Core Collapse

A star passes most of its lifetime burning H (main sequence). The resulting He builds up in the core and its mass increase, heating and contracting under the pressure of outer layer. The star contraction pauses as nuclear fusion provides the energy necessary to replenish the energy the star loses in radiation and neutrinos. When the T in the core is sufficiently large, He burning begins. After He burning the evolution is greatly accelerated by neutrino losses. The scheme repeats for different stages.

(i) Hydrogen burning $4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e$
(ii) Helium burning $3\alpha \rightarrow ^{12}\text{C} + 2\gamma$
(iii) Carbon burning $^{12}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O} + \gamma$
(iv) Oxygen burning $^{16}\text{O} + ^{16}\text{O} \rightarrow ^{28}\text{Si} + \alpha$
(v) Iron burning $^{28}\text{Si} + ^{28}\text{Si} \rightarrow ^{56}\text{Fe} + \gamma$

Teresa Montaruli, Apr. 2006
Evolution of a 15 $M_{\text{Sun}}$ star

<table>
<thead>
<tr>
<th>Stage</th>
<th>Time Scale</th>
<th>Fuel or Product</th>
<th>Ash or product</th>
<th>Temperature $(10^9 \text{K})$</th>
<th>Density $(\text{gm/cm}^3)$</th>
<th>Luminosity (solar units)</th>
<th>Neutrino Losses (solar units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>11 My</td>
<td>H</td>
<td>He</td>
<td>0.035</td>
<td>5.8</td>
<td>28,000</td>
<td>1800</td>
</tr>
<tr>
<td>Helium</td>
<td>2.0 My</td>
<td>He</td>
<td>C, O</td>
<td>0.18</td>
<td>1390</td>
<td>44,000</td>
<td>1900</td>
</tr>
<tr>
<td>Carbon</td>
<td>2000 y</td>
<td>C</td>
<td>Ne, Mg</td>
<td>0.81</td>
<td>$2.8 \times 10^5$</td>
<td>72,000</td>
<td>$3.7 \times 10^5$</td>
</tr>
<tr>
<td>Neon</td>
<td>0.7 y</td>
<td>Ne</td>
<td>O, Mg</td>
<td>1.6</td>
<td>$1.2 \times 10^7$</td>
<td>75,000</td>
<td>$1.4 \times 10^8$</td>
</tr>
<tr>
<td>Oxygen</td>
<td>2.6 y</td>
<td>O, Mg</td>
<td>Si, S, Ar, Ca</td>
<td>1.9</td>
<td>$8.8 \times 10^6$</td>
<td>75,000</td>
<td>$9.1 \times 10^8$</td>
</tr>
<tr>
<td>Silicon</td>
<td>18 d</td>
<td>Si, S, Ar, Ca</td>
<td>Fe, Ni, Cr, Ti</td>
<td>3.3</td>
<td>$4.8 \times 10^7$</td>
<td>75,000</td>
<td>$1.3 \times 10^{11}$</td>
</tr>
<tr>
<td>Iron core collapse$^a$</td>
<td>~1 s</td>
<td>Fe, Ni, Cr, Ti</td>
<td>Neutron Star</td>
<td>&gt; 7.1</td>
<td>$&gt;7.3 \times 10^9$</td>
<td>75,000</td>
<td>$&gt;3.6 \times 10^{15}$</td>
</tr>
</tbody>
</table>

$^a$The presupernova star is defined by the time when the contraction speed anywhere in the iron core reaches 1,000 km s$^{-1}$.  

