Nonthermal Electron Evolution in Supernova Remnants

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Abstract: We use a simple formalism to describe the acceleration and evolution of electrons in supernova remnants (SNRs). The variation in the rate of electron injection and radiative cooling can create an inflection in the electron distribution between cooled and uncooled particles. However, the inclusion of adiabatic cooling smears out this inflection. We apply this model to the SNR RX J1713.7-3946 and find we can fit it if we include inhomogeneous emission from numerous smaller knots.

MODEL

SNR Dynamics

SNR dynamics governed by conservation of Energy:

$$E = \frac{1}{2}M_0 v_0^2 = \frac{1}{2}\left[M_0 + \frac{4\pi}{3} m_p n_{CSM} r(t)^3\right] v^2(t)$$

Swept up power is:

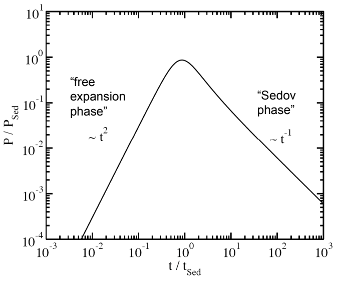
$$\frac{dE}{dt} = 2\pi r^2 n_{CSM} m_p v^3 \ .$$

This power peaks when swept up matter is equal to the matter in the initial blast, at the *Sedov radius*:

$$r_s \equiv \left[\frac{3M_0}{4\pi m_p n_{CSM}}\right]^{1/3}$$

And *Sedov time*:

$$t_s \equiv \frac{r_s}{v_0}$$



Above: SNR swept up power, as a function of time.

Electron Acceleration

Assume injected particles are equal to a constant fraction (η) of SNR swept up power:

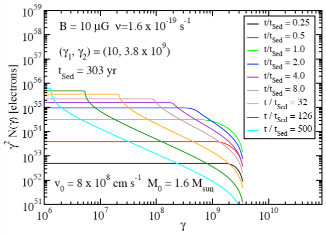
$$mc^2 \int_{\gamma_1}^{\gamma_2} d\gamma\ \gamma\ Q(\gamma, t) = \eta 2\pi r^2 n_{CSM} m_p v^3 \ ,$$

Electron Evolution

Electron distribution evolution is governed by the continuity equation:

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial \gamma}[\dot{\gamma}\ N(\gamma;t)] + \frac{N(\gamma;t)}{t_{esc}(\gamma,t)} = Q(\gamma,t)$$

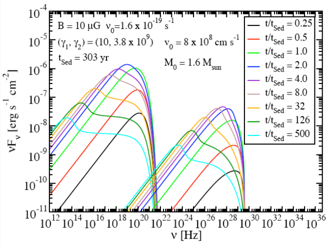
Radiative Cooling Only



Left: Electron Evolution for power-law injection with $Q_e(\gamma, t) \sim \gamma^{-2}$. Cooling is only due to synchrotron and Compton-scattering the cosmic microwave background (CMB) and the cooling rate has the form

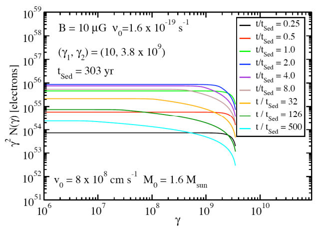
$$-\dot{\gamma} = \nu\ \gamma^2$$

Notice the inflection at the cooling break for t > t$_s$, due to the decrease in the electron injection rate.



The inflection can be visible in the observed spectral energy distribution (SED) particularly at late times. The figure *left* shows the synchrotron and Compton-scattered CMB resulting from the above electron distribution.

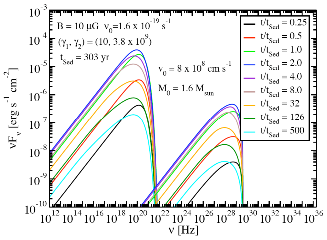
Radiative and Adiabatic Cooling



The figure *left* shows the electron distribution evolution using the same parameters as above, but including adiabatic cooling, so that the cooling rate is

$$-\dot{\gamma} = \nu\ \gamma^2 + \frac{\gamma}{t}$$

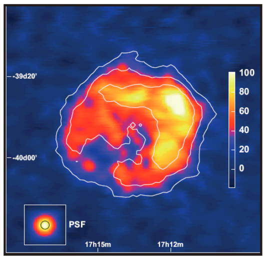
In general, the adiabatic term will dominate. This cooling eliminates the inflection at the cooling break seen in the case where adiabatic losses are neglected.

