Galactic Wind Haze and its γ spectrum

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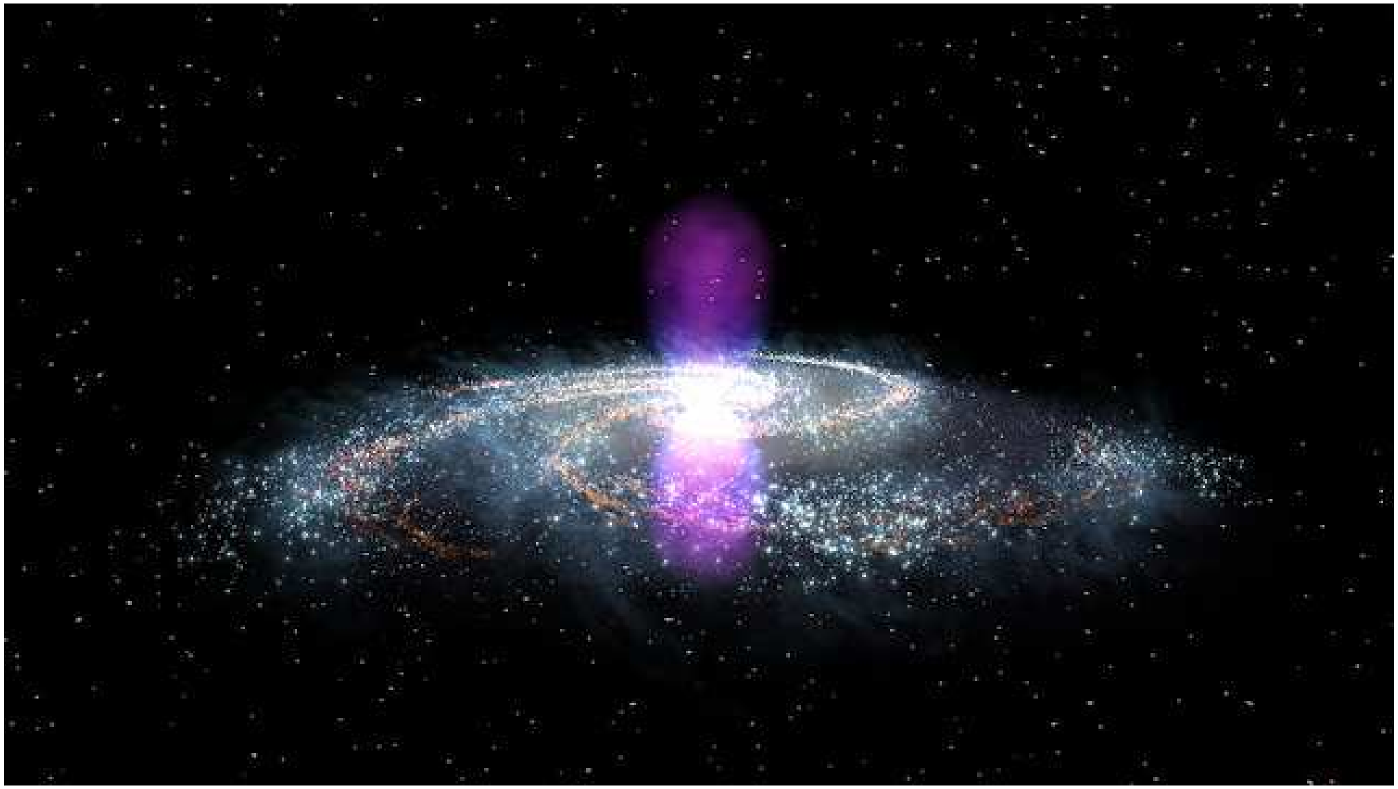
Introduction-1

