“Interactions between Cosmic Rays and Molecular Clouds in the vicinity of Supernova Remnants”

IC 443

Puppis A

~GHz Radio  Spitzer 24 μm  Thermal X-rays  Fermi γ-ray contours

Jack Hewitt (NASA/Goddard)
~12 firm SNR identifications in GeV/TeV!

1451 Fermi 1-year sources
121 TeV catalog sources
265 known radio SNRs

Cas A
Young SNR

W51C

W44
Older SNR/MCs

IC 443
Supernovae are grand experiments:
$10^{51}$ ergs injected at a point in the ISM.

- **Particle Accelerators** -
  efficient mechanism (DSA) *but* non-linear

- **Destructively probe nearby clouds** -
  strong shocks: reset chemistry, process dust grains

Wednesday, March 16, 2011
What is the CR yield from SNRs?
how does it vary with... evolution, environment

How do CRs diffuse into the ISM?
study escape / diffusion in dense gas

Extreme Laboratories

Accelerator

Massive Target

Cloud probed by radiative shocks
“Middle Aged” Supernova Remnants interacting with Molecular Clouds
Signatures of SNR/MC Interaction

Prototype: IC 443
- distance = 1.5 kpc
- radius = 7.4 pc
- age ≤ 30,000 yr
- towards Gal. anti-center

- NE fast shock, low density radiative shell
  \( v_S \sim 100 \text{ km/s} \)

- Southern \( \text{H}_2 \) ridge
  \( v_S \sim 100 \text{ km/s} \)

2MASS NIR imaging, Rho et al. (2001)
Signatures of SNR/MC Interaction

Prototype: IC 443

Bright Hα emission reveals radiative shell

Hα bisected by dark clouds seen in CO
Signatures of SNR/MC Interaction

Prototype: IC 443

Flat radio spectrum
\[ \alpha = -0.36 \implies \Gamma = -1.7 \]

Bright radio shell matches both NE, S shocks

W breakout (faint radio) lowers pressure in shell

Interior thermal X-rays
\[ 10^7 \text{ K plasma} \]

Ambient CO (1-0) Lee+ 2008
Radio 90cm ~1 keV X-rays
Signatures of SNR/MC Interaction

Prototype: IC 443

Surrounding dust shell seen with Spitzer 24μm

$T_{\text{dust}} \sim 18-30$ K
(Noriega-Crespo+ 2009)
Signatures of SNR/MC Interaction

Prototype: IC 443

broad molecular lines reveal shock kinematics along Southern ridge

2MASS NIR imaging, Rho et al. (2001)

(van Dishoeck+ 1993)
SNR/MC Interaction Picture

NE FRONT
(2MASS-J, Hα, VS X-RAY)
fast ionizing shocks

INTERACTION REGION
(2MASS-K)
slow, molecular shocks

GIANT MOLECULAR CLOUD

shock breakout into rarified ISM

Troja+ (2006)
**SNR/MC Interaction Picture**

**Typical Molecular Cloud**
- dense clumps, $n \sim 10^3 \text{ cm}^{-3}$
- interclump gas, $n \sim 5$-25 cm$^{-3}$
- interclump pressure $\sim 10^5 \text{ K cm}^{-3}$

$\sim 10^4 \text{ M}_{\odot}$ cloud yields $\sim 1$ O-star

1. Massive progenitor clears vicinity via winds / photo-ionization

2. Type II SNe

3. SNR adiabatically evolves in low density

4. SNR reaches edge of wind bubble / MC. Radiative “snowplow” phase

5. Radiative shell encounters dense clumps. Strong compression ($\sim 10$-100)

(Chevalier 1999)
SNR/MC Line Diagnostics

SNR/MCs have a rich IR/sub-mm spectrum

Must explain mix of IR lines:
molecular $\text{H}_2$
ionized Fe, Ne, Si, S
dust continuum, PAHs

from IR lines (Reach & Rho, 2000)
Spectra: both $H_2$ and ionic lines

Ionic lines spatially separated from $H_2$ along IRS slit

$=>$ multiple shocks
• Two \( \text{H}_2 \) components (warm, hot)
  \( T(\text{H}_2) = 320 \text{ K}, 1150 \text{ K} \)
  \( \text{OPR} = 1.0 \text{ to } 3.0 \)

