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LETTER TO THE EDITOR

Simultaneous HESS and Chandra observations of Sagitarius A* during an X-ray flare

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ABSTRACT

The rapidly varying (~10 min timescale) non-thermal X-ray emission observed from Sgr A* implies that particle acceleration is occuring close to the event horizon of the supermassive black hole. The TeV γ-ray source HESS J1745−290 is coincident with Sgr A* and may be closely related to its X-ray emission. Simultaneous X-ray and TeV observations are required to elucidate the relationship between these objects. We report on joint HESS/Chandra observations performed in July 2005, during which an X-ray flare was detected. Despite a factor of ≈9 increase in the X-ray flux of Sgr A*, no evidence is found for an increase in the TeV γ-ray flux from this region. We find that an increase in the γ-ray flux of a factor of 2 or greater can be excluded at a confidence level of 99%. This finding disfavours scenarios in which the keV and TeV emission are associated with the same population of accelerated particles and in which the bulk of the γ-ray emission is produced within ~10^{14} cm (~100 $R_{\rm S}$) of the supermassive black hole.

Key words. X-rays: individuals: Sgr A* – gamma rays: observations

1. Introduction

Measurements of stellar orbits in the central parsec of our galaxy have revealed the existence of a supermassive, (3.6 ± 0.3) × 10^6 solar mass, black hole coincident with the radio source Sgr A* (Eisenhauer et al. 2005). The compact nature of Sgr A* has been demonstrated both by direct VLBI measurements (Shen et al. 2005) and by the observation of X-ray and near IR flares with timescales as short as a few minutes (see for example Porquet et al. 2008; Eckart et al. 2006; Porquet et al. 2003). Variability on these timescales limits the emission region to within <10 Schwarzschild radii ($R_{\rm S}$) of the black hole. X-ray flares from Sgr A* reach peak luminosities of 4×10^{35} erg s^{-1}, two orders of magnitude brighter than the quiescent value (Porquet et al. 2003; Baganoff et al. 2003), and exhibit a range of spectral shapes (Porquet et al. 2008). Several models of the origin of this variable emission exist, many of which invoke non-thermal processes close to the event horizon of the central black hole to produce a population of relativistic particles (see e.g. Markoff et al. 2001; Yuan et al. 2003; Aharonian & Neronov 2005a; Liu et al. 2006a,b).

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Model-independent evidence that ultra-relativistic particles exist close to Sgr A⋆ can be provided by the observation of TeV γ-rays from this source. Indeed, TeV γ-ray emission has been detected from the Sgr A region by several ground-based instruments (Kosack et al. 2004; Tsuchiya et al. 2004; Aharonian et al. 2004; Albert et al. 2006). The most precise measurements of this source, HESS J1745−290, are those performed using the HESS telescope array. The centroid of the source is located $7'' \pm 14''_{\rm stat} \pm 28''_{\rm sys}$ from Sgr A⋆, and has an rms extension of $<1.2'$ (Aharonian et al. 2006a), with work underway to reduce these uncertainties (van Eldik et al. 2007).

TeV emission from Sgr A⋆ is expected in several models of particle acceleration in the environment of the black hole. In some of these scenarios (Levinson & Boldt 2002; Aharonian & Neronov 2005a), TeV emission is produced in the immediate vicinity of the SMBH, and variability is expected. In alternative scenarios, particles are accelerated close to Sgr A⋆ but radiate within the central ∼10 parsec region (Aharonian & Neronov 2005b), or are accelerated at the termination shock of a wind driven by the SMBH (Atoyan & Dermer 2004). However, several additional candidate objects exist for the origin of the observed γ-ray emission. The radio centroid of the supernova remnant (SNR) Sgr A East lies ∼1′ from Sgr A⋆, only marginally inconsistent with the position of the TeV source presented by Aharonian et al. (2006a). Shell-type SNR are now well established TeV γ-ray sources (Aharonian et al. 2007a,b) and several authors have suggested that Sgr A East is the origin of the TeV emission (see for example Crocker et al. 2005). However, improvements in the uncertainty in the centroid position of HESS J1745−290 (van Eldik et al. 2007) effectively exclude the possibility of Sgr A East being the dominant γ-ray source in the region. The pulsar wind nebula candidate G 359.95−0.04 discovered by Wang et al. (2006) is located only 9′′ from Sgr A⋆ and can plausibly account for the TeV emission (Hinton & Aharonian 2007). Particle acceleration at stellar wind collision shocks within the central young stellar cluster has also been hypothesised to explain the γ-ray source (Quataert & Loeb 2005). Finally, the possible origin of this source in the annihilation of WIMPs in a central dark matter cusp has been discussed extensively (Hooper et al. 2004; Profumo 2005; Aharonian et al. 2006a).