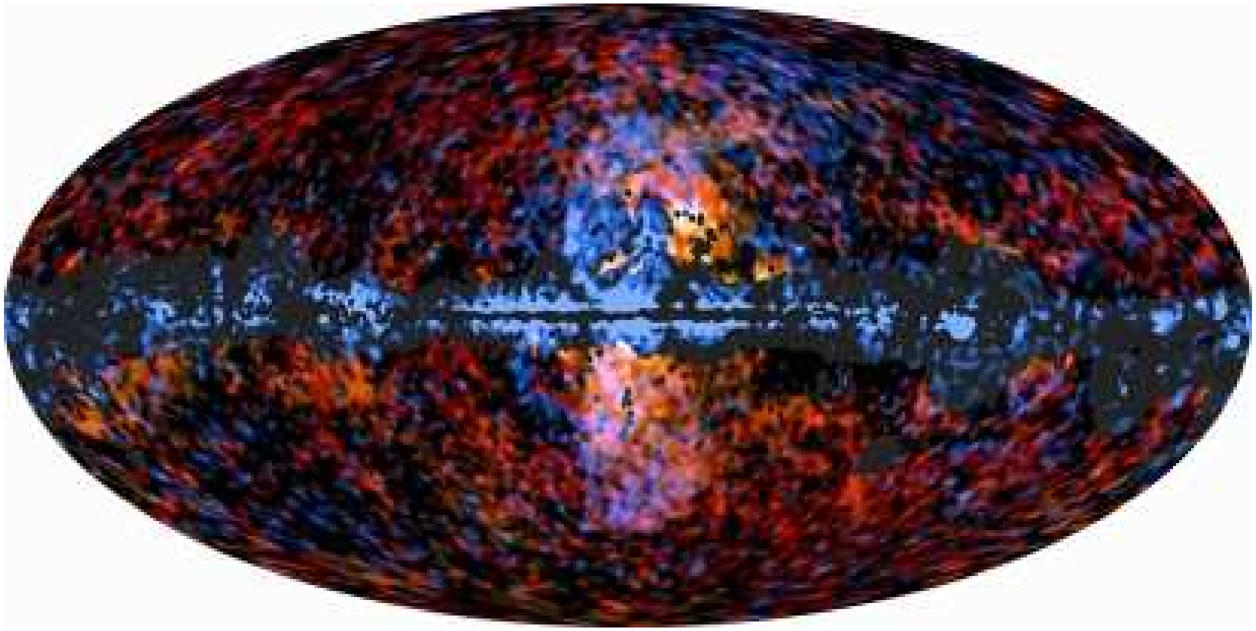


NASA image release Nov 9, 2010

A mysterious structure in our galaxy!

Extending 50^o above and below the Galactic center with a width of 40^o in longitude

Introduction-2



Planck mission observes Galactic Haze at microwave freq. (red and yellow 30-44GHz)

Superimposed over the Fermi data (shown in blue 10-100GeV)

Haze is concentrated around the central area of Galaxy

Emission from other parts of our Galaxy is distinctly different from Haze emission

Haze spectrum is $I_\nu^H \propto \nu^2 T_\nu^H \propto \nu^{-0.55}$ and synchrotron emission from other parts of Galaxy $I_\nu^s \propto \nu^{-1.05}$ (Planck Collaboration 2012)

Fermi Bubbles

Bubbles extend upto 10kpc above and below the Galactic plane, symmetrically located

Within $1 - 100$GeV, $E_\gamma^2 dN/dE_\gamma = 3 \times 10^{-7} GeV\, cm^{-2} sec^{-1} sr^{-1}$ (Su et al. 2010)

Many possible models suggested...

- γ ray emission from cosmic ray proton interactions pp (Crocker& Aharonian 2011)
- possible AGN jet activity in our Galaxy (Guo et al. 2011)
- last quasar outburst (Zubovas et al. 2011)
- collimation of a wide angle outflow from $SgrA^*$ by CMZ (Zubovas et al. 2012)
- relativistic e^- accelerated by 2^{nd} order Fermi accel then their IC(Mertch & Sarkar 2011)

Galactic Wind Driven by Star Formation

Galactic wind driven by star formation and cosmic rays....

Star formation rate $0.04 - 0.08 M_{sun} yr^{-1}$ lasting about 1-10 Myr (Immer et al. 2012)

