CRs PRODUCTION AND γ-RAY EMISSION FROM *TYCHO*'s SUPERNOVA REMNANT

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SUMMARY: We apply the non-linear diffusive shock acceleration theory (NLDSA) in order to describe the properties of *Tycho*'s SNR (G120.1+1.4). Analyzing the multi-wavelength spectrum, from radio up to TeV, we conclude that Tycho is accelerating protons up to ~400 TeV, converting a fraction of ~12% of its kinetic energy into cosmic rays.

ABSTRACT

The NLDSA theory applied to SNR shocks allows us to take into account self-consistently the dynamical reaction of the accelerated particles, the generation of magnetic field in the shock proximity and the dynamical reaction of the magnetic field on the plasma. For Tycho we find that the strength of the magnetic field obtained as a result of streaming instability induced by cosmic rays well accounts for the the X-ray emitting filaments being produced by strong synchrotron losses in a ~300μG magnetic field. In such a strong magnetic field the velocity of scattering center in the upstream region can be enhanced and, as a consequence, the accelerated particles feel an effective compression factor less than 4, resulting into a steeper energy spectrum with respect to the standard prediction, n(E)$\propto$ E^{-2}. Taking into account the speed of magnetic turbulence, we consistently predict the observed gamma-ray spectrum, from the GeV band observed by *Fermi-LAT* up to the TeV band observed by *VERITAS*, as due to π^0 decay produced in hadronic collisions of a population of accelerated ions with a slope ~2.2. Remarkably the same model predict a relativistic electron population whose synchrotron emission well explain both the radio spectrum, as well as the non-thermal X-ray emission. Moreover we show that the combined analysis of radio and X-ray provides independent evidence that magnetic field downstream has to be amplified up to hundreds of μG.

MODEL FOR REMNANT EVOLUTION

In this work we use the stationary version of NLDSA theory, but we couple this theory to the hydrodynamical evolution of the remnant following Truelove & Mc Kee (1999). We divide the remnant evolution in several time steps and we assume that for each time step the stationary theory can be applied. Tycho is the remnant of a type Ia SN, hence we consider a SN explosion energy E_{SN} = 10^{51} erg, an ejecta mass M_{ej} = 1 M_{Sol} and a structure function of the ejecta $(v/v_{ej})^{-7}$. We assume that the remnant expands in a homogeneous medium with density ρ_0 = 0.3 protons/cm^3 and temperature T_0 = 10^4 K. With these parameter Tycho is at the end of the free expansion phase, hence the forward shock radius and velocity can be described as:

$$R_{sh}(t) = 4.06\left(\frac{t}{T_{ST}}\right)^{4/7} pc \qquad V_{sh}(t) = 4875\left(\frac{t}{T_{ST}}\right)^{-3/7} km/s$$

Time evolution of radius and velocity of forward shock.

With T_{ST} = 463 yr and the current age of the remnant being 439 yr. These parameters give a distance from the Earth d = 3.3 kpc, roughly consistent with all existing estimates and a shock speed V_{sh} = 4990 km/s also consistent with proper motion measurements in X-ray and radio.

PARTICLE ACCELERATION

On top of the SNR evolution the spectrum of accelerated particles is calculated according to the semi-analytic kinetic formalism put forward in Caprioli, Amato & Blasi (2010) which solves self-consistently the equations for conservation of mass, momentum and energy along with the diffusion-convection equation describing the transport of non-thermal particles for quasi-parallel, non-relativistic shocks. In particular, we impose the CR distribution function to vanish at a distance ~$\chi_{esc} R_{sh}$ upstream of the shock, mimicking the presence of a free-escaping boundary beyond which highest-energy particles cannot diffuse back at the shock and get lost in the interstellar medium:

$$\frac{D(p_{max})}{V_{sh}} \simeq \chi_{esc} R_{sh} = 0.1\, R_{sh}$$

Prescription to determine the instantaneous maximum momentum

A simple analytical way to account for magnetic field amplification due to resonant streaming instability in CR modified shocks has been put forward in Caprioli et al. (2009), so that in the limit M_0>>1, M_A>>1 the solution for the wave transport equation reads:

$$P_w(x) = \frac{B^2(x)}{8\pi\rho_0 V_{sh}^2} = U(x)^{-3/2}\frac{1+U(x)}{4M_A(x)}P_{cr}(x)$$