Given the limited angular resolution of current VHE γ-ray telescopes, the most promising tool in identifying the TeV source is the detection of *correlated variability* between the γ-ray and X-ray, and/or NIR regimes. A significant increase in the flux of HESS J1745−290, occuring simultaneously with a flare detected in a waveband with sufficient angular resolution to isolate Sgr A⋆, would unambiguously identify the γ-ray source. Therefore, whilst not all models of the TeV emission from Sgr A⋆ predict variability in the VHE source, coordinated IR/keV/TeV observations can be seen as a key aspect of the ongoing program to understand the nature of this enigmatic source.

2. Observations and results

A coordinated multiwavelength observing campaign targeting Sgr A⋆ was performed during July/August 2005. As part of this campaign, observations with HESS occurred for 4–5 h each night from July 27 to August 1 (MJD 53 578–53 584). Four Chandra observations with IDs 5950-5954 took place between July 2 and August 2. A search for flaring events in the X-ray data yielded two significant events during the Chandra campaign, the first during observation (obs.) ID 5952 on July 29, and the second during obs. ID 5953 on July 30. The second of these flares occurred during a period of HESS coverage and is described in detail here.

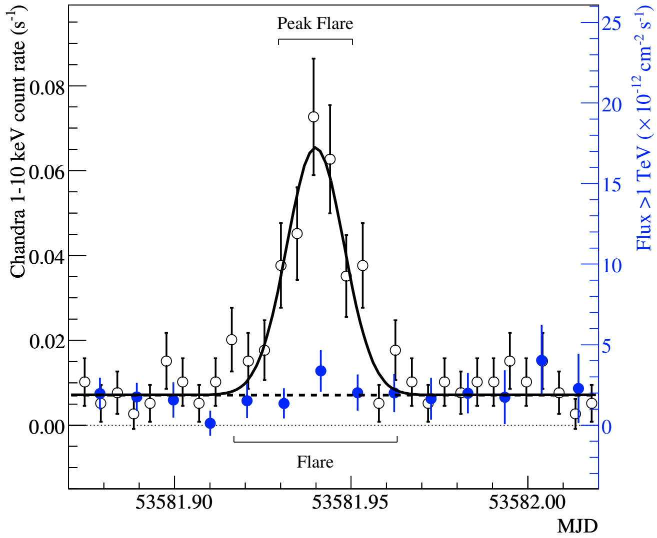

Fig. 1. X-ray and γ-ray light curves for the Galactic Centre on MJD 53 581. The open circles show the (background-subtracted) Chandra 0.3–8 keV count rate from within 2.5′′ of Sgr A⋆ in 400-s bins. The X-ray flare is well described by a Gaussian (solid curve), and the time periods labelled *Flare* and *Peak Flare* are those used for the X-ray spectral analysis. The closed circles show the VHE γ-ray light curve from HESS in 15 min bins, scaled such that the historical VHE flux level (Aharonian et al. 2006a) (dashed line) matches the quiescent X-ray count-rate.

The 49 ks of ACIS-I data from obs. ID 5953 were analysed using CIAO version 3.4 and a light curve was extracted from a circular aperture of radius 2.5′′, centred on Sgr A⋆ (RA $17^{\rm h}45^{\rm m}40.039^{\rm s}$, Dec −29°00′28.12′′). Consistent results were obtained using a 1.5′′ aperture. The background level was estimated from a surrounding region of 8.3′′ radius, offset by 5.8′′ to the East of Sgr A⋆ to avoid contamination from the stellar complex IRS 13 (Maillard et al. 2004) and G 359.95−0.04. All photons in the energy range of 300 eV to 8 keV were included in the analysis. The resulting background-subtracted light curve (with 400 s binning) is shown in Fig. 1. A significant flare, peaking at MJD 53 581.940 ± 0.001, was detected. Before and after the flare the event rate was consistent with a constant value of (7.1 ± 0.1) counts ks^{-1}, which is consistent with the level found by Baganoff et al. (2003). The shape of the flare is well described by a Gaussian of full width half maximum $t_{\rm flare} = (1.6 \pm 0.2)$ ks. No indication of additional variation or significant substructure was found when testing residuals with 200 s, 500 s, and 1500 s binning. The flare reached a peak level of (65 ± 9) counts ks^{-1} (from the Gaussian fit), ≈9 times the quiescent level. The flare duration is comparable with that of other flares detected previously from Sgr A⋆ (for example Eckart et al. 2006), and is amongst the brightest detected by Chandra so far with a net integrated signal of (101 ± 11) counts.