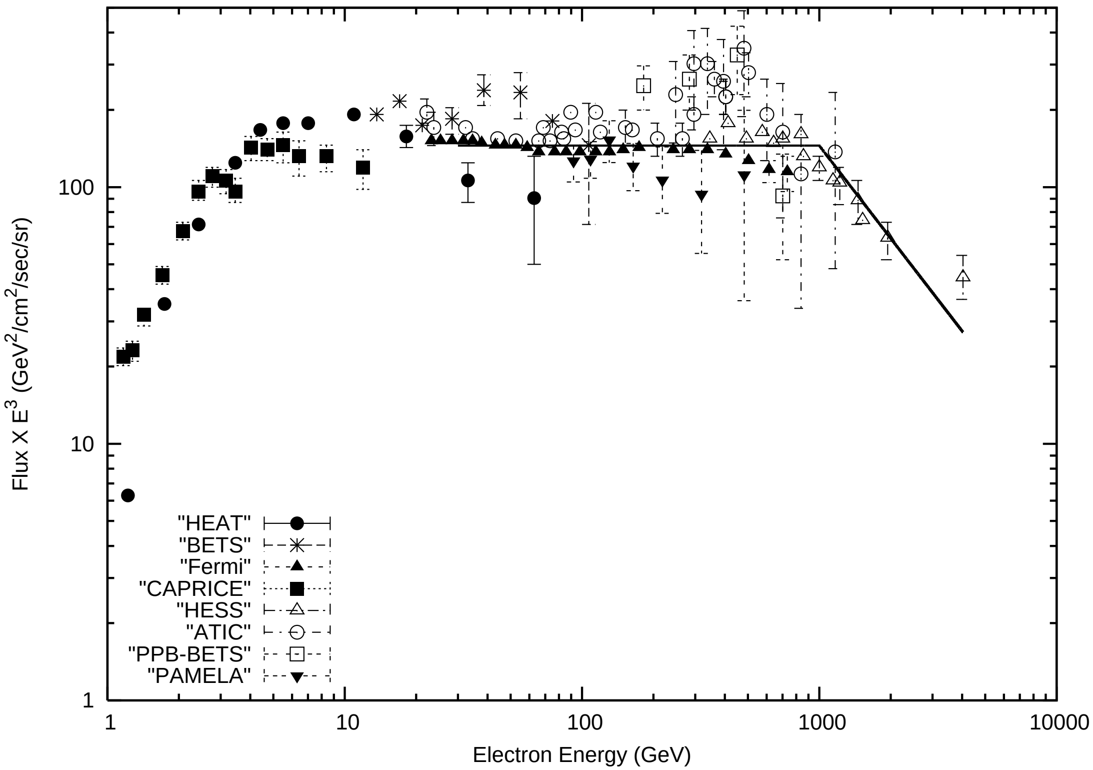
Momentum deposition from supernova and stellar winds to the bubbles blown to a distance of 10kpc in 15Myr, energy deposited $10^{54} erg$ consistent with observation (Su et al. 2010)

Energy density in a bubble of radius 5kpc is $1.4 \times 10^{-11} erg/cm^3$, and the equipartition magnetic field estimated to be $4 \mu G$ consistent with recent magnetic field measurement in the bubble (Carretti et al. 2013)

Unstable wind traversed by many shocks, a large number of shocks combined into a very large shock, that looks like a bubble

