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Flares from Galactic Centre pulsars: a new class of X-ray transients?

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ABSTRACT
Despite intensive searches, the only pulsar within 0.1 pc of the central black hole in our Galaxy, Sgr A*, is a radio-loud magnetar. Since magnetars are rare among the Galactic neutron star population, and a large number of massive stars are already known in this region, the Galactic Centre (GC) should harbour a large number of neutron stars. Population syntheses suggest several thousand neutron stars may be present in the GC. Many of these could be highly energetic millisecond pulsars which are also proposed to be responsible for the GC gamma-ray excess. We propose that the presence of a neutron star within 0.03 pc from Sgr A* can be revealed by the shock interactions with the disc around the central black hole. As we demonstrate, these interactions result in observable transient non-thermal X-ray and gamma-ray emission over time-scales of months, provided that the spin-down luminosity of the neutron star is $L_{\rm sd} \sim 10^{35}$ erg s^{-1}. Current limits on the population of normal and millisecond pulsars in the GC region suggest that a number of such pulsars are present with such luminosities.

Key words: accretion, accretion discs – black hole physics – radiation mechanisms: non-thermal – shock waves – stars: neutron – stars: winds, outflows.

1 INTRODUCTION

The compact radio source Sgr A* is believed to be the location of the massive black hole in the Galactic Centre (GC) of mass $M_{\rm BH} = 4.3 \times 10^6$ M$_\odot$ (and corresponding gravitational radius $R_{\rm g} = GM_{\rm BH}/c^2 \simeq 6.4 \times 10^{11}$ cm). *Chandra* has resolved the hot gas surrounding Sgr A* at a scale of 10^{17} cm (Baganoff et al. 2001). Bremsstrahlung emission from this region accounts for much of the observed quiescent soft ($T \sim 1$ keV) X-rays of luminosity $L_{\rm x} \sim 2 \times 10^{33}$ erg s^{-1}. The inferred gas density at this distance $n \sim 100$ cm^{-3} (Baganoff et al. 2003). Accretion on to the black hole is likely to power an IR source of luminosity $\sim 10^{36}$ erg s^{-1} (Genzel, Eisenhauer & Gillessen 2010). Both IR and X-ray flaring is observed on time-scales ranging from minutes to hours. Flares are believed to be associated with processes that take place at the inner accretion disc, close to the black hole horizon (Baganoff et al. 2001; Ghez et al. 2004).

Discovering radio pulsars in the GC is one of the holy grails in astrophysics due to their promise as probes of the central supermassive black hole (see e.g. Psaltis et al. 2016), and in deciphering the nature of the interstellar medium in its vicinity (Cordes & Lazio 1997). The inner pc in the GC is expected to have hundreds of radio emitting pulsars (see e.g. Pfhal & Loeb 2004; Deneva et al. 2009; Wharton et al. 2012). The discovery of a magnetar within ∼0.1 pc strengthens the case for their presence (Eatough et al. 2013; Mori et al. 2013; Rea et al. 2013). In addition, some 20 massive stars are known to orbit Sgr A* within 10^{17} cm (Ghez et al. 2004). Such stars are expected to give birth to pulsars. Further evidence for a significant population of millisecond pulsars (MSPs) in the GC region was recently presented by Brandt & Kocsis (2015). These authors demonstrate that the 2 Gev excess gamma-ray emission from the GC detected by *Fermi* is consistent with an ensemble of the order of 1000 MSPs in this region. Similar conclusions were also reached by other authors (Qiang & Zhang 2014). It should be noted, however, that the *Fermi* results can also be explained by a dark matter model (e.g. Hooper & Goodenough 2011). A significant effort is being invested into further searches for dark matter in the GC (see e.g. van Eldick 2015).

One way to discriminate between the MSP and dark matter scenarios would be the detection of MSPs in the GC. Macquart & Kanekar (2015) predict optimal results for future radio surveys in the 8 GHz band. Although such searches are now being carried out, their success is strongly dependent on the scattering environment in the GC region which is still not well understood. The principal focus of this paper is to develop a new approach to constraining the pulsar population in the GC. As shown schematically in Fig. 1, we propose that when a neutron star (NS) approaches within ∼0.03 pc from Sgr A*, the ram pressure from the accretion disc shocks the pulsar wind fairly close to the NS. Pairs accelerated at the termination shock power a non-thermal, synchrotron flare that will last for months to years and can be detected in the X-ray band and, possibly, at other wavelengths.