Teresa Montaruli, Apr. 2006
Collapse

Each cycle requires a higher T for ignition due to the stronger Coulomb repulsion between nuclei. For most stars the process stops when the pressure is not sufficient to heat the core at the necessary T for the next ignition and the stars turns into a white dwarf. The most massive stars can develop an iron core of (iron is the “ground state” of nuclear matter, the most tightly bound of all nuclei and no further nuclear burning is possible). The Fe core is substained by the degenerate pressure of its electrons until it reaches the Chandrasekar mass of $1.4 \, M_{\text{Sun}}$. After this limit the core collapses. photodisintegration (radiation melt down some of the Fe nuclei to He) contribute in reducing pressure:

$$\gamma + ^{56}\text{Fe} \leftrightarrow 13\, \alpha + 4\, n$$

$$\gamma + \alpha \leftrightarrow 2\, p + 2\, n$$
**Collapse**

**Neutronization** follows (time scale of ms): electron capture

\[ e^- + p \rightarrow \nu_e + n \]

About \( 10^{57} \nu_e \) are emitted contributing to the collapse.

The core collapses to a hot n rich sphere of about 30 km in radius (proto-neutron star).

The **short range nuclear force halts the collapse** when the density is about 2 \( \times \) atomic nucleus density \( 4-5 \times 10^{14} \) g/cm\(^3\). Neutrinos remain trapped in the collapsing core and are in thermal equilibrium within the core. The energy is released in thermal processes like *(thermalization)*

* \[ e^+ + e^- \rightarrow \nu_j + \bar{\nu}_j \]*

With an emission of the order of 10 s.

The shock wave produced by the abrupt halt of the collapse and the bounce of the core travels towards the surface of the star. This is the explosion visible in the optical.
**Collapse**

Neutronization follows (time scale of ms): electron capture

\[ e^- + p \rightarrow \nu_e + n \]

About \( 10^{57} \) \( \nu_e \) are emitted contributing to the collapse

**Neutronization burst of \( \nu_e \)**

\[ N_{\nu_e} \approx N_e = N_{\mu} \approx \frac{M_{\text{core}}}{m_p} \]

\[ Y_e \approx 0.9 \times 10^{57} \]

\( Y_e \equiv n_{e^-} - e_{e^+} \) is electron fraction per baryon

The total energy

\[ E_{\text{binding}} = G \frac{M_{\text{core}}^2}{R_f} - G \frac{M_{\text{core}}^2}{R_i} \approx G \frac{M_{\text{core}}^2}{R_f} \approx 3 \times 10^{53} \text{ erg} \]

is accounted for by neutrinos while the ejecta carry only \( 10^{51} \) erg (1%)
Stellar collapse and SN explosion

- **Main Sequence Star**
  - Hydrogen Burning
  - Newborn Neutron Star

- **Red Giant Star**
  - Helium Burning

- **Onion Structure**
  - Hydrogen Burning
  - Explosion
  - H, He, O-Si, Fe

- **Collapse (Implosion)**
  - Degenerate iron core:
    - $\rho \approx 10^3 \text{ g cm}^{-3}$
    - $T \approx 10^{10} \text{ K}$
    - $M_{Fe} \approx 1.5 M_{\odot}$
    - $R_{Fe} \approx 8000 \text{ km}$

- **Gravitational binding energy**
  - $E_b \approx 3 \times 10^{53} \text{ erg} \approx 17\% M_{\odot} c^2$

- **This shows up as**
  - 99% Neutrinos
  - 1% Kinetic energy of explosion
    - (1% of this into cosmic rays)
  - 0.01% Photons, outshine host galaxy

- **Neutrino luminosity**
  - $L_v \approx 3 \times 10^{53} \text{ erg / 3 sec}$
    - $\approx 3 \times 10^{19} L_{\odot}$

- **While it lasts, outshines the entire visible universe**
Classification of SuperNovae

**Type I**
(no H)

**Type Ia**
(no H, strong Si)

**Type Ib**
(no H, obvious He)

**Type Ic**
(no H, He, Si)

**Type II**
(obvious H)

Type II, outer H layer remains at collapse;
Type Ib, outer H layer stripped before collapse;
Type Ic, outer H and He layers stripped before collapse.
### Classification of Supernovae