Cosmic Ray Electron Spectrum

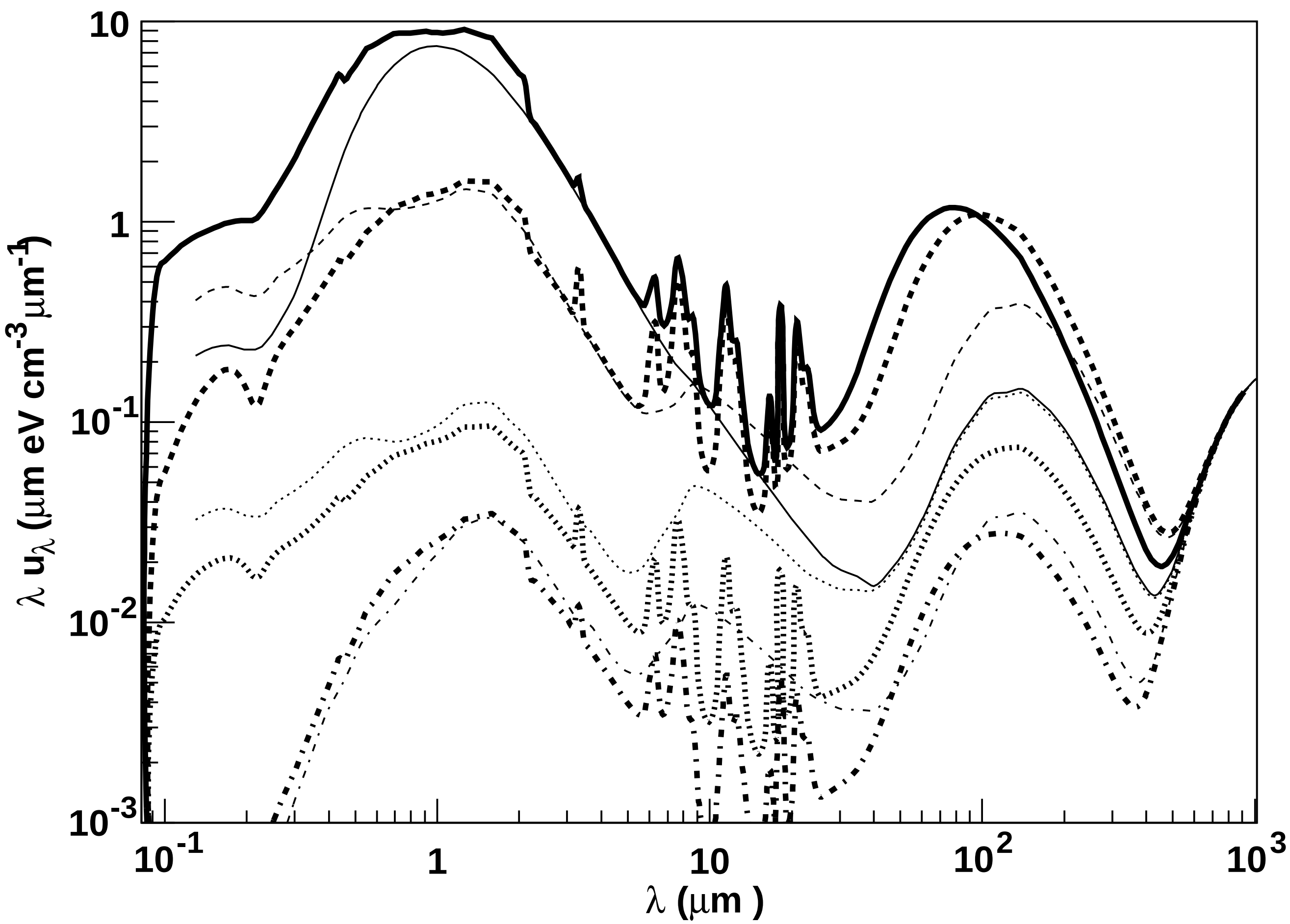
We show the observed cosmic ray electron spectrum



Below the break at 1 TeV the observed e spectrum near the earth

$$\frac{dN_e}{d\gamma_e} = 23.55 \times 10^{-6} \gamma_e^{-3} cm^{-3} \tag{1}$$

Background Photon Field-1

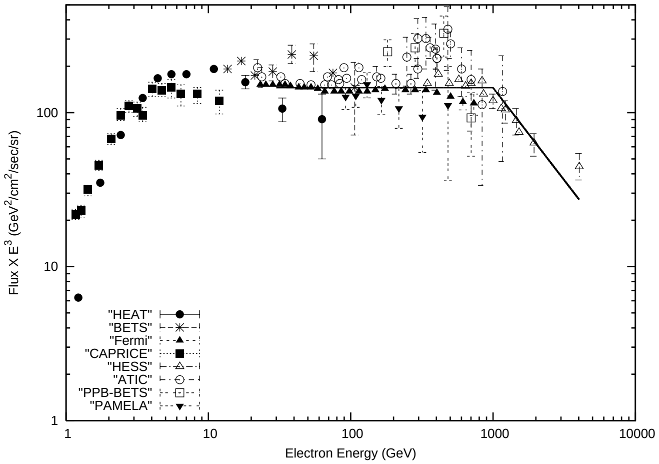


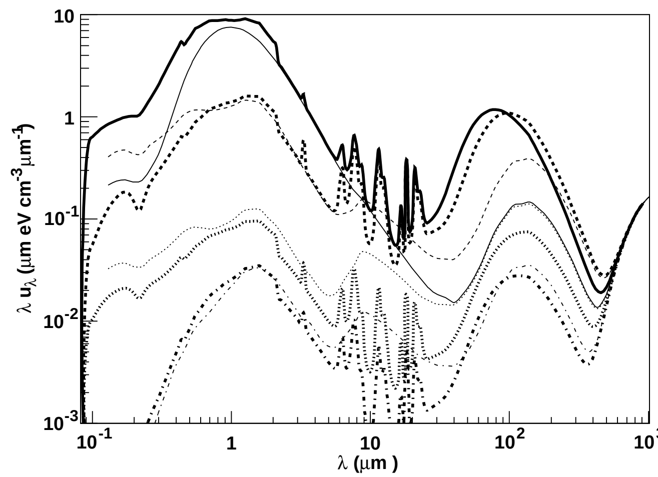
Interstellar Radiation Field from Moskalenko et al. 2006

Background Photon Field and IC

We also included CMB in our work, effect is not significant

Relative importance of the peaks very important in deciding the final gamma ray spectrum





Calculation of Inverse Compton power...