This *Letter* is organized as follows. In Section 2 we detail the emission processes of our model. In Section 3 we review the evidence for a significant number of NS in the GC region.

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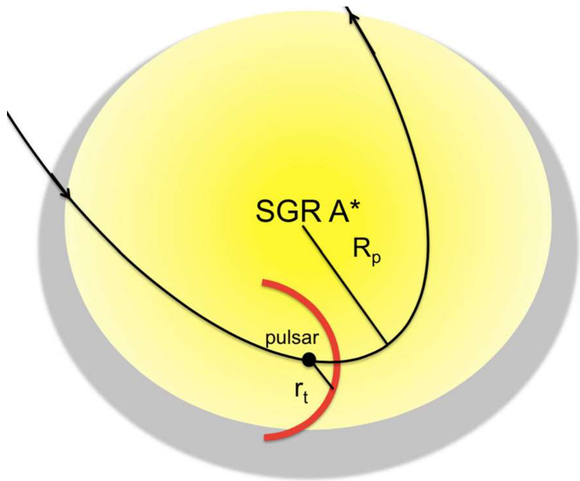

Figure 1. Sketch showing the essence of our model. A NS passing through the accretion disc around Sgr A*, with pericentre distance $R_{\rm p}$, has a wind that is sufficiently energetic to produce a synchrotron emitting, bow-shock region with termination distance $r_{\rm t}$ which can be observable at X-ray energies.

In Section 4 we discuss prospects for observing this population via our proposed mechanism.

2 TRANSIENT X-RAY EMISSION FROM GALACTIC CENTRE NEUTRON STARS

NSs residing in the inner 0.1 pc of the GC are characterized by fast motions with the winds undergoing strong interactions with the gas surrounding Sgr A* and its accretion disc. Here, we demonstrate that when the NS dives into the accretion disc, its relativistic wind is shocked, giving a powerful non-thermal X-ray and gamma-ray transient that lasts from ~ 1 month to years. Pulsar winds are known to be bright X-ray and γ-ray sources when they interact with an ionized medium (e.g. Romani et al. 1997). These interactions are particularly intense in systems where the pulsar has a close, massive star companion (Dubus 2013; Paredes et al. 2013). The interaction model we propose, shown schematically in Fig. 1, is based on earlier work by Giannios & Sironi (2013) and can be applied to any type of spin-powered pulsar.

We consider a NS with spin-down luminosity $L_{\rm sd}$ in an eccentric orbit around the central supermassive black hole with pericentre passage at distance $R_{\rm p} \ll 1$ pc as shown in Fig. 1. At $R \sim 10^{17}$ cm, the gas density is probed by its bremsstrahlung emission to be of the order of $n \sim 100$ cm^{-3} assuming a modest gas filling factor of $\sim 1/4$ at this scale (Baganoff et al. 2003). At $R < 10^{17}$cm, the gas may have sufficient angular momentum to form an accretion disc. Because of the low accretion rate to the black hole, the accretion is likely to take place through a geometrically thick disc with its density profile being rather model dependent. The density profile may scale as $n \propto R^{-3/2}$ as, e.g. motivated by the advection-dominated accretion flow solution (Narayan & Yi 1995) or $n \propto R^{-1}$ as, e.g. motivated by general relativistic magnetohydrodynamic simulations (Tchekhovskoy & McKinney 2012). In the case of a convection-dominated accretion flow solution, the density profile is shallower ($n \propto R^{-1/2}$; Quataert & Gruzinov 2000). For the estimates that follow we adopt an intermediate profile $n = 1000/R_{16}$ cm^{-3}, where $R = 10^{16} R_{16}$ cm. A similar density profile is expected if one allows for moderate mass-loss in the disc through winds (Blandford & Begelman 1999).