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Ia</th>
<th>Ib</th>
<th>Ic</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spectrum</strong></td>
<td>No Hydrogen</td>
<td>Silicon</td>
<td>No Silicon</td>
<td>Hydrogen</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Helium</td>
<td>No Helium</td>
<td></td>
</tr>
<tr>
<td><strong>Physical Mechanism</strong></td>
<td>Nuclear explosion of low-mass star</td>
<td>Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Light Curve</strong></td>
<td>Reproducible</td>
<td>Large variations</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Neutrinos</strong></td>
<td>Insignificant</td>
<td>~ 100 × Visible energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Compact Remnant</strong></td>
<td>None</td>
<td>Neutron star (typically appears as pulsar) Sometimes black hole?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate / h^2 SNe</td>
<td>0.36 ± 0.11</td>
<td>0.14 ± 0.07</td>
<td>0.71 ± 0.34</td>
<td>Rate approx. 1 SN / 30 years / galaxy</td>
</tr>
</tbody>
</table>

1 Snu = 1 SN/10^{10} L_{\text{sun,B}}/100 \text{ yrs}
# Type Ia vs. Core-Collapse Supernovae

<table>
<thead>
<tr>
<th>Type Ia</th>
<th>Core collapse (Type II, Ib/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon-oxygen white dwarf (remnant of low-mass star) accretes matter from companion</td>
<td>Degenerate iron core of evolved massive star accretes matter by nuclear burning at its surface</td>
</tr>
</tbody>
</table>

**Chandrasekhar limit is reached**  
\[ M_{\text{Ch}} \approx 1.5 M_{\text{sun}} (2Y_e)^2 \]

**Collapse sets in**

- Nuclear burning of C and O ignites  
  → Nuclear deflagration  
  (“Fusion bomb” triggered by collapse)

- Powered by nuclear binding energy

- Gain of nuclear binding energy  
  \(~ 1\, \text{MeV per nucleon}\)

- Collapse to nuclear density  
  Bounce & shock  
  Implosion \(\rightarrow\) Explosion

- Powered by gravity

- Gain of gravitational binding energy  
  \(~ 100\, \text{MeV per nucleon}\)  
  99% into neutrinos

**Comparable “visible” energy release of** \(~ 3 \times 10^{51}\, \text{erg}~\)}
Some definitions

Definition of Specific intensity
Electromagnetic energy $dE$ passing
Through surface $dA$ and coming
from an angle $\theta$ within a solid angle
$d\Omega$ during time $dt$:

$$dE = I_v(\theta, \phi) \cos \theta dv dA dt d\Omega$$

$$dA' = dA \cos \theta$$

$$I_v = I_v(\theta, \phi)$$

$$[I_v] = W \cdot m^{-2} \cdot sr^{-1} \cdot Hz^{-1}$$

The Intensity (integral)

$$I(Wm^{-2}sr^{-1}) = \int_{\nu_1}^{\nu_2} I_v d\nu$$

Flux density = intensity integrated over the solid angle (of the source) is called:

$$dF_v = I_v \cos \theta d\Omega$$

$$F_v = \int_{\Omega} I_v \cos \theta d\Omega$$

$$[F_v] = W \cdot m^{-2} \cdot Hz^{-1}$$

1 Jansky = 1 Jy = $10^{-26}$ $W \cdot m^{-2} \cdot Hz^{-1}$
Flux and Luminosity

- Flux density at telescope
  \[ F_\nu = \int_{\Omega_{\text{source}}} I_\nu \cos \theta \, d\Omega \approx \int_{\Omega_{\text{source}}} I_\nu \, d\Omega \]
  
  \[ F_\nu = \frac{1}{R^2} \int_{\Omega_{\text{source}}} I_\nu \, dA \]

- Luminosity (isotropic source):
  - differential
    \[ L_\nu = 4\pi R^2 F_\nu \]
  