Electron spectrum $\propto E_e^{-3}$ below 1 TeV and $E_e^{-4.2}$ above

(2) $$\frac{dE_{IC}}{dV\,dE_\gamma dt} = \frac{3}{4} C\,\eta\,c\,\sigma_T \int \left(\frac{E_\gamma}{\epsilon}\right) v(\epsilon) d\epsilon \int_{\gamma_{e1}}^{\gamma_{e2}} {\gamma_e}^{-p-2} f\left(\frac{E_\gamma}{4{\gamma_e}^2\epsilon}\right) d\gamma_e$$

$$x = \frac{E_\gamma}{4\gamma_e^2\epsilon},\ f(x) = 2x ln x + x + 1 - 2x^2$$

Gamma Ray Spectrum-IC

Klein Nishina correction becomes important for $\gamma_e \epsilon \geq 0.2 m_e c^2$ (Geoganopoulos et al. 2001, 2004)

In KN regime $f(x) = 2xlnx + x + 1 - 2x^2 + \frac{(4\epsilon\gamma_e x)^2}{2(1+4\epsilon\gamma_e x)}(1-x)$ and $x = \frac{E_\gamma}{4\epsilon\gamma_e^2(1-E_\gamma/\gamma_e)}$

Due to KN effect the IC of 1eV and higher energy IR photon flux gives a small contribution to the final γ spectrum

Galactic Center region the electron flux is $\eta > 1$ times the flux observed near the Earth.

γ ray flux produced by IC scattering of IR photons is calculated.

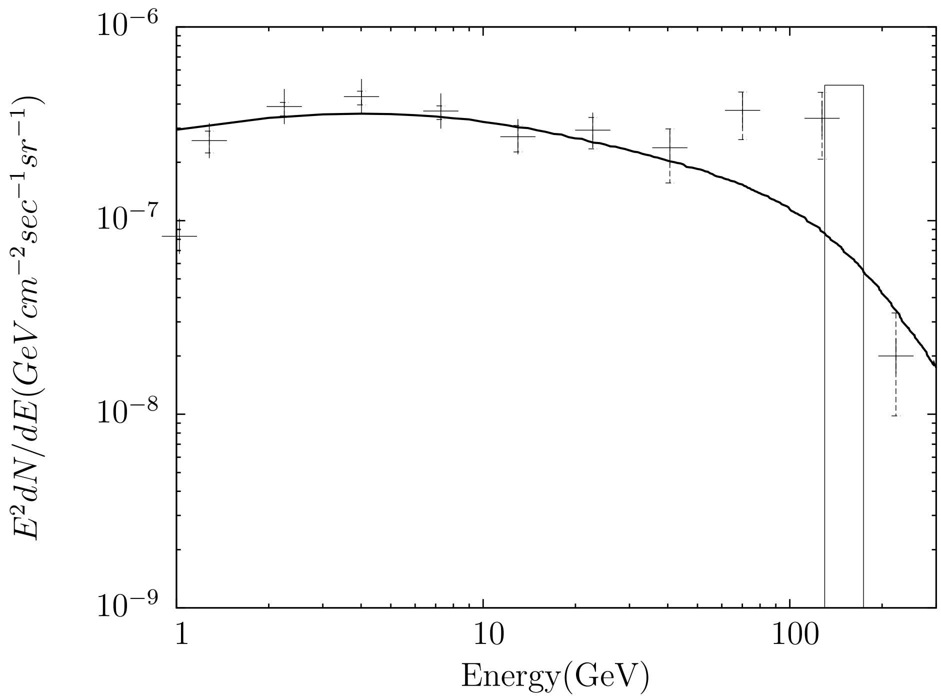
$$E_\gamma^2 \frac{dN(E_\gamma)}{dE_\gamma} = E_\gamma \frac{Vol}{4\pi D_{GC}^2} \frac{dE_{IC}}{dV dE_\gamma dt} \frac{1}{\triangle\Omega} \tag{3}$$

$D_{GC} = 7.5$ kpc gives $4\pi D_{GC}^2 = 10^{45.8}$ cm^2.

