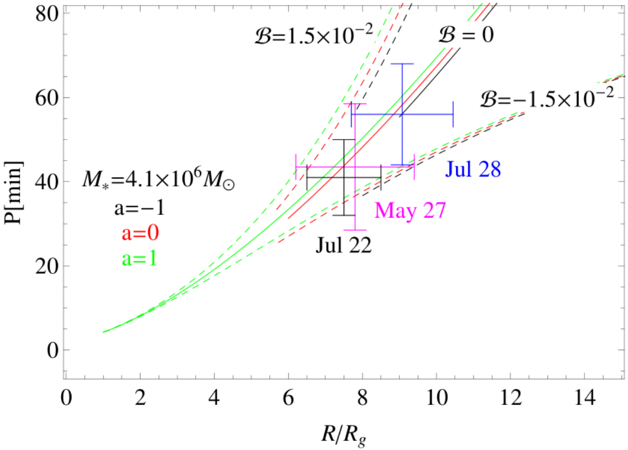
$$\rho_q \approx 10^{-4} \left(\frac{B}{10{\rm G}} \right) \left(\frac{T}{45{\rm min}} \right)^{-1} \left(\frac{M}{4 \times 10^6 M_\odot} \right) {\rm cm}^{-3}$$

is at least 10^{10} times less than the total number density. Thus plasma is quasi-neutral!

Dynamics of the flare components

Given the nonzero net charge density from charge separation in a plasma, one can get upper and lower limits on the Lorentz force $10^{-5} < \frac{F_{\rm Lor.}}{F_{\rm grav.}} \equiv \mathcal{B} < 10.$

Tighter constraints we get from GRAVITY flares fitting



$$-0.015 < \mathcal{B} < 0.01.$$

$$\mathcal{B} = \frac{q_{\rm hs}\, G\, B\, M_\bullet}{2\, m_{\rm hs}\, c^4},$$

$$\frac{|q_{\rm hs}|}{m_{\rm hs}} < 10^{-3}\left(\frac{B}{10{\rm G}}\right)^{-1} {\rm C/g},$$

$$\frac{N_{\rm charged}}{N_{\rm neutral}} = \frac{q_{\rm hs}}{e}\,\frac{m_{\rm p}+m_{\rm e}}{m_{\rm hs}} < 10^{-8}$$

Dynamics of the flare components

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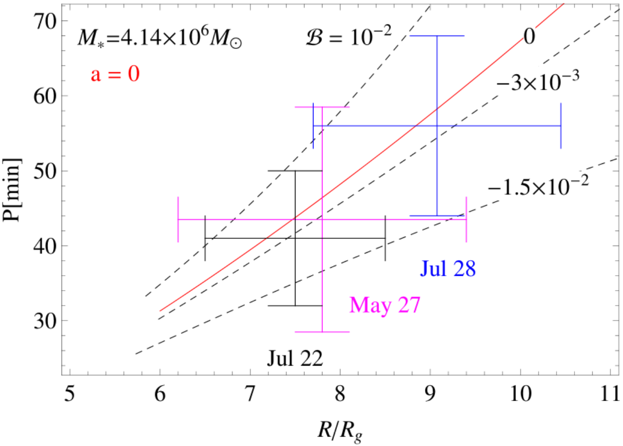


