Fast winds in active galactic nuclei as sources of ultra-high-energy cosmic rays

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The answer, my friend, is…
Composition: Auger, ICRC 2015  

From the depth of shower maximum to primary mass ($\ln A$)

- **EPOS-LHC (Mean of $\ln A$)**
- **EPOS-LHC (Variance of $\ln A$)**
- **QGSJetII-04 (Mean of $\ln A$)**
- **QGSJetII-04 (Variance of $\ln A$)**

**Similar trend for both models:**
- Heavier composition at low energies (largest mass dispersion).
- Lightest one at $\approx 2 \times 10^{18}$ eV, getting heavier again towards higher energies (smaller mass dispersion).

[N.B. Very few data above $\approx 40$ EeV]

**Not only inferences on mass but test of models too**

The conversion to $\sigma^2(\ln A)$ through QGSJetII-04 yields unphysical results.
Meta-analysis: Composition WG

TA data cannot distinguish between mix and QGSJETII-03 protons at this level of systematic uncertainty.
“The TA measurements, dare I say it, is consistent with a light composition.”

「信じてもらえないかもしれないが、TAの測定値は軽い組成と無矛盾、と言っておこう。」

TA data cannot distinguish between mix and QGSJETII-03 protons at this level of systematic uncertainty.
AGN jets as UHECR sources

high-power (FR 2) objects
hot spot: clear accel. site BUT
too few <1 within D~<100 Mpc
non-proton composition?

low-power (FR 1) objects
relatively numerous BUT
accel. site?
inner jet-> low B? escape?
non-proton composition?
ultra-fast outflows (UFOs) in AGN
blue-shifted X-ray absorption lines
- \(\sim40\%\) of all AGNs
  both radio-quiet/radio-loud
- fast outflow: \(v\sim0.05-0.3c\)
- highly ionized:
  Fe XXV/XXVI
  \(\xi_{\text{ion}}\sim10^3-10^6\) erg s\(^{-1}\) cm
- high column density:
  \(N_H\sim10^{22}-10^{24}\) cm\(^{-2}\)
- variable: \(t_{\text{var}}\geq\sim\)ks
ultra-fast outflows (UFOs) in AGN

- $R \sim 0.0003$-$0.03$ pc  
  ($\sim 10$-$10^4 R_g$)
- $M \sim 0.01$-$1 \dot{M}_{\odot}$/yr
- $L_{\text{kin}} \sim 0.01$-$1 L_{\text{Edd}}$
- broad opening angle $\sim <100$ deg
- independent of relativistic jet

accretion disk winds

Tombesi+ 13

formation mechanisms: thermal?  
radiation (continuum or line)?  
magnetic?  
hybrid (thermal+radiation, radiation+magnetic)?...
collisionless shocks in AGN winds

external shocks

R_{sh,ex} \sim 0.1 \text{pc} - \text{few kpc}
- mechanical/thermal feedback on host galaxy gas
  -> origin of M_{BH} - \sigma_{bulge} correlation?
- particle acceleration and nonthermal emission?

Faucher-Giguere & Quataert 12
observable signature of AGN wind external shock

Wang & Loeb 15 also Nims+ 15

radio, X-ray observable by future facilities -> probe of SMBH feedback in action -> UHECRs as consequence of SMBH feedback?
wind shocks: electron & proton acceleration

main parameters

\( v_{\text{out}}, L_{\text{nuc}} \): observed

\( L_e, L_p < L_{\text{kin}} \): obs. constrained

\( R_s \): few \( R_g - R_{\text{bulge}} \)

\( B_s \) (\( \varepsilon_B = B^2 / 8\pi / L_{\text{kin}} / 4\pi R^2 v_{\text{out}} \))

dynamical time \( t_{\text{dyn}} = R / v_{\text{out}} \), \( t_{\text{lc}} = R_s / c = 500 \text{ s} \)

acceleration time \( t_{\text{acc}} \sim 10 (v_s / c)^{-2} E / c e B \)
acceleration vs. cooling

\[ v_{\text{out}} = 0.1c, \quad L_{\text{kin}} = 10^{45} \text{ erg/s} \]
\[ R_s = 0.1 \text{ pc}, \quad B_s \sim 3G(e_B \sim 1) \rightarrow n_p \sim 5 \times 10^3 \text{ cm}^{-3} \]

Electrons up to \( \sim 1 \text{ TeV} \), cooling for \( \sim < 10 \text{ MeV} \)  
NB: \( \gamma\gamma \)
Protons up to \( \sim 3 \times 10^{18} \text{ eV} \), Fe up to \( \sim 10^{20} \text{ eV} \)
acceleration vs. cooling \( v_{out}=0.01c, L_{\text{kin}}=10^{45} \text{ erg/s} \)
\( R_s=100 \text{ pc}, B_s \sim 3 \text{mG}(\varepsilon_B \sim 1) \)

protons up to \( \sim 3 \times 10^{18} \text{ eV} \) (Fe up to \( \sim 10^{20} \text{ eV} \))
(electrons up to \( \sim \text{PeV} \))
UHECR sources: acceleration

E \leq Z \varepsilon B R (v/c)

confinement

E_{\text{max}} \quad \text{acceleration vs: escape source lifetime adiab. expansion loss radiative loss}

B \sim R^{-1}

magnetars

“Hillas plot” adapted from Yoshida & Dai 98

clusters, etc.
UFO AGN skymap

The locate of analyzed AGN sample

Energy: 0.1 - 100 GeV

Period of analysis: 2008/8/4 - 2014/9/30

NB: far from a uniform sample of such objects
summary  AGN winds as UHECR sources
- widespread existence of powerful, mildly relativistic baryonic(ionic) outflows in AGN, independent of rel. jets
- collisionless external shocks
  “action site” of SMBH feedback onto host galaxies potential particle acceleration site
- potential sources of UHECRs
  - acceleration OK IF B~Beq
  - number, energetics OK
  - guaranteed Fe composition
  - direct consequence of SMBH feedback

- more detailed modeling in progress
- potential PeV neutrino sources if internal shocks occur near nucleus (~wind launching site)
acceleration vs. cooling  \( R=0.001 \text{ pc} \rightarrow B_{eq} \approx 300 \text{ G}, n_p \approx 5 \times 10^7 \text{ cm}^{-3} \)

electrons only to \( \sim 100\text{MeV} \) NB: internal photons, \( \gamma \gamma \)
protons up to \( \sim 10^{16} \text{ eV} \), limited by photomeson \( \rightarrow \nu, n \) emission
potential consequences of near-nucleus $p\gamma$ interactions

no UHECRs, no GeV-TeV emission but:
- non-thermal X/MeV emission
- TeV-PeV neutrino emission $\leftrightarrow$ IceCube results
  -> broad-line region from neutrino-heated stars?
- TeV-PeV neutron injection
  -> decay back to protons within 1-100 pc, CR-driven wind?
  -> mass loading of jets?

revival of “old ideas”
(but with more concrete prospects for proton acceleration)

Kazanas & Protheroe 83, Zdziarski 86, Sikora+87, Rudak+ 89, Begelman+ 90
Mannheim & Biermann 89, Stecker+ 91, Atoyan 92, Szabo & Protheroe 92…