  - total
    \[ L = 4\pi R^2 \int_0^\infty F_\nu \, dv \]
1. Collapse (infall phase)
2. Shock break out
3. Matter accretion
4. Kelvin-Helmholtz cooling

\[ \phi_{\nu_\alpha} \simeq C \frac{E^2}{e^{E/T_{\nu_\alpha}} + 1} \]

Initial differential neutrino fluxes

\[ E_{\nu_e}^{\text{tot}} = E_{\bar{\nu}_e}^{\text{tot}} = E_{\nu_\mu}^{\text{tot}} = E_{\bar{\nu}_\mu}^{\text{tot}} = E_{\nu_\tau}^{\text{tot}} = E_{\bar{\nu}_\tau}^{\text{tot}} \simeq \frac{E_{\text{binding}}}{6} \]
What determines the time scale?

<table>
<thead>
<tr>
<th>Main neutrino reactions</th>
<th>Electron flavor</th>
<th>Other flavors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu_e + n \rightarrow p + e^-$</td>
<td>$\nu + N \rightarrow N + \nu$</td>
</tr>
<tr>
<td></td>
<td>$\bar{\nu}_e + p \rightarrow n + e^+$</td>
<td>$\nu + N \rightarrow N + \nu$</td>
</tr>
</tbody>
</table>

**Mean free path**

$$\lambda = (\sigma n_B)^{-1} \approx 28 \text{ cm} \left(\frac{100 \text{ MeV}}{E_\nu}\right)^2$$

**Nucleon density**

$$n_B = \frac{\rho_{\text{nuc}}}{m_N} \approx 1.8 \times 10^{38} \text{ cm}^{-3}$$

**Diffusion time**

$$t_{\text{diff}} \approx \frac{R^2}{\lambda} \approx 1.2 \text{ sec} \left(\frac{R}{10 \text{ km}}\right)^2 \left(\frac{E_\nu}{100 \text{ MeV}}\right)^2$$

- $\nu_\mu, \nu_\tau$ only NC so leave with highest $T=8 \text{ MeV}$ and $<E>\sim 25\text{MeV}$
- $\nu_e, \bar{\nu}_e$ also CC hence leave with lower $T=3.5 \text{ MeV}$ and $5 \text{ MeV} \Rightarrow 16 \text{ MeV}$ and $11 \text{ MeV}$. $\nu_e$ have lower energy since the material is n rich and thus they interact more.
SN almost as bright as Galaxies!

SN 1998dh in NGC7541

SN 1994D in NGC 4526

SN 1998S in NGC 3877
The historical SNs

Over the past 2000 yrs we have historical records of AD 185, 1006, 1054 Crab Nebula, 1181, 1572 Tycho’s SN, 1604 Kepler’s SN


Table 1. Summary of the historical supernovae, and the source of their records

<table>
<thead>
<tr>
<th>date</th>
<th>length of visibility</th>
<th>remnant</th>
<th>Historical Records</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Chinese</td>
</tr>
<tr>
<td>AD1604</td>
<td>12 months</td>
<td>G4·5+6·8</td>
<td>few</td>
</tr>
<tr>
<td>AD1572</td>
<td>18 months</td>
<td>G120·1+2·1</td>
<td>few</td>
</tr>
<tr>
<td>AD1181</td>
<td>6 months</td>
<td>3C58</td>
<td>few</td>
</tr>
<tr>
<td>AD1054</td>
<td>21 months</td>
<td>Crab Nebula</td>
<td>many</td>
</tr>
<tr>
<td>AD1006</td>
<td>3 years</td>
<td>SNR327.6+14.6</td>
<td>many</td>
</tr>
<tr>
<td>AD393</td>
<td>8 months</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>AD386?</td>
<td>3 months</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>AD369?</td>
<td>5 months</td>
<td>–</td>
<td>one</td>
</tr>
<tr>
<td>AD185</td>
<td>8 or 20 months</td>
<td>–</td>
<td>one</td>
</tr>
</tbody>
</table>
Supernova 1054 Petrograph

Possible SN 1054 Petrograph by the Anasazi people (Chaco Canyon, South-Western U.S.)