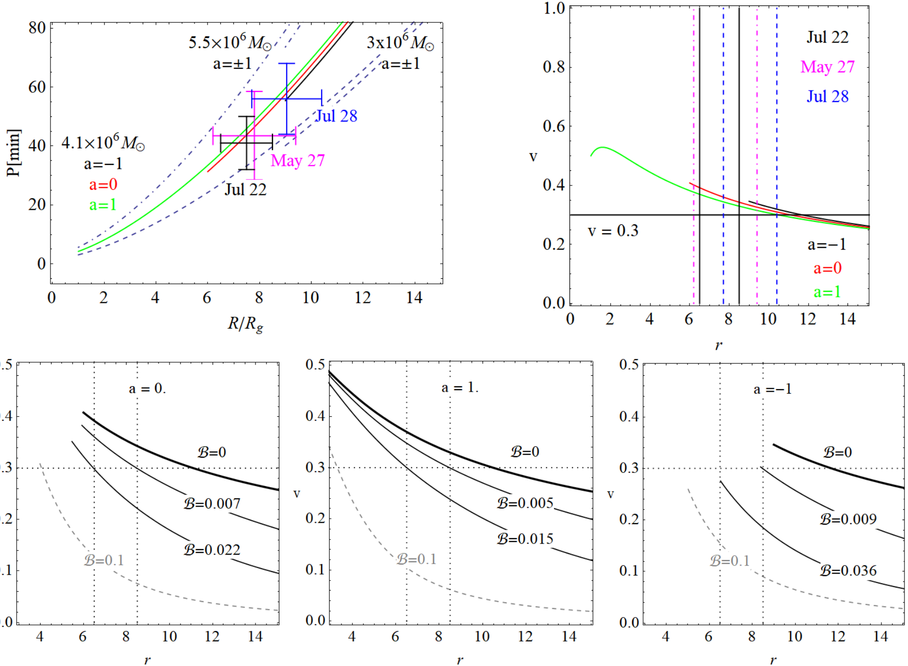
$$\mathcal{B} \sim -3 \times 10^{-3}$$

$$\mathcal{B} = \frac{q_{\rm hs}\, G\, B\, M_\bullet}{2\, m_{\rm hs}\, c^4},$$

$$\left.\frac{q_{\rm hs}}{m_{\rm hs}}\right|_{\rm mean} \approx -3\times10^{-4}\ {\rm C/g},$$

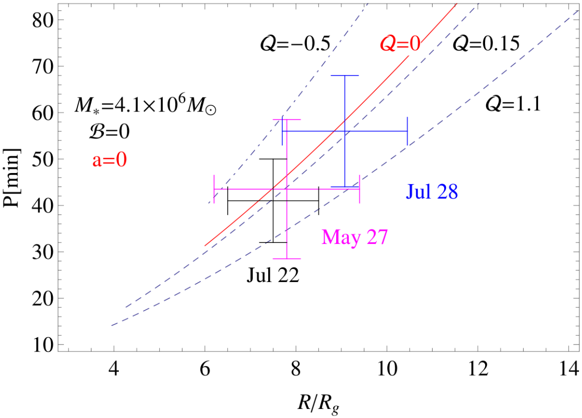
$$\left.\frac{N_{\rm charged}}{N_{\rm neutral}}\right|_{\rm mean} \approx 3 \times 10^{-9}$$

Hot-spot orbiting SgrA*: Velocity – Period – Radius



Dynamics of the flare components

Given that the hot spot carries small electric charge one can also consider the possible influence on its motion of unscreened charge of the black hole $\sim 10^{15}$C



$$\mathcal{Q} = \frac{q_{\rm hs}\, Q_{\rm BH}}{G\, m_{\rm hs}\, M_\bullet}.$$

$$-0.5 \ < \ \mathcal{Q} \ < \ 1$$

$$\frac{|q_{\rm hs}|}{m_{\rm hs}} < 2\times10^{-2} \ \ {\rm C/g},$$

$$\left.\frac{q_{\rm hs}}{m_{\rm hs}}\right|_{\rm mean} \approx 7\times10^{-3}\,{\rm C/g}.$$

Charge density estimates

Charge separation: $$\rho_q \approx 10^{-4} \left(\frac{B}{10\mathrm{G}}\right) \left(\frac{T}{45\mathrm{min}}\right)^{-1} \left(\frac{M}{4\times 10^6 M_\odot}\right) \mathrm{cm}^{-3}$$

Fitting period-radius: $$\rho_{\mathrm{q}} < 10^{-2} \left(\frac{B}{10\mathrm{G}}\right)^{-1} \left(\frac{\rho_{\mathrm{N}}}{10^6\,\mathrm{cm}^{-3}}\right) \mathrm{cm}^{-3},$$

Fitting centroids $$\rho_{\mathrm{q}}^{\mathrm{mean}} \approx 3\times 10^{-3} \left(\frac{B}{10\mathrm{G}}\right)^{-1} \left(\frac{\rho_{\mathrm{N}}}{10^6\,\mathrm{cm}^{-3}}\right) \mathrm{cm}^{-3},$$

Coulombic interaction: $$\rho_{\mathrm{q}} \approx 10^{-2\pm 1} \left(\frac{Q}{\sim 10^{15}\mathrm{C}}\right)^{-1} \left(\frac{\rho_{\mathrm{N}}}{10^6\,\mathrm{cm}^{-3}}\right) \mathrm{cm}^{-3}$$

Luminosity: $$\rho_q \approx 10^{-4\pm 1} \left(\frac{B}{10\mathrm{G}}\right)^{-\frac{1}{2}} \left(\frac{m}{10^{18\pm 2}\mathrm{g}}\right)^{\frac{1}{2}} \left(\frac{L}{10^{33}\mathrm{erg\,s^{-1}}}\right)^{\frac{1}{4}} \mathrm{cm}^{-3}$$