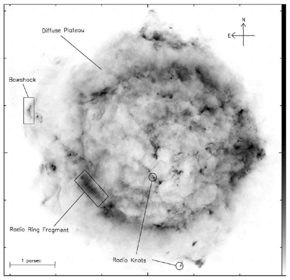


Left: The synchrotron and Compton-scattered spectra for the electron distribution solved without adiabatic losses.

APPLICATION TO RX J1713.7-4946

The SNR RX J1713.7-4946 is the result of a supernova observed by Chinese astronomers in 393 C.E. (Wang et al. 1997), and has a distance of about 1 kpc (Fukui et al. 2003). It has been resolved in X-rays (Uchiyama et al. 2007, Tanaka et al. 2008), TeV gamma-rays (Aharonian et al. 2004, 2006, 2007), and GeV gamma-rays (Abdo et al. 2011).

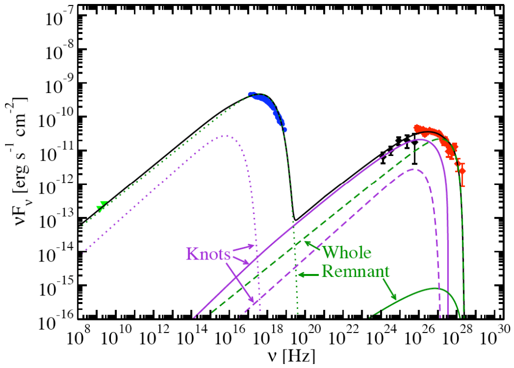




Above: TeV image of RX J1713.7-4946 by H.E.S.S. (Aharonian et al. 2006). *Right:* 4.8 GHz VLA image of the young SNR Cas A (Atoyan et al. 2000). Notice the knotty structure. No such images of RX J1713.7-4946 exist due to its radio faintness and low latitude.

Model Fit

We attempted to fit the SED of RX J1713.7-4946 with our leptonic model (green curve), given the remnant's age, size, and distance. The fit does a poor job of fitting the LAT gamma-rays. It has been observed, though, that there are inhomogeneous knots in this SNR (Uchiyama et al. 2007). These knots could be the origin of the GeV emission from this source. We add a synchrotron/synchrotron self-Compton (SSC) component from these smaller knots (violet curve) to show that this is plausible that the total (black curve) can reproduce all of the data.
Below: SED of RX J1713.7-4946 with model fits.



Curves above are model fit and components:
Black solid curve: Total
Dotted curves: synchrotron
Dashed curves: Compton-scattered CMB
Solid curves: SSC

Symbols above are data:
Green inverted triangles: ATCA upper limits (Aharonian et al. 2006)
Blue circles: *Suzaku* data (Tanaka et al. 2008)
Black diamonds: *Fermi*-LAT data (Abdo et al. 2011)
Red diamonds: HESS data (Aharonian et al. 2007)

SNR Shell parameters

Parameter	Value
q	2.1
γ_{min}	10
γ_{max}	2.5 x 10^8
η	2. x 10^{-5}
B	12 μG
E	1.4 x 10^{51} erg s^{-1}
M_0	1.2 M_{sun}
n_{CSM}	0.2 cm^{-3}
R	7 pc

Knot Parameters

Parameter	Value
q	2
γ_{min}	10
γ_{peak}	10^7
γ_{max}	2.5 x 10^8
N_{knots}	100
B	10 μG
R	0.01 pc

Conclusions:
The model presented here successfully fits the SED of RX J1713.7-4946, but makes a number of simplifying assumptions. It assumes a constant circumstellar medium density, a constant power-law injection index, which in reality would be related to the time-dependent compression ratio. It also neglects nonlinear acceleration effects and hadronic emission. If SNRs are the source of cosmic rays, hadronic emission could be an important gamma-ray source in older remnants, when the electrons have had time to lose a substantial amount of their energy. However, the model presented here may be a good representation of younger remnants, where leptonic emission can be dominant.

References:

Abdo, A. A., et al., 2011, ApJ, in press, arXiv:1103.5727
Aharonian, F. A. et al. 2004, Nature, 432, 75
Aharonian, F. A. et al. 2006, A&A, 449, 223
Aharonian, F. A. et al. 2007, A&A, 464, 235
Atoyan, A.M., Aharonian, F.A., Tuffs, R.J., & Voelk, H.J., 2000, A&A, 355, 211,
Fukui, Y. et al., 2003, PASJ, 55, L61
Tanaka, T., et al. 2008, ApJ, 685, 988
Uchiyama, Y., Aharonian, F. A., Tanaka, T., Takahashi, T., & Maeda, Y., 2007, Nature, 449, 576

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