Assuming a highly elliptical orbit, the characteristic velocity of the NS at pericentre

$$v_{\rm p} \simeq \sqrt{2R_g/R_{\rm p}}c \sim 3.4 \times 10^8 R_{16}^{-1/2}\ {\rm cm s^{-1}}. \quad (1)$$

This expression also holds for quasi-circular orbits, within a factor of 2. At pericentre, the ram pressure $\rho v_{\rm p}^2 \simeq 1.9 \times 10^{-4} R_{16}^{-2}$ cgs of the disc is maximal and shocks the NS wind at a distance from the NS at which it matches the wind pressure, $L_{\rm sd}/4\pi r^2 c$. The resulting termination distance from the NS,

$$r_{\rm t} = \sqrt{\frac{L_{\rm sd}}{4\pi\rho v_{\rm p}^2 c}} \sim 3.7 \times 10^{13} L_{35}^{1/2} R_{16}\ \tilde{}{\rm cm}. \quad (2)$$

The shocked wind moves at a mildly relativistic speed $\sim c/2$ and expands on a time-scale

$$t_{\rm exp} \sim 2r_{\rm t}/c \sim 2.5 \times 10^3 L_{35}^{1/2} R_{16}\ {\rm s}. \quad (3)$$

At the termination shock, pairs are expected to be accelerated to provide a non-thermal particle distribution. We set the particle distribution $N(\gamma) \propto \gamma^{-2}$ for $\gamma \geq \gamma_{\rm min} \sim 10^5$ up to a maximum synchrotron burnoff limit (de Jager et al. 1996). The magnetic field pressure at the shocked region can be parametrized as a fraction ϵ_B of the gas pressure. Assuming rough equipartition between particles and magnetic field at the shock downstream (see e.g. Porth, Komissarov & Keppens 2014): $B \sim 0.04 \epsilon_{B,1/3}^{1/2} R_{16}^{-1}$G. Electrons accelerated to $\gamma_{\rm x} \sim 3.5 \times 10^6 \nu_{\rm 5keV}^{1/2} \epsilon_{B,1/3}^{-1/4} R_{16}^{1/2}$ by the shock will emit synchrotron emission in the $\nu = 5$ keV range and cool on a time-scale

$$t_{\rm syn} \simeq \frac{7.5 \times 10^8}{\gamma_{\rm x} B^2}\,{\rm s} \simeq 1.3 \times 10^5 R_{16}^{3/2} \epsilon_{B,1/3}^{-3/4} \nu_{\rm keV}^{-1/2}\ {\rm s}. \quad (4)$$

The power radiated in the X-ray band is, therefore,

$$L_{\rm x} \sim (t_{\rm exp}/t_{\rm syn}) L_{\rm sd} \simeq 2 \times 10^{33} L_{35}^{3/2} \epsilon_{B,1/3}^{3/4} R_{16}^{-1/2} \nu_{\rm 5keV}^{1/2}\ {\rm erg\,s^{-1}}. \quad (5)$$

In this framework, the emission from a pulsar of $L_{\rm sd} \sim 10^{35}$ erg s^{-1} at a pericentre passage of $R_{\rm p} \leq 10^{17}$ cm powers detectable X-ray flares because: (i) their X-ray luminosities are comparable to the quiescent emission from Sgr A*; (ii) their spectra are distinctly non-thermal extending into the hard X-ray band.

Figs 2 and 3 show the synchrotron emission spectra at pericentre for different spin-down luminosities of the NS and pericentre distances $R_{\rm p}$. At photon energies below $E_{\rm min} \simeq 4\gamma_{\rm min,5}^2 \epsilon_{B,1/3}^{1/2} R_{16}^{-1}$ eV, the emission spectrum slope scales as $f_{\rm E} \propto E^{1/3}$ with the break energy determined mainly by the minimum Lorentz factor of the electron distribution behind the termination shock $\gamma_{\rm min}$. For $E > E_{\rm min}$, the flux $f_{\rm E} \propto E^{-1/2}$ up to energy $E_{\rm c} \simeq 16 L_{35}^{-1} \epsilon_{B,1/3}^{-3/2} R_{16}$ MeV above which the particles are cooling rapidly. For $E \gtrsim E_{\rm c}$, the pairs radiate at a rate comparable to the spin-down luminosity of the pulsar for the adopted particle power-law slope of −2. This estimate is likely to be optimistic for the γ-ray emission from the transient since, for a steeper particle index $p < -2$, the γ-ray emission is weaker. The luminosity from the shocked wind at pericentre can easily exceed that of the quiescent X-ray emission and, under favourable conditions, be comparable to that in the *Fermi-LAT* band.