$Vol \sim 10^{66} cm^3$ and $\triangle\Omega = 1sr$

Gamma Ray Spectrum-IC

Comparison of our calculated γ energy spectrum with the data from Su et al. (2010)



Turn over near 130 GeV shown with a line

Possible interpretations for 130 GeV line feature

(i) Break in the cosmic ray e spectrum at 1 TeV

(ii) Triple Pair production in $e\gamma \rightarrow e^- e^+ e^-$ interactions, IC off the pairs gives gamma ray line

$e\gamma \rightarrow e^- e^+ e^-$

For IR photons of energy 1 eV and higher $e\gamma$ triple pair production is more important than IC scattering in KN regime, $e\gamma$ cascade continues until the energy of the e is below the threshold for triple pair production $3m_e c^2$ in CM frame

Energy of the electrons and IR photons in the centre of mass(CM) frame and observer's frame are related as

$$E_{CM} = [m_e^2 c^4 + 2E_e \epsilon (1 - cos\theta \beta_e)]^{1/2} \tag{4}$$

Minimum energy of e in observer's frame for pair production

$$E_e = \frac{8 m_e^2 c^4}{2\epsilon (1 - \beta_e cos\theta)} \tag{5}$$

$\beta_e \sim 1$, $e\gamma$ collisions are isotropic in obs's frame

Threshold energy for $\epsilon = 1eV$, $\theta = \pi$, $E_{th,e} = 522GeV$

Triple pairs share the parent electron's energy in 2:1:1 to 1:1:1 ratios,γ line 130-174 GeV

Cross section for $e\gamma \rightarrow e^- e^+ e^-$ V. Votruba Phys Rev 73, 1468 (1948)

Cosmic Ray Nuclei Spectrum

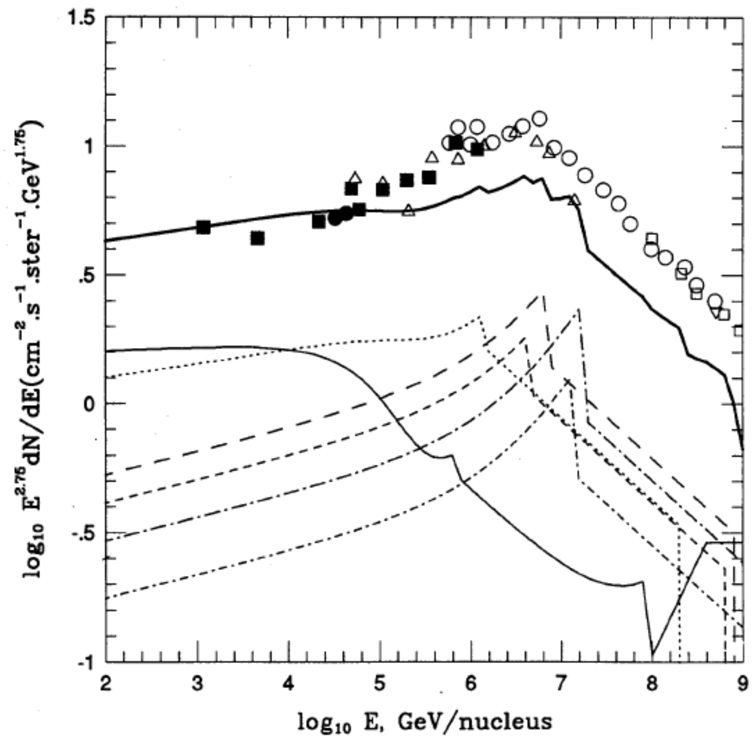
Cosmic rays from SN explosions into the interstellar medium:ISM-SN-CRs

Cosmic rays from SN explosions into a stellar wind:Wind-SN-CRs

Cosmic Rays origin: ISM-SN-CRs and Wind-SN-CRs Biermann et al. 2001

Wind-SN-CRs CR spectrum injection spectrum $E^{-7/3}$ and a polar cap component E^{-2} with a sharp cut-off near knee

Polar cap component of CRs is important near 1 PeV



CR nuclei spectrum from Stanev, Biermann and Gaisser A& A 1993

Cosmic Ray Electron Spectrum

Secondary electrons produced in nuclear de-excitation (Ramaty et al. 1979) followed by energetic particle interactions as a result Lorentz factor remain approx same

$\gamma_{knee} \simeq \gamma_{break} \simeq 10^6$

Observed electron spectrum is the polar cap component in the loss limit above 100 GeV