Magnetic pressure induced by resonant streaming instability

We consider the Alfvén speed computed in the amplified magnetic field:

$$v_A(x) = \frac{\delta B(x)}{\sqrt{4\pi\rho(x)}}$$

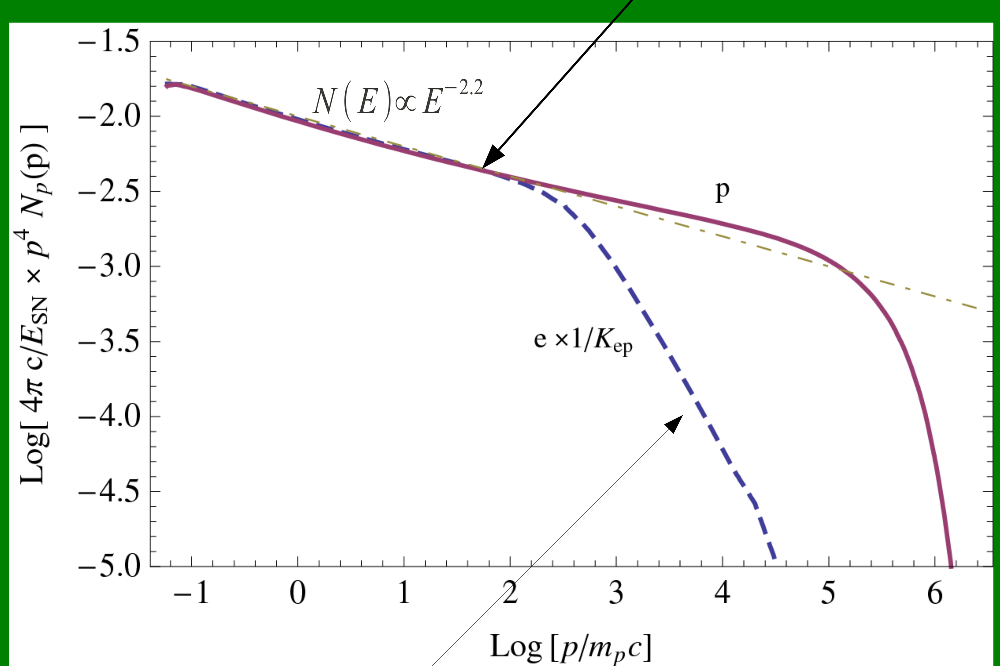
Alfvén speed in the amplified magnetic field

The Alfvén speed is not negligible with respect to the shock speed, hence the effective compression ratio felt by particles is smaller than the typical strong shock value 4:

$$r_{subshock}(x) = \frac{u_1 - v_{A,1}}{u_2 + v_{A,2}}$$

Effective compression ratio felt by particles at the sub-shock

This produce particle distribution function with a spectrum steeper than E^{-2}



Total spectrum of protons and electrons (divided by K_{ep}) at the present age of the remnant, as a function of the particle momentum.

The electron spectrum is computed taking into account losses due to synchrotron emission, inverse Compton scattering and adiabatic expansion of the remnant.

$$f_e(p) = K_{ep} f_{p,0}(p)\left[1+0.523\left(\frac{p}{p_{e,max}}\right)^{9/4}\right]^2 e^{-(p/p_{e,max})^2}$$

Electron spectrum at the shock (Zirakashvili & Aharonian 2007).