• \( \text{H}_2 \) fitting with shock models (Le Bourlot 2002)
  \( V_S = 10, 40 \text{ km/s} \)
  \( n_H = 10^5, 10^4 \text{ cm}^{-3} \)
  \( P_S = 1 \times 10^{-6}, 3 \times 10^{-7} \text{ dyne cm}^{-2} \)

over-pressure in warm, dense clumps
SNR/MC Interaction Picture

IC 443 is the exception:
unconfused by Galactic Plane
only 1.5 kpc away

Catalog of SNR/MCs
(Jiang et al. 2009)
• 34 known (24 w/Masers)
• 11 probable
• 20 possible

Radiative signatures:
• IR shock cooling lines
• Broad molecular lines
• OH(1720 MHz) Masers
• Flat radio index
• Interior thermal X-rays
• High energy γ-rays

65/275 Galactic SNRs (~25%)
OH Masers: Signposts of SNR/MCs

- Uniquely trace slow shocks into dense molecular clump in SNRs
  - discovery paper: Frail et al. (1994)
  - pump models: Lockett et al. (1999), Wardle (1999)

- Need line-of-sight geometry to maximize velocity-coherence
  \[ V_{\text{LSR}} \Rightarrow \text{kinematic distance} \]

Diagram of SNR/MC interaction

from Wardle & Yusef-Zadeh (2002)
OH Masers: Signposts of SNR/MCs

- Only 24/265 SNRs have detected OH masers
- Require narrow conditions:
  - dense gas, $n=10^5$ cm$^{-3}$  \[ \Rightarrow \text{MC } \sim 10^{4-5}\ M_{\text{sol}} \]
  - $T_{\text{k}}=50-125\ K$: cooling gas behind shock front
  - $T_{\text{dust}}<75\ K$: intense FIR kills 1720 MHz pumping, inverts 1667/5 MHz
- Projected sizes $\sim 10^{16}\ cm \approx \text{shock width}$
- Zeeman splitting $\Rightarrow$ line-of-sight B $\sim 0.1-5\ mG$
OH Masers: Signposts of SNR/MCs

- Confined to the inner Galaxy, near dense gas:

  Longitude-velocity diagram of CO in Milky Way

- Why target the Maser SNR subset with *Fermi*?
  - Known distance, B-field, radiation field, target mass ($M_{\text{CO}}$)
  - $n \sim 10^5$ cm$^{-3}$ implies large cloud
  - Correlation with EGRET, TeV sources (Hewitt et al. 2009)
OH Masers: Signposts of GeV SNRs

SNRs among most luminous Galactic Fermi sources
$L_{\text{GeV}} \sim 10^{35}$ erg/s

Assume $\pi^0$-decay (Drury et al. 1994)

$$F_\gamma \sim M_{\text{cloud}} d_{\text{kpc}}^{-2} \omega_{\text{CR}}$$

Given $M_{\text{cloud}}$, $d_{\text{kpc}}$ infer CR ionization enhanced $\sim 50$

$$\zeta_{\text{CR}} \approx \omega_{\text{CR}} \zeta_{\text{local}} > 10^{-16} \text{ s}^{-1}$$

Detailed modeling to resolve Hadronic or Leptonic origin

non-detections (eg, Kes69, G16.7) explained by low $[M_{\text{CO}} d^{-2}]$
OH Masers: Signposts of GeV SNRs

\[ \gamma \text{-ray break!} \]
\[ E_{br} \sim 3 \text{ GeV} \]
\[ p_{br} \sim 20 \text{ GeV/c} \]

Clear match with cloud and interaction region.

Suggestive of pion decay

Spectrum requires break from GeV to TeV

*Note: Fermi position now consistent with TeV*
GeV/TeV Emission from SNR/MCs

• Three possibilities:
  • Pulsar Wind Nebula (PWN)
  • Shock interaction bring CRs into contact with cloud
  • Escaping CRs illuminate adjacent cloud
• Also must explain spectral break from GeV to TeV
• **PWN:** often displaced by the reverse shock.

*Disfavored by GeV/Cloud correlation, steep TeV spectrum*
GeV/TeV Emission from SNR/MCs

- **Shock interaction:** Shock comes into physical contact with cloud.