3 concentric circles, diameter ~ 1 foot, with huge red flames trailing to the right.

SN 1054

Halley’s Comet? Crescent Moon?

Crab 2 kpc
Pulsar
Type II
Tycho Brahe 1572

3kpc Type Ia

De Nova et nullius aevi memoria prius visa Stella
SN 1604

4-8 kpc Type II?

Johannes Kepler,
_De Stella Nova in Pede Serpentarii_, (1606)
Cassiopeia A

2.8 kpc, neutron star

John Flamsteed
August 16, 1680
Neutrino Signal of Supernova 1987A

Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty $\pm 1\text{ min}$

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty $\pm 50\text{ ms}$

Baksan Scintillator Telescope
(Soviet Union)
Clock uncertainty $+2/-54\text{ s}$

Within clock uncertainties, signals are contemporaneous
Detection of SN neutrinos

Largest cross section

\[ \bar{\nu}_e + p \rightarrow n + e^+ \]

\[ \sigma_{\bar{\nu}_e p} \sim \frac{G_F^2}{\pi} \left(1 + 3 g^2 \right) E_{\nu}^2 \sim 9.77 \times 10^{-44} \left( \frac{E_{\nu}}{1 \text{ MeV}} \right) \text{ cm}^2 \]

\[ E_e = E_\nu - 1.3 \text{ MeV} \]

\[ \sim 300 \text{ e}^+/\text{kt in water} \]

**H_2O Detectors:**

SK 22.5 kt (fiducial) 31 Apr 96-15 Jul 01: search for \( \nu \) bursts 1704 d \( E_{\text{th}} = 6.5 \) MeV

Expected: 3500 events for 10 kpc SN 12 Msun (2% decrease due to Eth changement in SK-II due to 1/2 PMTs), limit on number of explosions/yr:

0.49 SN/yr (90%c.l.) full efficiency up to 100 kpc in SNEWS

AMANDA II 677 Oms \( V_{\text{eff}}/\text{OM} \sim 400-500 \text{ m}^3 \)

4.3 SN/yr (90%c.l.) in Galaxy (Ahrens et al, 2002): expect 15 fake/yr \( \Rightarrow \) SNEWS bckg < 1/week

SNO 1+1.4 kt (D_2O+H_2O)

**Scintillator detectors**

LVD 1 kt (Jun 92 - Mar 03 - Jan 01 final configuration) 3511 d \( E_{\text{th}} = 4-7 \) MeV

0.2 SN/yr (90%c.l.) in Galaxy, in SNEWS since 98

Expected events from SN at 8.5 kpc 320 (210 in MACRO upper limit 0.27 SN/yr)

Others: Kamland (1 kt), MiniBoone (0.6 kt), Borexino (0.3 kt), ...

expected rate in Galaxy: 2-4 /century
SN1987A
AMANDA as supernova detector
Optical Background and Filtering in ANTARES

Counting rate due to $^{40}$K $\beta$ decay and bacteria bioluminescence. Bursts are due to macro-organism.

All data ($>0.3$ pe) sent to shore 1GB/s
Offline filter: 1 MB/s casualty condition

Teresa Montaruli, Apr. 2006
Ice is an extremely quite environment!

1st IceCube string

- The IceCube optical sensors were optimized for low noise.
- Research on glass material resulted in lower contamination with radioactivity.
- Fewer background photons from the glass.