The γ-ray data consist of 72 twenty-eight minute runs, 66 of which pass all quality selection cuts described by Aharonian et al. (2006b). All runs on the night of the X-ray flare pass these cuts and we find no evidence for cloud cover in simultaneous sky temperature (radiometer) measurements (see Aharonian et al. 2006b; Le Gallou & HESS Collaboration 2003). The data were analysed using the HESS standard *Hillas parameter* based method with the *standard* γ-ray selection cuts

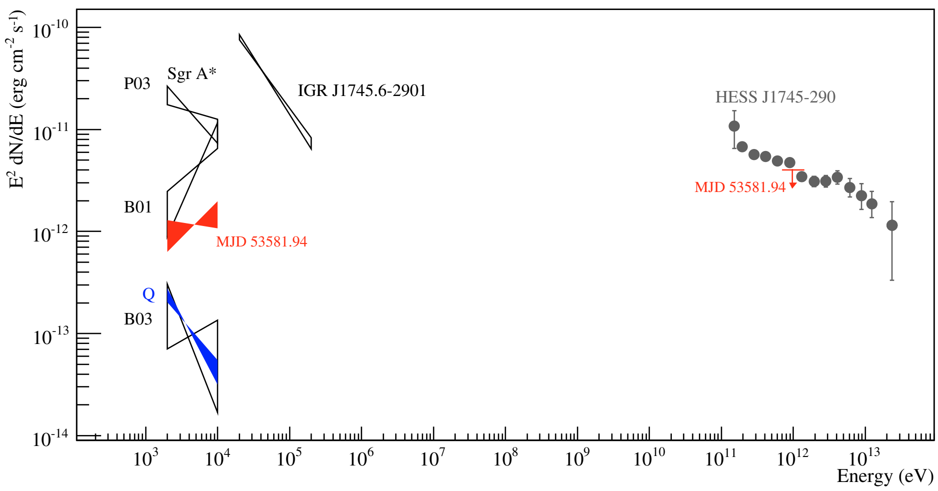

Fig. 2. High energy (>1 keV) spectral energy distribution for Sgr A* and the plausibly associated objects IGR J1745.6−2901 (from Bélanger et al. 2004) and HESS J1745−290 (from Aharonian et al. 2006a). Archival X-ray data are shown for the quiescent state: B03 (Baganoff et al. 2003); the largest reported flare seen using Chandra: B01 (Baganoff et al. 2001); and the largest flux detected using XMM: P03 (Porquet et al. 2003). The quiescent state measured during these observations is indicated by a "Q". The *Peak Flare* Chandra spectrum and simultaneous HESS limit (on a flaring component) are indicated by the flare time of MJD 53 581.94.

(including a cut on angular distance from Sgr A* of 6.7′) described in (Aharonian et al. 2006b), resulting in an energy threshold of 160 GeV. There is no evidence of variations in the flux on timescales of days, and the mean γ-ray flux $F(>1\,\mathrm{TeV})$ for this week of observations was $(2.03 \pm 0.09_{\mathrm{stat}})\times10^{-12}$ cm^{-2} s^{-1}, consistent with the average value for HESS observations in 2004, $(1.87 \pm 0.1_{\mathrm{stat}} \pm 0.3_{\mathrm{sys}})\times10^{-12}$ cm^{-2} s^{-1} (Aharonian et al. 2006a). An independent analysis based on the *Model Analysis* method described by de Naurois (2006), produced consistent results.

The time window for the γ-ray analysis is defined to be the region within $\pm1.3\sigma$ of the best-fit peak time of the X-ray flare (containing ≈80% of the signal). The mean flux within this window (marked "Flare" in Fig. 1) is $F(>1\,\mathrm{TeV}) = (2.05 \pm 0.76)\times10^{-12}$ cm^{-2} s^{-1}. This flux level is almost identical to the mean flux level for the entire week of observations. There is, therefore, no evidence for an increase in γ-ray flux of HESS J1745−290 during the X-ray flare and a limit to the relative flux increase of less than a factor 2 is derived at the 99% confidence level. In principle, a (positive or negative) time lag might be expected between the X-ray flare and any associated γ-ray flare. The existence of a counterpart γ-flare with a flux increase of a factor ≫2 (relative to the mean γ-ray flux level) requires a lag of at least 80 min (to fall outside the period of HESS observations).