The pericentre passage of the pulsar takes place over a time-scale

$$t_{\rm p} \sim R_{\rm p}/v_{\rm p} \sim 3 \times 10^7 R_{16}^{3/2}\ {\rm s}. \quad (6)$$

This is also the characteristic time-scale over which the pulsar wind undergoes the most intense interaction with the surrounding accretion disc and, as a result, marks the duration of the flares. Whether one expects a single flare or a pair of flares depends on the relative inclination of the orbit of the NS with respect to that of the accretion

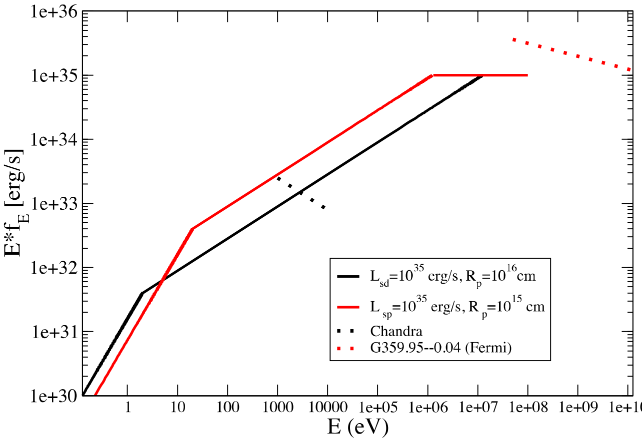

Figure 2. Synchrotron spectra from the shocked pulsar wind for NS orbit with pericentre distance $R_\mathrm{p} = 10^{16}$ cm (black curve) and $R_\mathrm{p} = 10^{15}$ cm (red curve), respectively. The pair minimum Lorentz factor $\gamma_\mathrm{min} = 10^5$ and the spin-down power $L_\mathrm{sd} = 10^{35}$ erg s^{-1}. The maximum synchrotron energy is set at ∼100 MeV. The black dotted line shows the *Chandra* quiescent emission from Sgr A* and the red, dash–dotted line the *Fermi* level of emission seen for the source G359.95–0.04 at the same region.

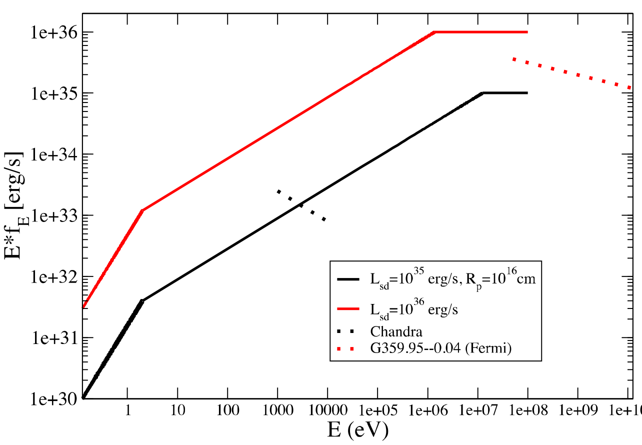

Figure 3. Same as Fig. 1 but for pulsar spin-down luminosity $L_\mathrm{sd} = 10^{35}$ erg s^{-1} (black curve) and $L_\mathrm{sd} = 10^{36}$ erg s^{-1}, respectively. The NS has orbit with pericentre distance $R_\mathrm{p} = 10^{16}$ cm.

disc (see Giannios & Sironi 2013). If the disc is co-planar with the stellar orbit (e.g. they are co- or counter-rotating) the emission from the bow shock will peak at pericentre. For large inclination of the two orbital planes, two flares are expected: one before and one after the pericentre passage. Since for thick discs, where the height is comparable to the radius, the time-scale for each crossing of the mid-plane of the disc is similar to the duration of the pericentre passage t_p (for light-curve examples, see Giannios & Sironi 2013).

The previous estimates of the synchrotron emission from the shocked pulsar wind are based on a simple one-zone model. The shocked fluid follows a bow shock structure. The accelerated particles radiate substantially close to the termination shock but they continue to radiate further back in the tail. The pulsar spends at pericentre much longer the time it takes for the shocked fluid to leave the termination shock: $t_\mathrm{p}/t_\mathrm{exp} \sim 10^4 R_{16}^{1/2} L_{35}^{-1/2}$. In the tail of the bow shock, the shocked fluid is still confined by the thermal pressure from the accretion disc. The pressure of the disc is not negligible $P_\mathrm{d} \sim 0.5\rho_\mathrm{d} v_k^2 \sim P_\mathrm{ram}/4$; containing substantial turbulent magnetic field of strength $B_\mathrm{d} \sim 0.02\epsilon_{B,1/3}^{1/2} R_{16}^{-1}$ G. Therefore, after a modest