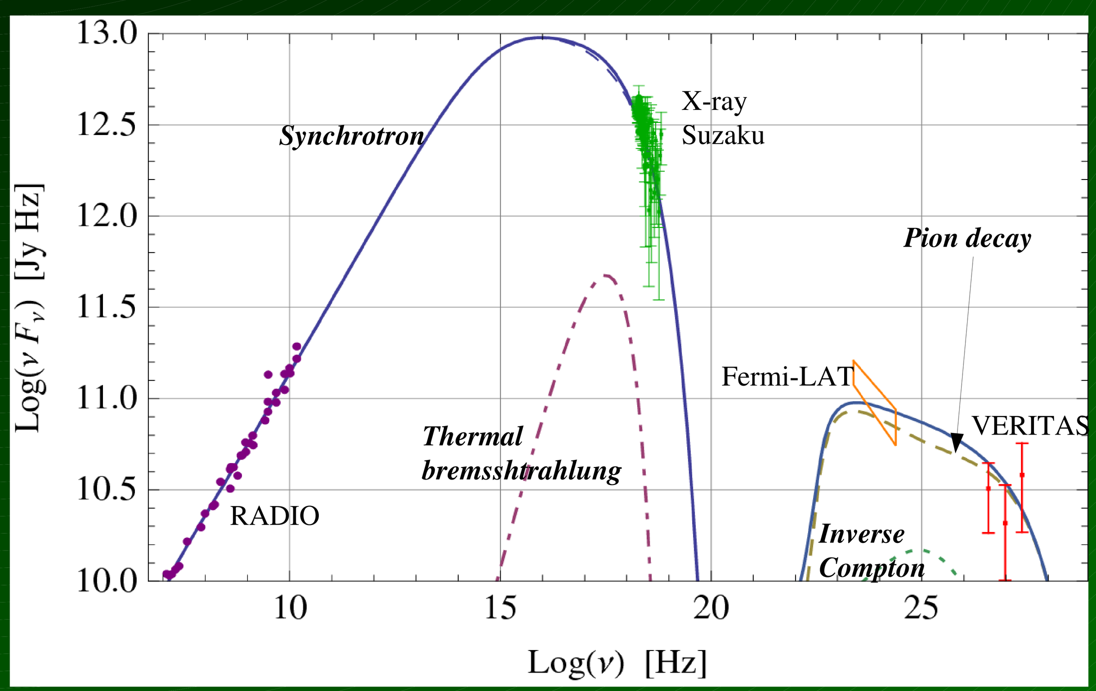
MULTIWAVELENGTH SPECTRUM

Remarkably we are able to fit all the observed non-thermal spectrum using only three free parameters. Two of them are related to the unknown processes which regulate the injection of protons and electrons into the shock acceleration mechanism, while the third one is the density of the circumstellar medium where the remnant expands (we adopt n_0 = 0.3 cm^{-3}).

In our best fit model CR-streamig instability amplify the magnetic field upstream of the shock from the unperturbed Galactic value of ~5μG up to ~90μG, which becomes ~300μG immediately downstream of the shock because of the compression. Such a large magnetic field has two direct consequences:

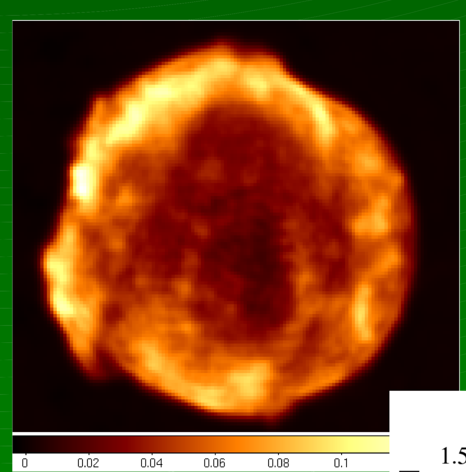
1) it produces narrow X-ray laments because of the rapid synchrotron losses of electrons;

2) it determines the roll-over frequency of synchrotron spectrum (~4 eV) which allow to fit simultaneously radio and X-ray emission.



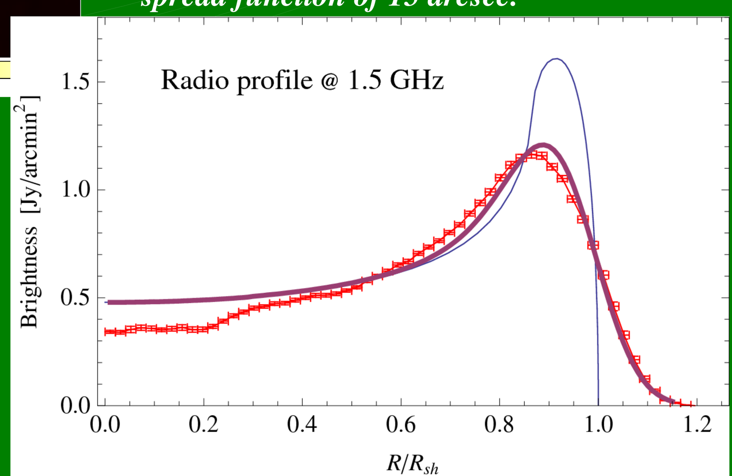
RADIAL PROFILE of RADIO EMISSION

The radial profile of both radio and X-ray emissions provides a strong evidence that the magnetic field inside the SNR is considerably amplified.