The results of a spectral analysis of the X-ray emission from Sgr A* during obs. ID 5953 are presented in Table 1. Spectra are given for the entire period (*Overall*), intervals of ±2 ks (*Flare*) and ±0.9 ks (*Peak Flare*, $\pm1.3\sigma$) around the maximum, and for the part of the dataset outside ±3 ks of the maximum (*Quiescent*). For all four data-sets, the background subtracted spectra were fitted with an absorbed power-law model using a fixed value of $n_{\mathrm{H}} = 9.8\times10^{22}$ cm^{-2}, as found from fitting the (*Overall*) dataset with n_{H} free, which is consistent with the value found by Baganoff et al. (2003) of $(9.8^{+4.4}_{-3.0})\times10^{22}$ cm^{-2}. The flare spectrum is harder than that found in the quiescent state (at the 2.5σ level). The quiescent state spectrum is consistent with that found previously (Baganoff et al. 2003).

The simultaneous spectral energy distribution for the Galactic Centre from these observations is compared, in Fig. 2, with previous measurements of Sgr A* and the possible high energy counterparts IGR J1745.6−2901 (Bélanger et al. 2004) and HESS J1745−290.

Table 1. Parameters of absorbed power-law ($\mathrm{d}N/\mathrm{d}E \propto E^{-\Gamma}$) fits to the 0.2–10 keV spectral data of *Chandra* obs. 5953. F_{2-10} is the absorbed model flux between 2 and 10 keV in units of 10^{-13} erg cm^{-2} s^{-1}. The absorbing column n_{H} is fixed at 9.8×10^{22} cm^{-2} for all fits. Uncertainties are expressed as 1 standard deviation errors.

	Γ	F_{2-10}	χ^2/d.o.f.
Overall	2.58 ± 0.20	2.71	24.6/24
Quiescent	3.08 ± 0.27	1.82	16.3/17
Flare	1.83 ± 0.43	14.8	2.88/6
Peak Flare	1.70 ± 0.41	19.0	3.1/5

3. Conclusion

The absence of a significant increase in the >160 GeV γ-ray flux of HESS J1745-290 during a major X-ray flare (corresponding to an increase in flux by a factor of approximately 9 at maximum) suggests strongly that the keV and TeV emission cannot be attributed to the same parent population of relativistic particles. A possible component of the γ-ray signal that has the same flaring behaviour as the X-rays is limited to a flux less than 100% of the quiescent state signal or 4.2×10^{-12} erg s^{-1} cm^{-2} (2–10 TeV), which should be compared with the 1.9×10^{-12} erg s^{-1} cm^{-2} 2–10 keV flux during the same period (≈10× the quiescent flux). The region of variable X-ray emission is limited by causality arguments to a size of $r_{\mathrm{X}} < ct_{\mathrm{flare}}$ or $\sim10^{14}$ cm. Following Atoyan & Dermer (2004), the radiation energy density at these distances from Sgr A* is $U_{\mathrm{rad}} \geq 3\times10^{-4}$ erg cm^{-3}. If the X-ray emission is interpreted as synchrotron emission of ~TeV electrons, then the flux limit to inverse Compton (IC) emission at VHE energies during the flare implies that $U_{\mathrm{mag}} > 0.5\,U_{\mathrm{rad}}$ and hence $B > 50$ mG in this region. Since stronger magnetic fields are, in general, expected in this region (see e.g. Yuan et al. 2003), our result does not constrain models where the X-ray flares are assumed to be produced by synchrotron emission of relativistic electrons. We note that the arguments given above assume that the synchrotron flare is caused by an increase in the number of relativistic electrons. The alternative explanation that an increase in synchrotron emission occurs due to an impulsive increase in the magnetic field (with no direct effect on the IC flux) cannot be excluded.

The fact that HESS J1745−290 does not appear to be associated with radiation processes within 10^{14} cm (or $\sim$100 R_S) of the supermassive black hole does not exclude all scenarios in which Sgr A* is the acceleration site for the particles responsible for the TeV emission. Scenarios in which the energy losses of the accelerated particles occur much farther from Sgr A* (for example Aharonian & Neronov 2005b; Atoyan & Dermer 2004; Ballantyne et al. 2007) remain viable explanations for this γ-ray source.

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