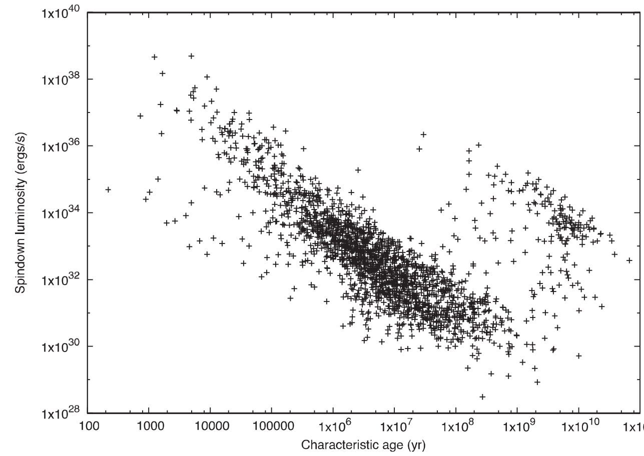

Figure 4. Scatter diagram showing spin-down energy loss rate ($\propto \dot{P}/P^3$) versus characteristic age ($\propto P/\dot{P}$) for a sample of 1982 pulsars taken from the ATNF pulsar catalogue (Manchester et al. 2005).

initial expansion, the shocked wind will undergo a much longer process of mixing with the disc material. Substantial emission for the ultrarelativistic particles is expected at this stage possibly enhancing the power of the transient. The calculation of the emission from this region requires a more detailed hydrodynamical calculation that is beyond the scope of this *Letter*.

3 NEUTRON STARS WITHIN 0.1 PARSEC OF SGR A*

As demonstrated above, pulsars and MSPs with spin-down luminosity $L_\mathrm{sd} \sim 10^{35}$ erg s^{-1} and with orbit with pericentre distance of $r_\mathrm{p} \sim 0.01$ pc from Sgr A* make promising sources for an observable transient. Given the highly elliptical orbits of the stars observed in the region (see the next section for details), these NS are expected to spend most of their orbit at apocentre distance of $r_\mathrm{app} \sim 0.1$pc. As can be seen from the current sample of pulsars shown in Fig. 4, a significant fraction, approximately 7 per cent of all observed pulsars, have $L_\mathrm{sd} > 10^{35}$ erg s^{-1}. For MSPs, the corresponding fraction is 8 per cent. It is important to note, however, that these estimates are based on observationally selected samples of radio pulsars which are necessarily biased towards bright objects. As we show below, the true fraction of pulsars and MSPs in the population will be less. In the following we estimate, using various arguments, how many pulsars and MSPs may reside in the region of interest.

3.1 The young NS population

A simple argument can be made by noting that we have observed one magnetar with projected distance of ∼0.1 pc from Sgr A* (Eatough et al. 2013; Mori et al. 2013). In total, there are 26 magnetars currently known in the Milky Way (for a complete list, see Olausen & Kaspi 2014, and the McGill Magnetar Catalogue[1]). Their typical lifetime from spin-down age arguments is 10^4 yr, giving a crude estimate on the magnetar birthrate to be one every $10^4/26$ yr $\simeq 400$ yr. When compared to the pulsar birthrate of 2–3 per century (Vranesevic et al. 2004; Faucher-Giguere & Kaspi 2006), we conclude that for every 10 NS born, one of these will be a magnetar. The

[1] http://www.physics.mcgill.ca/∼pulsar/magnetar

existence of one magnetar in Sgr A* therefore suggests the existence of ∼10 NS younger than 10^4 yr. Most of the pulsars in Fig. 4 with characteristic ages below 10^4 yr have $L_{sd} > 10^{35}$ erg s^{-1}. Interestingly, those pulsars with ages below 10^4 yr but $L_{sd} < 10^{35}$ erg s^{-1} are thought to be associated with the magnetar population: J1550−5418 (Camilo et al. 2007), J1622−4950 (Levin et al. 2010), J1734−3333 (Espinoza et al. 2011).