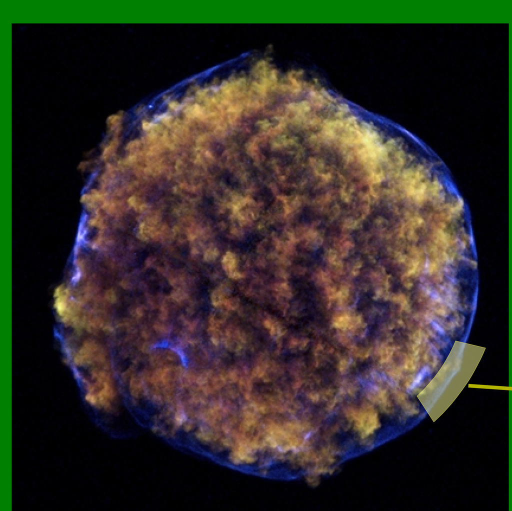
VLA image at 1.5 GHz, (data from the NRAO/VLA Archive - January 2007)

Surface brightness of radio emission at 1.5 GHz as a function of the radius. The thin solid line is the projected radial profile computed from our model while the thick solid line shows the same profile convoluted with a Gaussian with a point spread function of 15 arcsec.

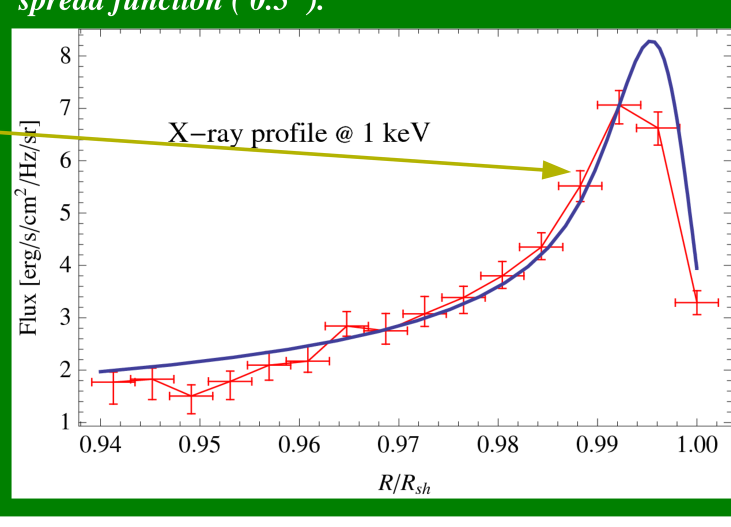


X-RAY FILAMENTS

The large magnetic field produced by CR-streaming instability, B~300 μG, well explains the sharp X-ray filaments observed by *Chandra*: energetic electrons suffer of strong synchrotron losses and produces a sharp decrease of the X-ray emission.

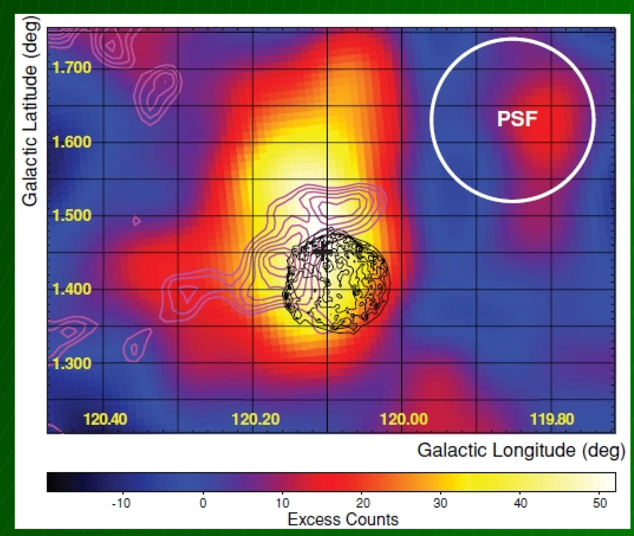


Projected X-ray emission at 1 keV compared with the Chandra data points (Cassam-Chenai et al., 2007). The solid line shows the projected radial profile of synchrotron emission convolved with the Chandra point spread function (0.5'').