September 2005 InIce Noise Rates

- The IceCube optical sensors were optimized for low noise.
- Research on glass material resulted in lower contamination with radioactivity.
- Fewer background photons from the glass.
Galactic point Sources
The case of RXJ1713.7-3946

Open problem: elusive $\pi^0$ produced in accelerated nuclei collisions with SN ambient material. Still not a clear evidence BUT…CANGAROO claim

Controversial
Reimer et al., A&A390,2002
Incompatible with EGRET
RXJ1713.7-3946

No cut-off in the HE tail of HESS spectrum favors $\pi^0$ decay scenario respect to the case of em processes
Study of electron density and B can help

No cut-off in the HE tail of HESS spectrum favors $\pi^0$ decay scenario respect to the case of em processes
Study of electron density and B can help
Predictions Galactic sources

Burgio, Bednarek, TM, New Astron. Rev. 49, 2005

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Distance (kpc)</th>
<th>$E_v$ (GeV)</th>
<th>$N_{\nu_e}$ (km$^2$ yr$^{-1}$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supernovae</td>
<td>10</td>
<td>$\sim 10^3$</td>
<td>$\sim 100$</td>
<td>Waxman &amp; Loeb 2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sim 10^2 - 10^8$</td>
<td>$50 - 1000$</td>
<td>Protheroe et al. 1998</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sim 10^5 - 10^8$</td>
<td>$100 - 1000$</td>
<td>Beall &amp; Bednarek 2002</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sim 10 - 10^8$</td>
<td>$\sim 1000$</td>
<td>Nagataki 2004</td>
</tr>
<tr>
<td>Plerions Crab</td>
<td>0.5 – 4.4</td>
<td>$&lt; 10^3 - 10^5$</td>
<td>$\sim 1 - 12$</td>
<td>Guetta &amp; Amatto 2003</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>$\sim 10^3 - 5 \cdot 10^5$</td>
<td>$&lt; 1$</td>
<td>Bednarek 2003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sim 10^3 - 5 \cdot 10^5$</td>
<td>a few</td>
<td>Bednarek &amp; Protheroe 1997</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sim 10^3 - 5 \cdot 10^5$</td>
<td>$&lt; 1$</td>
<td>Bednarek 2003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$10 - 10^6$</td>
<td>$\sim 4 - 14$</td>
<td>Amato et al. 2003</td>
</tr>
<tr>
<td>Shell SNRs</td>
<td>6</td>
<td>$&lt; 10^4$</td>
<td>$\sim 40$</td>
<td>Alvarez-Muñiz &amp; Halzen 2002</td>
</tr>
<tr>
<td>SNR RX J1713.7</td>
<td>8</td>
<td>$&lt; 10^5$</td>
<td>$\sim 140$</td>
<td></td>
</tr>
<tr>
<td>Sgr A East</td>
<td>8</td>
<td>$&lt; 10^5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulsars + Clouds</td>
<td>8</td>
<td>$10^4 - 10^7$</td>
<td>$\sim 2 - 30$</td>
<td>Bednarek 2002</td>
</tr>
<tr>
<td>Galactic Centre</td>
<td>1.7</td>
<td>$&gt; 10^3$</td>
<td>a few</td>
<td>Torres et al. 2004</td>
</tr>
<tr>
<td>Cygnus OB2</td>
<td></td>
<td>$10^4 - 10^7$</td>
<td>$\sim 0.5$</td>
<td>Bednarek 2003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$&lt; 10^3$</td>
<td>$&lt; 4$</td>
<td>Anchordoqui et al. 2003</td>
</tr>
<tr>
<td>Binary systems</td>
<td>2.6</td>
<td>$3 \cdot 10^2 - 10^3$</td>
<td>a few</td>
<td>Anchordoqui et al. 2003</td>
</tr>
<tr>
<td>A0535+26</td>
<td></td>
<td>$3 \cdot 10^2 - 10^3$</td>
<td>a few</td>
<td></td>
</tr>
<tr>
<td>Microquasars</td>
<td>1 – 10</td>
<td>$10^3 - 10^5$</td>
<td>$1 - 300$</td>
<td>Distefano et al. 2002</td>
</tr>
<tr>
<td>Magnetars</td>
<td>3 – 16</td>
<td>$&lt; 10^5$</td>
<td>$1.7 \left(0.1/\Delta \Omega \right) \left(5/d^2\right)$</td>
<td>Zhang et al. 2003</td>
</tr>
</tbody>
</table>
Microquasars