Total number density around Sgr A*: $\rho_{\mathrm{N}} \approx 10^6 - 10^8 \mathrm{cm}^{-3}$

Charge density estimates

Charge separation: $$\boxed{\rho_q \approx 10^{-4}\left(\frac{B}{10\mathrm{G}}\right)\left(\frac{T}{45\mathrm{min}}\right)^{-1}\left(\frac{M}{4\times 10^6 M_\odot}\right)\mathrm{cm}^{-3}}$$

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Fitting centroids $$\boxed{\rho_{\mathrm{q}}^{\mathrm{mean}} \approx 3\times 10^{-3}\left(\frac{B}{10\mathrm{G}}\right)^{-1}\left(\frac{\rho_{\mathrm{N}}}{10^6\,\mathrm{cm}^{-3}}\right)\mathrm{cm}^{-3},}$$

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Total number density around Sgr A*: $\rho_{\mathrm{N}} \approx 10^6 - 10^8\mathrm{cm}^{-3}$

Discrepancy can be omitted if we assume slightly stronger magnetic field ~100G.

Synchrotron emission of hot-spot

Cooling time in relativistic motion around BH $\tau_{\max} \approx \frac{1}{k\mathcal{B}^2 f(r)}, \quad \mathcal{B} \gg 1$

Energy loss is given by $\mathcal{E}(\tau) = \frac{\mathcal{E}_i e^{\mathcal{K}\tau}}{\sqrt{1+\mathcal{E}_i^2\left(e^{2\mathcal{K}\tau}-1\right)}}$ with $\mathcal{K} = 4k\mathcal{B}^2$

$$\mathcal{B}_{\mathrm{SgrA}^*} = \frac{|e|BGM}{2m_e c^4} \approx 1.86 \times 10^{10}, \quad k_{\mathrm{SgrA}^*} = \frac{2}{3}\frac{|e|^2}{m_e GM} \approx 10^{-25}.$$

Emission of previously observed flares at X-ray wavelengths gives the flare luminosity of order 10^{33} erg s^{-1}. This can be compared with the luminosity of a hot spot as a single charge emitting synchrotron radiation in magnetic field.

Luminosity

$$\boxed{L = \frac{2}{3}\frac{q^4 B^2 v^2 \gamma^2}{m^2 c^3}\left(1 - \frac{2R_g}{R_0}\right)^3 \text{ erg s}^{-1}}$$

General relativistic covariant equation of motion

$$\frac{Du^\mu}{\mathrm{d}\tau} = \frac{q}{m} F^\mu{}_\nu u^\nu + \frac{2q^2}{3m}\left(\frac{D^2 u^\mu}{d\tau} + u^\mu u_\nu \frac{D^2 u^\nu}{d\tau}\right)$$
$$+ \frac{q^2}{3m}\left(R^\mu{}_\lambda u^\lambda + R^\nu{}_\lambda u_\nu u^\lambda u^\mu\right)$$
$$+ \frac{q^2}{m} u_\nu \int_{-\infty}^{\tau} D^{[\mu} G^{\nu]}_{+\lambda'}(\tau,\tau') u^{\lambda'}(\tau')\, d\tau'.$$

- **Neutral geodesics**
- **Charged particles**
- **Backreaction SR**
- **Backreaction GR**

(DeWitt and Brehme 1960)

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$$\cancel{+\frac{q^2}{3m}\left(R^\mu{}_\lambda u^\lambda + R^\nu{}_\lambda u_\nu u^\lambda u^\mu\right)}$$
$$\cancel{+\frac{q^2}{m} u_\nu \int_{-\infty}^{\tau} D^{[\mu} G^{\nu]}_{+\lambda'}(\tau,\tau') u^{\lambda'}(\tau')\, d\tau'}.$$

- **Neutral geodesics**
- **Charged particles**
- **Backreaction SR**
- **Backreaction GR**

(DeWitt and Brehme 1960)

- Ricci terms are irrelevant in vacuum metrics
- Tail term can be estimated, e.g. around Schwarzschild BH as $F_{\mathrm{tail}} \sim \frac{GMq^2}{r^3c^2}$.

