The Galactic centre at $10^{12}$ eV

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What do observations by the new generation of ground-based, Imaging Air Cerenkov Telescopes (IACTs) tell us about conditions/processes at the Galactic centre (GC)?
• Work in tera-electronvolts: TeV = $10^{12}$ eV ~ erg

• I have stolen material from talks available on line by:
  1. Dermer and Attoyan
  2. Andrea Goldwurm
  3. HESS Collaboration
GC at Optical Wavelengths

- We can observe the GC at radio, sub-millimeter, infrared, X-ray and $\gamma$-ray wavelengths.
GC - NIR

- From NIR monitoring with VLA and Keck of stars in close orbits (periods ~ few decades), it is now conclusively determined that:
  1. the distance to the GC, $R_0$, is $\sim 8$ kpc
  2. at the dynamical GC there is a $\sim 4 \times 10^6$ solar mass black hole
Radio Zoom
Galactic Center Region at 90 cm
~ 300 pc

Nonthermal radio-emitting filaments
Large scale magnetic fields and relativistic electrons
SNRs, HII regions
Poloidal magnetic field within ~100 pc of nucleus
Sgr A: compact radio sources at nucleus of Milky Way

LaRosa et al. (2000)

Credit: Dermer and Atoyan
Molecular line observations trace gas density and show up central molecular zone of giant molecular cloud complexes bound in tight orbits (~100 pc) around Sgr A - these contain ~ 10% of the Galaxy’s molecular gas (3-8 \times 10^7 solar mass) in densities of $n_{H_2} \sim 10^4$ cm$^{-3}$
**Sgr A Resolved: Radio Features of Inner 10 pc (4 ‘×3 ’, or 9.3×7 pc)**

**Sgr A East** (blue): extremely energetic ($\approx 10^{52}$ ergs) region occurring $\approx 50,000$ yrs ago from chain of SNRs, a GRB, or star swallowed by BH. Diffuse X-ray emission.

**Sgr A West** (red): Gas and dust streamers ionized by stars and spiraling around the Galactic center, possibly feeding the nucleus.

**Sgr A*: A** bright compact radio source at intersection of the arms of the Sgr A West, coincident with Galactic dynamical centre

Other components:
1. cluster of evolved and young stars
2. dusty molecular ring (circumnuclear disk)
3. ionized gas streamers

**Credit:** Dermer and Atoyan

6 cm VLA radio of Sgr A East and Sgr A West (Yusef-Zadeh, Melia, & Wandle 2000)
Sgr A* in Radio

- GC contains bright radio source, Sgr A*, first identified in the 1970s and coincident with dynamical centre of Galaxy...~ 1 Jy and variable (tens of days)
- @ 3mm size: $\delta t \times c \sim 1$ AU ~ 20 $R_{Sch}$...emission associated with accretion disk
~TeV Observations of GC

- In 2004, definite detections of the GC at ~TeV energy was reported by:
  1. CANGAROO (Tsuchiya et al. 2004)
  2. Whipple (Kosack et al. 2004)
  3. HESS (Aharonian et al. 2004)
- Observation of GC with MAGIC has since been reported (Albert et al. 2006)
HESS Observation of GC

- Consistent with point source, radius < 3 arcmin ~ 7 pc
- Located within 1 arcmin of Sgr A* -- Hard spectrum:
  -$-2.25 \pm 0.04$ (stat.) $\pm 0.10$ (syst.)
- This spectrum confirmed by MAGIC which found $-2.2 \pm 0.2$
- Data consistent with steady source
What is the mechanism for γ-ray production?

- Broadly two classes of model:
  1. *leptonic* - high-energy electrons (10 TeV+) inverse-Compton scatter ambient light to TeV energies
  2. *hadronic* - protons (and heavier ions) collide with ambient matter and produce pions (cf. LHC)
A diffuse, hadronic model for the TeV point source at the GC

Ballantyne et al. 2007 ApJL 657,13

Crocker et al. 2007 ApJL 664, 95
Computational model

- A ~2 TeV proton is injected close to Sgr A* and scatters on magnetic field inhomogeneities.
- It leaves the computational volume after reaching 3 pc.
10 MeV - 10 TeV spectrum predicted by modelling
The circum-nuclear disk illuminated by cosmic ray impacts (contours of integrated 1-10 TeV emission)
Schematic: a HE proton enters from left scattering on magnetic field inhomogeneities. It collides with an H₂ molecule creating a shower of pions. We can detect some of the decay products of these pions with various detectors.
Predicted radio spectrum vs data for inner 2’ x 1’ around Sgr A*: the hadronic model is self-consistent
• Neutrinos: a smoking gun for the hadronic model for TeV gamma-rays from the GC? …the GC source should be detectable within two years by a Mediterranean-based neutrino telescope and, perhaps, over a similar timescale by IceCube at the South Pole
Diffuse Emission
Diffuse $\gamma$s in H.E.S.S. data?

- 50 hour H.E.S.S. Observation of GC in 2005
- Need to subtract the two bright sources

Credit: HESS Collab
Residuals after source subtraction

- Diffuse emission along the plane!

new source
HESS J1745-303

Credit: HESS Collab
CS contours over H.E.S.S. map

CS contours smoothed with HESS PSF

→ Target Material

› quite close match!

Credit: HESS Collab
Explaining Emission

• HESS collaboration, noting correlation between $\gamma$-rays and molecular density, posit hadronic collisions as source of emission – implies $10^{50}$ ergs in CR hadrons through the CMZ

• Yusef-Zadeh et al. (2007 ApJ 656, 847) noting independent correlation between Fe K $\alpha$ line emission and $\gamma$-rays suggest origin in IC scattering of IR background by primary electrons
Reasonable agreement overall but
- Deficit around $l = 1.3^\circ$
Interpreting $\gamma$-ray/gas Correlation

• HESS Collaboration suggests that breakdown of correlation at angular scales $\sim 1^\circ$ suggests NSS scenario where CR hadrons injected at central source

• Assuming diffusion coefficient typical for Galactic disk, viz., $10^{30}$ cm$^2$s$^{-1}$ @ TeV, diffusion time to $1^\circ$ is $\sim 10^4$ years – close to some estimates of age of Sgr A East SNR
Energy Spectrum

- The Galactic Centre Source: HESS J1745-290
  - (solid angle is integration radius used – source looks point-like)
- All emission in the GC has
  - $\Gamma_{\gamma} \approx 2.2$

Credit: HESS Collab
Couple of Points Concerning Spectral Index

- Spectrum much harder than would be produced by local CR population interacting in GC gas
- On the one hand, the fact that the SPIN of the diffuse emission and the GC point source are so similar might argue for a common accelerator (at Sgr A*, Sgr A East?)
- On the other hand, the fact that the spectral index of the diffuse emission does not vary across the region poses some problems for a model invoking diffusion: why doesn’t the SPIN harden at large distances?
Current work

• Propagation modelling over size scales of diffuse emission ~200 pc diameter region (seems to show that a truly diffuse source mechanism is required)
• Looking at diffuse radio emission from entire region (prediction from gamma-rays agrees with observed radio emission if the ambient field is $\sim mG$).