Galactic X-ray binaries with radio relativistic jets: star transferring mass to a compact object (n star or BH). Their structure make them similar to quasars but ~10^6 times smaller. Most have bursting activity (hrs-days)

Persistent: SS433 GX339-4
Neutrinos from $p-\gamma$ interactions (photons from synchr. Emission of electrons accelerated in jet or from accretion disc) Distefano, Waxman et al 2002

Neutrino flux at Earth

\[
\nu_{\mu} \text{ flux to the Earth} \\
\frac{d\nu_{\mu}}{d\Omega} \sim \frac{1}{2} \eta_p f_{\pi} \delta^4 \frac{L_{\text{jet}}}{4\pi D^2} \\
1 \text{ TeV} \lesssim E_{\nu_{\mu}} \lesssim 100 \text{ TeV}
\]

$\eta_p \sim 10\%$: fraction of the jet energy injected as Fermi protons

$L_{\text{jet}}$: kinetic luminosity of the jet

$\delta$: jet Doppler factor $\delta = \frac{1}{\sqrt{1-\beta^2}}$

$D$: source-Earth distance

$\Gamma \sim 1$ : linear size of the blob

From: Distefano, Waxman et al 2002

Microquasars
LS5039
Very Large Array

Source angular size ~ 50 arcsec
Source distance ~ 2.5 kpc
Gamma rays within radius ~ 0.6 pc
Likely to be associated to
3EG J1824-1514
Hard E^{-2} spectrum

107 m² mirrors
Resolution ~ 10 arcmin

Resolution ~ 10 arcmin

Integrated Comptel

Gamma rays within radius ~ 0.6 pc
Likely to be associated to
3EG J1824-1514
Hard E^{-2} spectrum

Source angular size ~ 50 arcsec
Source distance ~ 2.5 kpc
Gamma rays within radius ~ 0.6 pc
Likely to be associated to
3EG J1824-1514
Hard E^{-2} spectrum

Apr. 2006
Absorption by synchrotron cascading.

(1) Gamma ray production close to jet base $z < 10^8$ cm (more absorption, larger flux at low energy)

(2) Gamma ray production far from jet base $z < 10^{13}$ cm
The Galaxy

Halo

Sun

Galactic center

Spiral arms

Galactic plane ~ 1 kpc

8.5 kpc

15 – 20 kpc

1 pc = 3.3 ly

Theoretical hypothesis
Equilibrium between CR, B and ISM.

Propagation

Electromagnetic interactions

- Energy losses
- Diffusion on magnetic field and galactic winds
- Reacceleration

- Decays
- Spallation
- Neutrinos from pp collisions

Teresa Montaruli, Apr. 2006
\( \gamma \) observations

- EGRET observed a diffuse emission 100MeV-10 GeV from Galactic Centre region (300 pc): excess > factor 10 around 1 GeV
- INTEGRAL: resolved 91 point sources. 90% of ‘diffuse’ flux can be due to point sources <100 keV
- Milagro: discovery of TeV emission (astro-ph/0502303) 4.5\( \sigma \) excess from \(|b|<5^\circ \) and \(l\in[40^\circ,100^\circ]\)