$$\frac{F_{\mathrm{tail}}}{F_{\mathrm{N}}} \sim \frac{q^2}{mMG} \sim 10^{-19} \left(\frac{q}{e}\right)^2 \left(\frac{m_e}{m}\right) \left(\frac{10M_\odot}{M}\right)$$

e.g. Dewitt & Dewitt (1964), Smith & Will (1980), Gal'tsov (1982), …

- Radiation-reaction term can be estimated as $F_{\mathrm{RR}} \sim q^4B^2/(m^2c^4)$

$$\frac{F_{\mathrm{RR}}}{F_{\mathrm{N}}} \sim \frac{q^4B^2MG}{m^3c^8} \sim 10^3 \left(\frac{q}{e}\right)^4 \left(\frac{m_e}{m}\right)^3 \left(\frac{B}{10^8\mathrm{G}}\right)^2 \left(\frac{M}{10M_\odot}\right)$$

General relativistic covariant equation of motion

$$\frac{Du^\mu}{\mathrm{d}\tau} = \frac{q}{m} F^{\mu}{}_{\nu} u^\nu + \frac{2q^2}{3m}\left(\frac{D^2 u^\mu}{d\tau} + u^\mu u_\nu \frac{D^2 u^\nu}{d\tau}\right)$$

- **Neutral geodesics**
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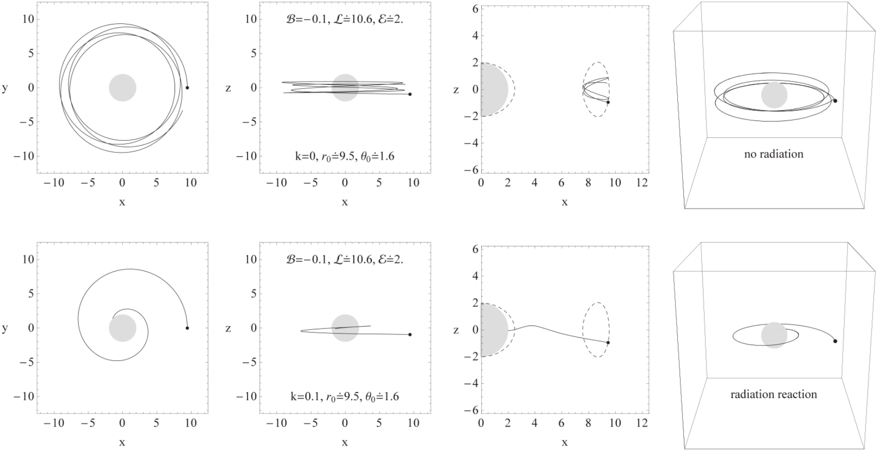
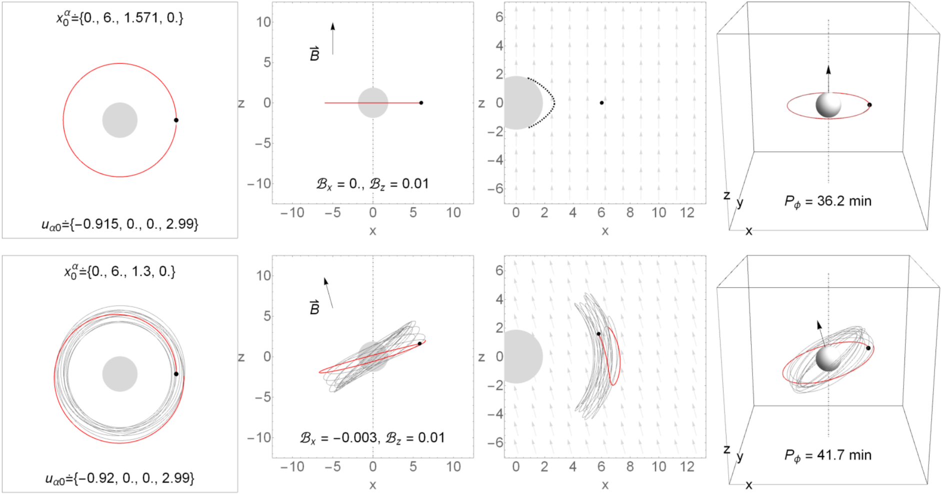
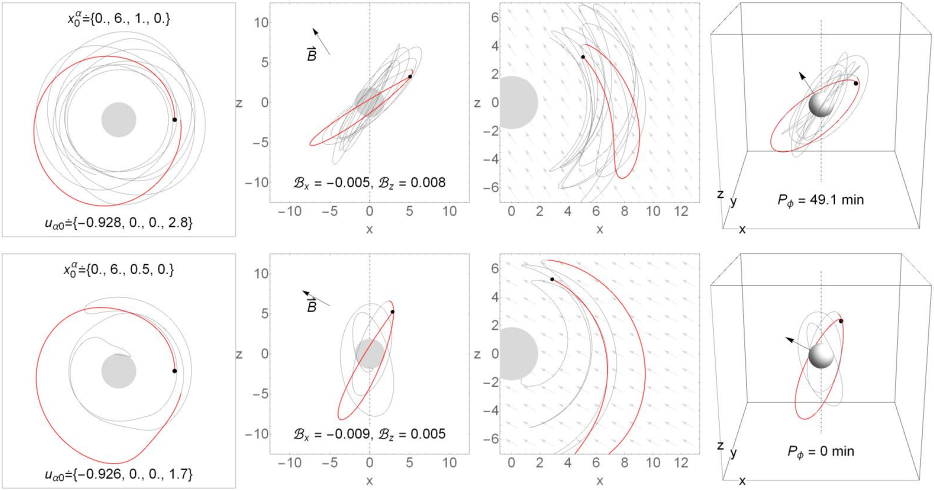