E^{-2-1}

Below the knee cosmic ray spectrum $E^{-3.2}$ in the diffusion limit

Beyond 1 TeV electron steepens to $E^{-3.7}$ in the loss limit, it can be even steeper, we have approximated as $E^{-4.2}$

Planck Data

CR electrons are also emitting synchrotron radiations which have been observed by Planck

Injection spectrum of cosmic ray electrons E^{-2} polar cap component, in the diffusion limit $E^{-2-1/3}$ and E^{-2-1} in the loss limit

Electron spectrum $E^{-7/3}$ synchrotron gives radio spectrum $\nu^{-2/3}$ and E^{-3} gives ν^{-1} which are close to the observed intensities $\nu^{-0.5}$ and $\nu^{-1.05}$

Two zones:Planck spectrum in inner zone 'haze' $I_\nu^H \propto \nu^{-0.5}$ due to synchrotron emission of polar cap component in the diffusion limit $E^{-7/3}$

Outer zone: Planck spectrum $I_\nu^s \propto \nu^{-1.05}$ due to synchrotron loss by polar cap component in the loss limit E^{-3}

Transition region betwenn two zones not yet clear in data, this could be the reason for a slightly flatter spectrum in inner zone and steeper spectrum in outer zone

Summary and Conclusions

- IC scattering of CRs with IR background gives Fermi Bubbles
- 130 GeV line due to the break in the CR e spectrum and peak near 0.01 eV in IR spectrum
- Also $e\gamma \rightarrow e^- e^+ e^-$ give gamma rays and line feature near 130GeV by IC emission of the pairs
- CR spectrum has a break at the same energy everywhere in Galaxy
- CR knee is same everywhere in the Galaxy
- SN explosion giving CRs, then all SN at the final stage have common properties....consistent with the theory of Bisnovatyi-Kogan(1970)

Ultrahigh Energy Cosmic Ray Nuclei from Cen A

Work done with Jagdish C. Joshi

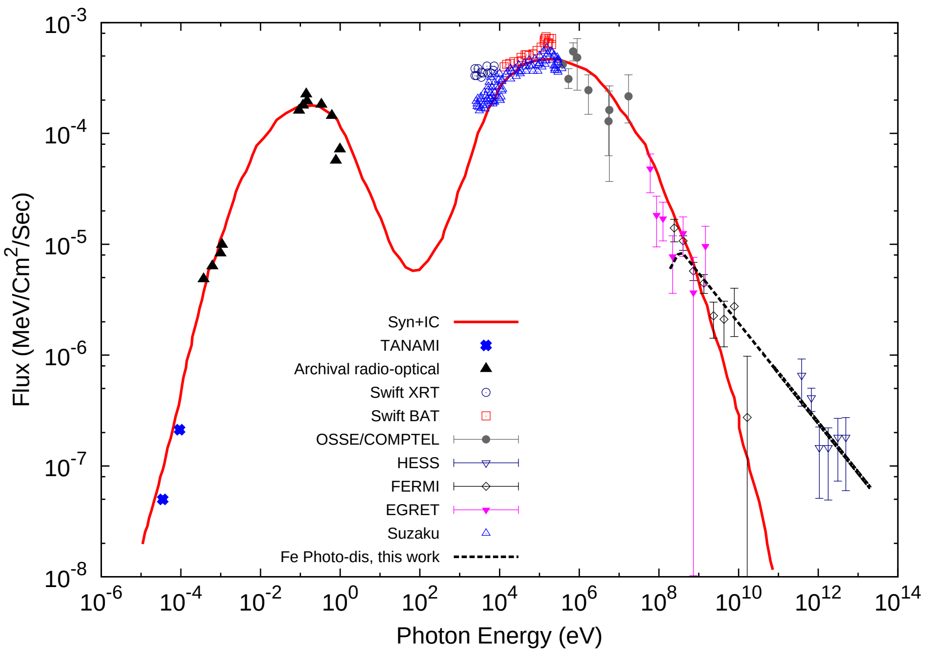
Ref: Phys Rev D 87 (2013) 023002

Observational Results

Observational results

- (i) 2 CR events detected from the direction of Cen A above 55EeV by Pierre Auger
- (ii) Fermi observations from the direction of the core of Cen A
- (iii) HESS observations from radio core and inner kpc jets of Cen A

$p\gamma$ interactions in the core region consistent with gamma ray and UHECR observational data (Sahu, Zhang & Fraija 2012)