Naively, assume all CRs within SNR come in contact with target mass. (often $<n(H_2)>$ over entire emitting volume). Same spectrum

**Leptonic Model**

- $e/p=1$
- $B=150 \mu G$
- $n_H=100 \text{ cm}^{-3}$
- $W_{CR}=4 \times 10^{48} \text{ ergs}$

**Hadronic Model**

- $e/p=0.02$
- $B=50 \mu G$
- $n_H=100 \text{ cm}^{-3}$
- $W_{CR}=7 \times 10^{49} \text{ ergs}$

Too naive?

Plotted components:
- synchrotron (thick solid)
- bremsstrahlung (dashed)
- neutral pion decay (solid)
- inverse Compton (dotted)
Shock interaction: Crushed-clouds (Uchiyama+ 2010)

Radiative fast shock with strong adiabatic compression ~10-100
re-accelerates existing CRs in interclump gas

\[ \rho_{\text{max}} = 50 \text{ GeV/c} \ (v_S/100 \text{ km/s})^3 \ (B/10 \mu \text{G}) \ (t/10 \text{ kyrs}) \]

No “new” CRs need to explain GeV luminosity!

\( \pi^0 \) secondaries explain flattened radio spectrum

but...

requires \( E_{SN} \sim 5 \times 10^{51} \text{ ergs} \)

cannot reach TeV \( \gamma \)-rays
(compression limited by B field)
• “Dead zone” proposed by Malkov et al. (2010)

• when shock propagates into dense gas:
  CR confinement deteriorates
  Alfven waves heavily damped
  CRs not scattered, escape

• Gives very specific change in particle momentum distribution:
  \( p < p_{br} \) has \( f(p) \propto p^{-s} \)
  \( p > p_{br} \) has \( f(p) \propto p^{-s-1} \)

where

\[
p_{br}/mc \approx 10B_{\mu}^2 T_4^{-0.4} n_0^{-1} n_i^{-1/2}
\]

• “Robust environmental signature of a weakly ionized medium into which the accelerated particles propagate”

• The break momentum is very uncertain!
  But spectral signature is very clear, \( \Delta s = -1 \)

(This is a steady state solution, and it’s not clear that steady-state is reached)
Escaping CRs from an SNR

- Instantaneous spectrum of escaping CRs peaked around $E_{max}$
- Spectral steepening as $B$ decreases, until ~100,000 years
- Dense clouds will prematurely “age” the SNR, but still don’t produce break
- Uniform medium may be appropriate for Type Ia, *not* for real ISM/CSM
• Example: HESS TeV emission in W28
  CO/TeV correlation => $\pi^0$-decay $\gamma$-rays from p-p collisions in molecular cloud

• This is a very dense region of Galactic sources!
• There are 2 Maser SNRs in above figures: W28 and G5.71-0.06
Constraining CR Diffusion

- Typical CR diffusion based on "Galactic average" (Berezinksii et al. 1990)
  \[ D \approx \frac{h^2}{t_{res}} \approx 10^{28} \left( \frac{E}{10 \text{ GeV}} \right)^{\delta} \text{ cm}^2\text{s}^{-1} \]

- Assume W28 accelerated CRs up until radiative phase (Gabici et al. 2010)
  5 PeV / 1 GeV CRs will escape SNR at age of 250 yr / 12,000 yr

- By fitting the flux of CRs in nearby clouds, can determine change in D, accel. efficiency.

Even for \( E_{\text{CR}} \approx 0.3 \ E_{\text{SN}} \)
find \( \chi = 0.06 \)
(for 1-10 TeV CRs)
evidence that CR diffusion is slower in dense medium
Escaping CRs from an SNR

- Escaping CRs from RX J1713.7-3946 (age ~1600 yrs) given different diffusion speeds
  Flux at 1 TeV, assuming 500 TeV escaping after 100 yrs (Casanova et al. 2010)

  “slow” \( D_0 = 10^{26} \text{ cm}^2 \text{ s}^{-1} \)

  \( D_0 \sim 10^{27} \text{ cm}^2 \text{ s}^{-1} \)

  “fast” \( D_0 \sim 10^{28} \text{ cm}^2 \text{ s}^{-1} \)

- Fast diffusion => no signature of “runaway” CRs!

- Cosmic ray diffusion: \( D(E) = D_0 E^\delta \) with \( D_0 \sim 10^{26} \text{ to } 10^{28} \text{ cm}^2 \text{ s}^{-1}, \delta \sim 0.5 \)?