An independent check on this simple estimate of ∼10 NS with $L_{sd} > 10^{35}$ erg s^{-1} can be made from the results of Chennamangalam & Lorimer (2014) who found an upper bound of 200 radio pulsars in the GC region that are beaming towards the Earth. Assuming a beaming fraction of 10 per cent the total number of radio-loud pulsars in this region is $\lesssim$ 2000. Making use of the PsrPopPy simulation software (Bates et al. 2014), we generated a sample of radio pulsars which evolve with time according to the prescription described in detail by Faucher-Giguere & Kaspi (2006). Under these assumptions, we find that the fraction of pulsars with $L_{sd} > 10^{35}$ erg s^{-1} is approximately 0.5 per cent. The results of Chennamangalam & Lorimer (2014) therefore limit the population of $L_{sd} > 10^{35}$ erg s^{-1} to be <10. Relaxing the assumption of spin down such that $L_{sd} > 10^{34}$ erg s^{-1} would raise this limit by a further factor of 3. Given the uncertainties involved in both these estimates, we conclude that one can reasonably expect of the order of several to a dozen non-recycled pulsars of substantial spin-down luminosity in the region of interest.

3.2 Millisecond pulsars

In their population study, making use of the diffuse gamma-ray emission observed by *Fermi*, Hooper & Goodenough (2011), Wharton et al. (2012) estimated the number of MSPs in the central 150 pc of Sgr A* to be <5000. Similar results were also found using earlier EGRET observations by Wang, Jiang & Cheng (2005). To estimate the fraction of MSPs potentially visible as X-ray transient sources, we again used the PsrPopPy package to simulate a population of pulsars spinning down from a spin period distribution recently derived by Lorimer et al. (2015) assuming a log-normal distribution of magnetic field strengths with a mean of 10^8 G and a standard deviation of 0.5 in the log. The fraction of sources with $L_{sd} > 10^{35}$ erg s^{-1} is approximately 0.1 per cent, suggesting a population of <5 sources. The corresponding fraction above 10^{34} erg s^{-1} is about 3 per cent, implying a population of <150 MSPs.

4 DISCUSSION

So far, one magnetar is known within 0.1 pc from the GC. There is also evidence that the source G359.95–0.04 at a projected distance of 0.3 pc from the GC is powered by the wind of an energetic pulsar (Wang, Lu & Gotthelf 2006). We demonstrated above that $N \sim 10$ MSPs and pulsars with $L_{sd} \gtrsim 10^{35}$ erg s^{-1} may be expected to orbit around Sgr A* within ∼0.1pc. These pulsars spend most of their orbit at apocentre distance that determines their orbital period of $T \simeq 450(r_{app}/0.1\mathrm{pc})^{3/2}$ yr. Depending on the ellipticity of their orbit, they can have brief excursions close to Sgr A*. The stars observed at this scale – the S cluster – are characterized by highly elliptical orbits of median eccentricity $e \simeq 0.8$ (Genzel et al. 2010). If the pulsars have similar orbits, their pericentre is $r_p = (1-e)r_{app}/(1+e) \simeq 0.01$ pc, well within the distance of interest here. The rate at which pulsars have their pericentre passage may be estimated to be $\sim N/T \sim 2.2N_1(r_{app}/0.1\mathrm{pc})^{-3/2}$ per century.

The relatively large gas density in this region, in connection with the large pulsar velocities, results in strong interactions of the pulsar wind with the ambient gas. Pairs accelerated at the shocked pulsar wind are strong synchrotron emitters. Given its high spatial resolution, *Chandra* is well positioned to observe these interactions in the X-ray band, *Fermi-LAT* may also be able to detect the source. Characteristic signatures include a flaring, non-thermal source with luminosity $\gtrsim 10^{33}$ erg s^{-1} that lasts for months or years.

Other observed sources within the *Chandra* PSF at SGR A * are the steady bremsstrahlung emission from ∼1 keV gas and flares from the black hole vicinity (Baganoff et al. 2001). The flares last for minutes to hours and are clearly distinct from the ∼*month* – *year* long flares that are discussed here. Month long flares from the same region may originate from the interaction on *non*-relativistic winds of massive stars with the disc (Giannios & Sironi 2013). In this case, however, the flares are expected to be thermal and with their emission peaking in the soft X-ray band, in contrast to the non-thermal transients discussed here.

The interaction can serve as a probe of the density, temperature and thickness of the accretion disc that surrounds Sgr A * at a scale that is hard to probe otherwise (see also Nayakshin, Cuadra & Sunyaev 2004; Giannios & Sironi 2013; Yusef-Zadeh et al. 2015). The duration of the event directly constrains the pericentre distance of the source $t_p \sim 3 \times 10^7 R_{16}^{3/2}$ s. Depending on the inclination of the NS orbit with respect to that of the accretion disc, one or two flares are possible. We encourage *Chandra* archival searches for such long transients as well as systematic monitoring of Sgr A*.

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