Covered pond with 2 layers of PMTs, from relative timing 0.75\(^\circ\) shower direction resolution, gamma-hadron discrimination based on shape of Cherenkov light emitted by showers

\[ \Phi_{\text{Milagro}}(>1\text{TeV})=5.1\times10^{-10} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \]
Steeper than EGRET alone 2.51 ±0.05

\[ 2.61\pm0.07 \]
Extreme Models

Hard nucleus model $E^{-2.4}$

For $E^{-2.4}$ 20 years of ANTARES to have 88% discovery prob

Hard electron model $E^{-2.9}$

\[
\frac{d\phi(E)}{dE} = 4E^{-\gamma}
\]

\[
\gamma = 2.94
\]
Galactic Centre

- High matter density and activity
- Compact radio source Sgr A* possibly associated to black hole $\sim 3 \times 10^6 \, M_{\odot}$ in the center
- Sgr A East SNR

HESS TeV-$\gamma$ spectrum in disagreement with the other experiments Variability? localization? HESS 1 arcmin
High Energy Stereoscopic System

Four 12 m diameter telescopes running since ~ 1yr in Namibia (+1 large) $E_{th} \sim 100$ GeV

Cherenkov light is emitted by showers induced by high-energy gamma rays. This light is very faint - about $10 \gamma s/m^2$ at $E_\gamma=100$ GeV - and the duration of the light flash is only a few nsec. Large mirrors, fast photon detectors and short signal-integration times are required to collect enough light from the shower, with minimal contamination from night-sky background light.

$\gamma$ direction < 0.1°
Neutrinos flux with different constraints

\[ E_{\mu} > 1 \text{TeV} \]
\[ \text{d} \Omega < 0.5^\circ \]

<table>
<thead>
<tr>
<th></th>
<th>ANTARES</th>
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<tr>
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<td>Signal events /year</td>
<td>Bkg events /year</td>
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<td><strong>GC</strong></td>
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<tr>
<td>HESS</td>
<td>2 ( 10^{-2} )</td>
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</tr>
<tr>
<td>HESS+EHECR</td>
<td>5 ( 10^{-2} )</td>
<td>7 ( 10^{-3} )</td>
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<tr>
<td>EGRET+EHECR</td>
<td>2.6</td>
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|                  |         |             |                                      |                                      |
| **RX J1713.7-3946** | 0.16   | 9 \( 10^{-3} \) | 15 yr                               | 0.4 yr                               |
| **PSR B1509-58**  |         |             |                                      |                                      |
| Constantini et al (2005) | 0.95 | 1.8 yr | 3 weeks                           |                                      |
| **HESS**           | 0.11    | 1.1 \( 10^{-2} \) | 22 yr                               | 0.6 yr                               |

\[ \text{d}F/\text{d}E_{\nu\mu+\bar{\nu}\mu} = 1.3 \times 10^{-5} \text{E}^{-2.0} \text{ m}^{-2} \text{ s}^{-1} \text{ GeV}^{-1} \]

\[ \text{d}F/\text{d}E_{\nu\mu+\nu\mu} = 4.1 \times 10^{-3} \text{E}^{-2.22} \text{ m}^{-2} \text{ s}^{-1} \text{ GeV}^{-1} \]
Upper bounds on X-galactic fluxes

Cosmic p accelerators produce CRs, γ’s and ν’s
Ultimate bound of any scenario involving ν and γ production from πs: diffuse extra-galactic γ background \( E^2F_\gamma < 6 \times 10^{-7} \text{ GeV} / \text{cm}^2 \text{ s sr} \) (EGRET)
Measured UHECR flux provides most restrictive limit (Waxman & Bahcall (1999))
- optically thin sources: nucleons from photohadronic interactions escape
- CR flux above the ankle (>3 \( \cdot 10^{18} \text{eV} \)) are extragalactic protons with \( E^{-2} \) spectrum \( \Rightarrow E^2F_\nu < 4.5 \times 10^{-8} \text{ GeV} / (\text{cm}^2 \text{ s sr}) \)

This bound does not apply to harder spectra or optically thick

Mannheim, Protheroe & Rachen (2000): Magnetic fields and uncertainties in photohadronic interactions of protons can largely affect the bound as these effects restrict number of protons able to escape