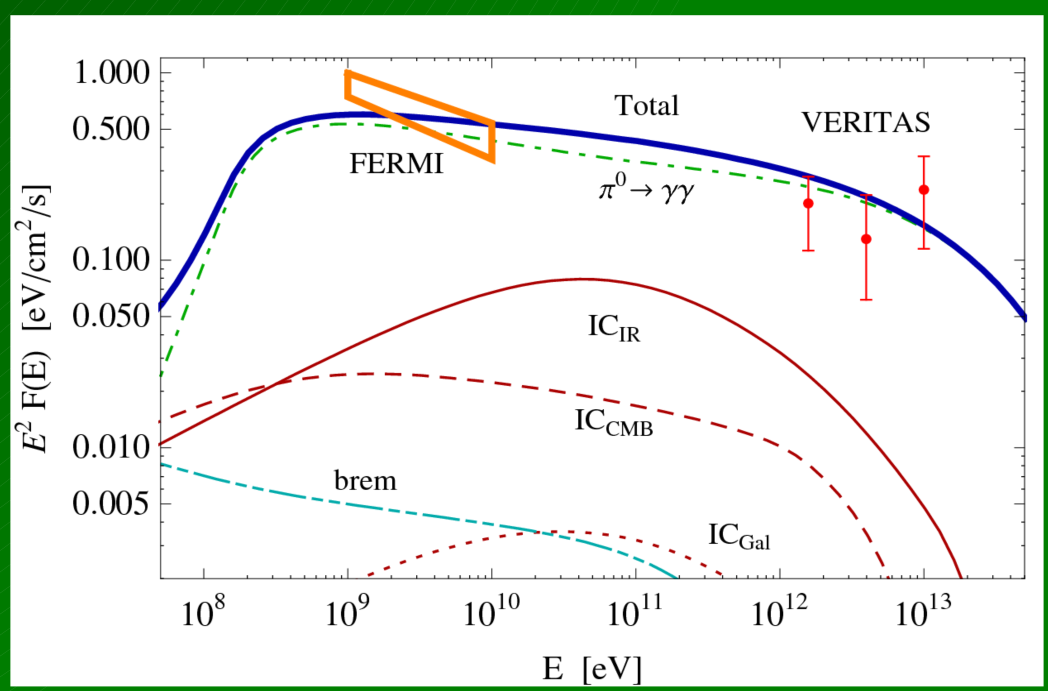
γ-RAY EMISSION

The most intriguing aspect of Tycho's broadband spectrum is its γ-ray emission, which has been detected in the last year both in the TeV band by VERITAS and in the GeV band by Fermi-LAT.



Tycho's SNR seen by VERITAS (Acciari et al. 2011) compared with X-ray contours by Chandra (black thin lines) and ^{12}CO emission (Heyer at al. 1998).

We show here, with unprecedented clarity, that the γ-ray emission detected from Tycho cannot be of leptonic origin, therefore representing the first convincing evidence that also protons can be accelerated in SNRs, at least up to energies of few hundreds of TeV. In fact the predicted proton spectrum of Tycho has E_{max} = 470 TeV.



Pion decay produced in hadronic collision between accelerated ions and gas nuclei, is the dominant process in the γ-ray band. The contribution due to the ICS of relativistic electrons is marginal. The reason is that the strong magnetic field produced by the CR-streaming instability imply a small number density of relativistic electrons (the electron to proton ratio is K_{ep} = 1.6x10^{-3}) otherwise the synchrotron X-ray emission would exceed the observations.

Even if we arbitrary reduce the value of the magnetic field strength, enhancing at the same time the electron number density in such a way that ICS dominates the TeV emission, for energy lower than 1 TeV the ICS spectrum is $E^{-1.6}$. Hence ICS cannot explain the GeV emission because both the spectral slope and the flux are incompatible with Fermi-LAT observations. The non-thermal bremsstrahlung is also ruled out: in our best fit model it produces a flux two order of magnitude lower than the Fermi-LAT detection, and cannot be arbitrary enhanced up to the detected flux without overpredict both the TeV and the X-ray emission.

The impossibility of fitting the gamma-ray spectrum with leptonic processes is strengthened by the fact that large magnetic field value is required also to fit the radio and X-ray emission.

In this work we also showed, for the first time, that the main contribution to the ICS is due to the IR photons produced by circumstellar dust heated by the shocked plasma (curve labeled with IC_{IR} in the above plot), which dominates on the CMB and Galactic photon background. This contribution, which is generally neglected, can be relevant also for other SNRs especially those produced by type Ia SNe.

Spitzer observation of Tycho at 24 μm. Emission due to dust heated by shocked gas up to ~100 K