  Assuming “fast” diffusion, \( D_0 = 10^{28} \text{ cm}^2 \text{ s}^{-1} \)

  ~1 GeV break develops in ~10-20 kyrs after acceleration ceases

  Spectral break measures \( \delta \) as \( E^{2-\delta} \)
When do CRs escape the SNR?

- $\tau_{pp} = \left( n_{\text{e}} c k \sigma_{pp} \right)^{-1} \approx 3 \times 10^5 \text{ yr} \left( \frac{n_{H_2}}{100 \text{ cm}^{-3}} \right)^{-1}$

$\Rightarrow$ CRs escape before cooling

for low density medium $\sim 1 \text{ cm}^{-3}$
Puppis A: pre-SNR/MC

- Age ~ 3.7 kyr
- Distance ~ 2 kpc
- Size ~ 30 pc

- increasing density to NE \( n_e \sim 4-8 \text{ cm}^{-3} \)
- X-ray/Dust correlation due to sputtering of grains in X-ray gas (Arendt et al. 2010)

- shock non-radiative except at bright knots
- shocked clumps have interaction age < 2 kyrs
Puppis A: pre-SNR/MC

- 2-year Fermi detection 15$\sigma$
- GeV source is extended, matches X-ray/IR morphology
- Shock has not yet reached MC but does show density gradient.

CO 1-0 Map
(Paron et al. 2005)

Fermi counts map 2-30 GeV
Green X-ray contour
White Radio contour
Puppis A: Non-thermal Modeling

Leptonic model ruled out by 200-400 MeV low energy upper limit

Leptonic

Hadronic

Plotted components:
- synchrotron (thick solid)
- bremsstrahlung (dashed)
- neutral pion decay (solid)
- inverse Compton (dotted)

Gamma = 2.0

E_{break} = 22 GeV
e/p = 0.02
n_H = 4 cm^{-3}
W_{CR} = 8 \times 10^{49} \text{ ergs}

can't fit Fermi spectrum
Comparing IC 443 and Puppis A

- older, interacting with $10^4 \, M_{\text{sol}}$
- $L(0.2-100 \, \text{Gev}) \sim 1 \times 10^{35} \, \text{erg/s}$

- younger, nearby MC
- $L(0.2-100 \, \text{Gev}) \sim 3 \times 10^{33} \, \text{erg/s}$

**different target density, same CR energy** $\Rightarrow$ **CR accel. peaks at <4 kyr?**
LECRs from SNR/MCs

Indriolo et al. (2010)

• $\text{H}_3^+$ directly traces CR ionizations in diffuse gas ($n \sim 300 \text{ cm}^{-3}$)

$$\zeta_2 n(\text{H}_2) = k_e n_e n(\text{H}_3^+)$$

• Sight-lines A, B show enhanced $\zeta_{\text{CR}} \sim 2 \times 10^{15} \text{ s}^{-1}$

• Sight-lines D, C have upper-limits of $\zeta_{\text{CR}} < 5 \times 10^{16} \text{ s}^{-1}$
  Other sight-lines have from within the SNR

but lie outside nearby MC

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Red: Optical (DSS)
Green: CO (Lee et al. 2010, in prep.)
Yellow: VERITAS significance (4, 6)
• Masers require $N_{\text{OH}} = 10^{16-17} \text{ cm}^{-2}$
  but in slow, dense C-type shocks,
  all OH converted to H$_2$O (Kaufman & Neufeld 1996)

Figure from Wardle 1999, ApJ 525L,

• Solution: dissociate $\sim$few% of post-shock H$_2$O into OH (Wardle 1999)
  indirect ionization could be from X-rays, CRs... maybe weak shock UV lines

for $T > 400$ K

\[
\begin{align*}
  O + H_2 &\rightarrow OH + H, \\
  OH + H_2 &\rightarrow H_2O + H
\end{align*}
\]
Summary for SNR/MCs

• Some CR acceleration is likely required of SNRs, but not clear it’s 10% $E_{SN}$

• Spectral break from GeV to TeV is probably due to shock into neutral medium

• $E >$TeV cosmic rays must have escaped if they were accelerated, but whether we see them is dependent on cloud geometry.

• All models appear testable with knowledge of shocks, magnetic field and CR diffusion.