Rates of Hadronic Integrations

(6) $$R_{phot-dis} = \frac{c\pi\sigma_0\epsilon'_0\Delta}{4\gamma_p^2}\int_{\epsilon'_0/2\gamma_p}^{\infty}\frac{dn(x)}{dx}\frac{dx}{x^2}.$$

Cross-section normalization constant $\sigma_0 = 1.45Amb$, the central value of GDR $\epsilon'_0 = 42.65A^{-0.21}MeV$ for $A > 4$ and width of the GDR $\Delta = 8MeV$, Lorentz factor of each nucleon is $\gamma_p = E_{Fe}/(56m_p)$

Seed photon density

(7) $$4\pi R^2 c\frac{dn(x)}{dx} = 4\pi D^2\delta_D^{-p}\frac{dN_\gamma^o(\epsilon_\gamma^o)}{d\epsilon_\gamma^o dt^o dA}$$

where $p = n + \alpha + 2$

γ ray flux in photo-dis model,

(8) $$\frac{d\phi_\gamma^o}{dE_\gamma^o dt^o dA}(E_\gamma^o) = \frac{1}{4\pi D^2}\frac{R}{\beta c}\frac{\bar{n}_{56}m_N}{2\bar{E}'_{\gamma,56}}\int_{\frac{m_N E_\gamma}{2E'_{\gamma,56}}}\frac{dN_{Fe}}{dE_N}(E_N)R_{phot,dis}\frac{dE_N}{E_N}$$

where $\beta = v/c \sim 1$ for UHECR nuclei

Photo-Disintegration of Heavy Nuclei

γ ray flux above energy 250 GeV is a single power law with index $2.73 \pm 0.45_{stat} \pm 0.2_{sys}$ (HESS observations)

$$\frac{d\phi^o(E^o_\gamma)}{dE^o_\gamma}(E^o_\gamma) = 2.45 \times 10^{-13}\left(\frac{E^o_\gamma}{1TeV}\right)^{-2.73} cm^{-2}sec^{-1}TeV^{-1} \tag{9}$$

Fe cosmic ray luminosity $\sim 10^{47} erg/sec$ higher than Eddington's Lum $10^{46} erg/sec$

Number of CR events above 55 EeV calculated with this flux

$$\frac{dN^o_{n,p}}{dE^o_{n,p}dt^o dA}(E^o_{n,p}) = \frac{\bar{E}'_{\gamma A}}{m_n \bar{n}_A}\frac{d\phi^o_\gamma}{dE^o_\gamma dt^o dA}(E^o_\gamma) \tag{10}$$

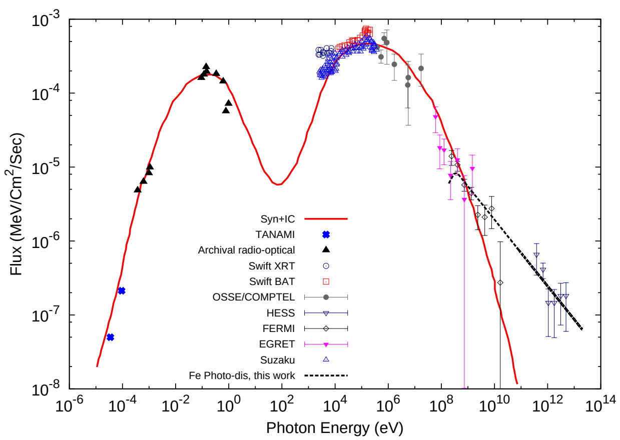
Number of events above 55EeV in Pierre Auger

$$N^o_{p,n} = \frac{15}{4} \times \frac{9000}{\pi}(km^2)\omega(\delta)\int_{E^o_l}^{E^o_u}\frac{dN^o_{p,n}}{dE^o_{p,n}}(E^o_{p,n})dE^o_{p,n} \tag{11}$$

Conclusions

- Luminosity budget slightly higher than Eddington's luminosity, however there are uncertainities in several parameters which may lower the luminosity budget,low energy photon density, size of the emitting region, Doppler factor of the emitting region
- $p\gamma$ and photo-dis of heavy nuclei can happen in the core region of Cen A
- Both processes are consistent with gamma ray and extreme energy cosmic ray observations from the direction of the core of Cen A
- More data on low frequency photon emission would be helpful for detailed modeling of the source

$p\gamma$ interactions Sahu et al. 2012



Fe-photodis our work 2013