Radiative Shocks in SNRs and Supernovae

John Raymond

Cygnus Loop
GALEX NUV
Radiative Shocks in SNRs and Supernovae

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Instabilities

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GALEX NUV
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Instabilities
Dust

Cygnus Loop
GALEX NUV
Non-radiative Shocks

t_{COOL} >> t_{DYN}  ----  Do not radiate a significant fraction of E
X-ray, Balmer line filaments
Collisionless

Log T

ionization  cooling

r_L or c/ω_{pi}  \sim 10^8 \text{ cm}
<< \text{mfp}  \sim 10^{14} \text{ cm}

T_e < T_p < T_i  \text{ for } V > 500 \text{ km/s}
Cosmic Rays
Radiative Shocks

- Ionizing photons
- Compressed B and CR

- $V = 150$ km/s
- $n = 2$ cm$^{-3}$
- $B = 10$ $\mu$G
Radiative Shocks

Ionizing photons

Compressed B and CR

$V = 150 \ \text{km/s}$
$n = 2 \ \text{cm}^{-3}$
$B = 10 \ \mu\text{G}$
Scaling

\[ E_{\text{DISS}} \sim \frac{1}{2} \rho_0 \, v_S^3 \, \text{erg/(cm}^2 \text{s)} \]

\[ T \sim 140,000 \, V_{100}^2 \]

\[ I_{\text{H}\alpha} \sim n_0 \, v_S^3 / \cos \theta \]

\[ I_{\text{[O\ III]\ II}} \sim n_0 \, V_S / \cos \theta \quad 100 - 200 \text{ km/s} \]

\[ L_{\text{COOL}} \sim \frac{1}{4} \, V_S \, t_{\text{COOL}} \sim V_S \, T / n \Lambda \sim V_S \, \alpha / n_0 \]

\[ T \sim N_H \sim n_0 \, t_{\text{COOL}} \quad \text{---- independent of } n_0 \]

\[ X_{\text{MAX}} \sim (\rho_0 \, V_S^2 / (B_0^2/8\pi))^{1/2} \quad n_{10,000} \sim n_0 \, X_{\text{MAX}} \]
Spectrum

N49:
Optical  -  Dopita et al. 2016
UV       -  Vancura et al. 1993

Optical
Dominated by [ ] lines
Balmer lines

UV
Dominated by resonance lines,
] lines, 2-γ continuum
Photoionization Precursor

Cygnus Loop Hα -- Szentgyorgyi et al.

N49 Echelle – Vancura et al.
Dust Created in Supernovae

G54.1+0.3

Temim et al.
Dust Destruction: Non-Radiative Shocks

Sputtering

RCW 86

B. Williams et al.
Dust Destruction: Sputtering

Thermal Sputtering: protons and $\alpha$ particles at $V_{\text{THERM}}$

Nonthermal Sputtering:

Plasma moves at $V_s/4$, but grains initially at $V_s$
Betatron acceleration

350 km/s shock
30 C IV 1550 photons per sputtered C atom
Thermal+nonthermal
Slavin et al. trajectories: tight coupling, multiple reflections, decoupling & trapping, decoupling & escape
Fraction Returned to Gas Phase

Close to half of pre-shock C is gas phase or PAH

Slavin et al. 2015
N49, \( V \sim 250 \text{ km/s} \)

Fe III – VI depleted by 10x
Fe II depleted by < 2x

Grain-grain collisions

Dopita et al. 2016

Cygnus Loop, \( V \sim 150 \text{ km/s} \)

Refractories depleted by 2x

Sputtering

Sankrit et al. 2014
Sublimation Due to Radiative Heating

Comet C/2011 W3 (Lovejoy)

Seconds at 2 $R_{\text{SUN}}$

Hour at 10 $R_{\text{SUN}}$
Instabilities

Cygnus Loop
HST

Note the different morphologies!
Instabilities: Thin Shell

AKA Vishniac Instability

Sets in after cooling
-- not during Sedov phase

Growth time \( \sim \) sound crossing time
\( h/V_{\text{Sound}} \) or \( h/V_{\text{Fast}} \)

Magnetic pressure increases \( h \sim V_{\text{Fast}}^2 \)

Vishniac 1983
Instabilities: Richtmyer-Meshkov

Basically Rayleigh-Taylor

Cloud-shock interaction

Contact Discontinuity

Accelerating shock

Growth time $\sim t_{cc} / (k \ r_c)^{1/2}$

Patnaude et al. 2002
Instabilities: Kelvin-Helmholtz

Shear

Limited by B field amplification

Growth time $\sim t_{cc} / k r_c$

S. Li et al 2014
Instabilities: Thermal

Thermal (Classic Field idea)

\[ V > 150 \text{ km/s} \quad (d\Lambda(T)/dT \text{ negative}) \]

\[ t_{\text{COOL}} < t_{\text{SOUND}} \]

Region cools at constant \( n \), then collapses, change \( V_s \)

\[ t_{\text{GROWTH}} \sim \text{several } t_{\text{COOL}} \]

Innes et al. 1987
Instabilities: Thermal

Cushioned by B

E conservation

More emission from high and low T

Velocity structure

Average spectrum affected at ~2 level

3D -- Bertschinger

Innes 1992
Clumpy ISM

Kolmogorov Spectrum of $n_0$

$n_0 V_s^2 \sim \text{constant}$

Vorticity

Shimoda et al. 2015
Photoionized radiative shocks

Compress gas and increase emissivity

Crab ejecta shocked by PWN

Sankrit et al. 1998
Radiative Shocks in Ejecta

Extremely rapid cooling

$T_e$ from balance of $\Lambda$ and Coulomb heating

Extreme thermal instability

Thermal Conduction

HST
Radio, X-rays, γ-rays

Compression (van der Laan)
Reacceleration

Lee et al. 2015

(a) Evolution of Broadband Spectrum

(b) Evolution of Integrated Flux

Straka et al. 1986
Cygnus Loop
Radiative Shocks in Supernovae

Type IIIn CSM shocks
SN2014C evolved from Ib to IIln (Milisavljevic et al.)
Basic scalings from SNR shocks to Nova and Supernova shocks apply.

Same instabilities should occur, but ambient medium and explosion asymmetry may be much different.

Knots in HR Del, etc. from instabilities or ejecta?

High density suppresses [ ] lines at high density. SN and Nova shocks may be optically thick in radio.

High $V_s$ and SSS imply photoionization may dominate UV and optical.