Tursunov, Kološ, Stuchlík, Gal'tsov, ApJ (2018)

Inclination of the spin and orbit



Inclination of the spin and orbit



$$\alpha < 50^\circ.$$

Summary: estimates based on three approaches

Charges of flares are estimated based on:

- Charge separation in a rotating plasma (Goldreich-Julian argument)

$$|q| \approx 3 \times 10^{12} \left(\frac{B}{10\mathrm{G}}\right) \left(\frac{v}{v_{\mathrm{isco}}}\right) \left(\frac{R}{R_s}\right)^3 \mathrm{C}. \quad \rho_q \approx 2 \times 10^{-5} \left(\frac{B}{10\mathrm{G}}\right) \left(\frac{v}{v_{\mathrm{isco}}}\right) \mathrm{cm}^{-3}.$$

- Fitting orbital motion of flare components

$$q_{\mathrm{hs}}^{\mathrm{min}} \approx -10^{13} \left(\frac{B}{10\mathrm{G}}\right) \left(\frac{m_{\mathrm{hs}}}{10^{17}\mathrm{g}}\right)^{-1} \left(\frac{M_{\mathrm{SgrA}^*}}{4 \times 10^6 M_\odot}\right)^{-1} \mathrm{C}\,,$$

$$q_{\mathrm{hs}}^{\mathrm{max}} \approx 10^{16} \left(\frac{B}{10\mathrm{G}}\right) \left(\frac{m_{\mathrm{hs}}}{10^{20}\mathrm{g}}\right)^{-1} \left(\frac{M_{\mathrm{SgrA}^*}}{4 \times 10^6 M_\odot}\right)^{-1} \mathrm{C}\,,$$

- Total intensity of synchrotron radiation from charged hot-spot

$$q_{\mathrm{hs}}^{\mathrm{min}} \approx -10^{14} \left(\frac{B}{10\mathrm{G}}\right)^{-\frac{1}{2}} \left(\frac{m}{10^{17}\mathrm{g}}\right)^{\frac{1}{2}} \left(\frac{L}{10^{33}\mathrm{erg\,s^{-1}}}\right)^{\frac{1}{4}} \mathrm{C}\,,$$

$$q_{\mathrm{hs}}^{\mathrm{max}} \approx 10^{16} \left(\frac{B}{10\mathrm{G}}\right)^{-\frac{1}{2}} \left(\frac{m}{10^{20}\mathrm{g}}\right)^{\frac{1}{2}} \left(\frac{L}{10^{33}\mathrm{erg\,s^{-1}}}\right)^{\frac{1}{4}} \mathrm{C}\,,$$

All estimates give nearly same orders of magnitude.

Summary

- **SgrA* is weakly charged**

$$Q_{\bullet\mathrm{ind}}^{\mathrm{max}} \lesssim 10^{15} \left(\frac{M_\bullet}{4\times10^6 \mathrm{M}_\odot}\right)^2 \left(\frac{B_{\mathrm{ext}}}{10\mathrm{G}}\right) \mathrm{C}$$

$$Q_{\mathrm{max}} = 6.86 \times 10^{26} \left(\frac{M_\bullet}{4\times10^6 \mathrm{M}_\odot}\right) \sqrt{1-\tilde{a}_\bullet^2}\, \mathrm{C}$$

- **Charge separation** in a magnetized plasma changes the dynamics of **hot-spots** and associated **flare components**.

Size	Mass	ρ_N	ρ_e	Q_{flares}
$\sim R_g$	$10^{17} - 10^{20}\mathrm{g}$	$10^6 - 10^8 \mathrm{cm}^{-3}$	$10^{-5}\mathrm{cm}^{-3}$	$-10^{13}/10^{16}\mathrm{C}$

- We constrain the inclination of the spin with respect to the magnetic field $\alpha < 50°$.

Thank you !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