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Acceleration of cosmic rays in Tycho's SNR

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Abstract. We apply the non-linear diffusive shock acceleration theory in order to describe the properties of SN 1572 (G120.1+1.4, hereafter simply Tycho). By analyzing its multi-wavelength spectrum, we show how Tycho's forward shock (FS) is accelerating protons up to ~ 500 TeV, channeling into cosmic rays more than 10 per cent of its kinetic energy. We find that the streaming instability induced by cosmic rays is consistent with all the observational evidences indicating a very efficient magnetic field amplification (up to ~ 300μG), in particular the X-ray morphology of the remnant. We are able to explain the gamma-ray spectrum from the GeV up to the TeV band, recently measured respectively by Fermi-LAT and VERITAS, as due to pion decay produced in nuclear collisions by accelerated nuclei scattering against the background gas. We also show that emission due to the accelerated electrons does not play a relevant role in the observed gamma-ray spectrum.

Key words. SNRs: Tycho – acceleration of particles – cosmic rays – gamma-rays

1. Introduction

The detection of high energy gamma-rays from supernova remnants (SNRs) has long been considered as the most promising tool to probe the so-called *supernova paradigm* for the origin of Galactic cosmic rays (CRs) (see e.g. Drury et al. 1994).

In the last few years several SNRs have been detected in gamma-rays, both in the GeV and in the TeV band but, in spite of this larger and larger amount of data, a clear-cut evidence that such an emission is due to the decay of neutral pions produced in nuclear interactions between accelerated nuclei and the background plasma is still lacking. The reason is that also processes involving relativistic electrons (*leptonic scenario*) may provide a similar gamma-ray signature (see e.g. Ellison et al. 2007, for a general discussion on this topic). A possible way to discriminate between *leptonic* and *hadronic* scenario is investigating the effects that particle acceleration produces at all observable wavelengths and not only in the gamma-ray band, simultaneously using multiple set of data to constraint the model. The Tycho's remnant, freshly detected in gamma-ray by Fermi-LAT (Giordano et al. 2011) and VERITAS (Acciari et al. 2011), can be considered one of the most promising object where to test the shock acceleration theory and hence the CR–SNR connection, thanks to the large amount of data available also at others wave bands.

In this work we apply the non-linear diffusive shock acceleration (NLDSA) theory to the Tycho's SNR following the semi-analytical approach put forward by Amato & Blasi (2005, 2006); Caprioli et al. (2010b,a) and references

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therein. The NLDSA theory is coupled to the remnant evolution in order to derive its radiative properties at the present time. We compare the results of our kinetic model with the multi-wavelength integrated spectrum of Tycho from the radio to the TeV range, and also with the radial profile of X-ray and radio emissions. For a detailed description of the model and results please refer to Morlino & Caprioli (2011).

2. Description of the model

Recent observations of scattered-light echo have confirmed that Tycho is the remnant of a Type Ia SN exploded in 1572 (Krause et al. 2008), hence we model its evolution by following the analytic prescriptions given by Truelove & Mc Kee (1999) for Type Ia SNR. More precisely, we consider a SN explosion energy $E_{SN} = 10^{51}$ erg and one solar mass in the ejecta, whose structure function is taken as $\propto (v/v_{ej})^{-7}$. Following the conclusion of Tian & Leahy (2011), we assume that the remnant does not interact with any molecular clouds but expands into the uniform interstellar medium (ISM) with proton number density n_0 (which we left as a free parameter) and temperature $T_0 = 10^4$ K (which is constrained by the presence of neutral hydrogen). The radial structure of density and temperature profiles is then calculated by assuming that the shocked ISM is roughly in pressure equilibrium.

On top of this SNR evolution, the spectrum of accelerated particles is calculated according to the semi-analytic kinetic formalism put forward in Caprioli et al. (2010b) and references therein, 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. The injection is regulated by a free parameter, $\xi_{\rm inj}$, in such a way that all particles from the thermal plasma with momentum $p > \xi_{\rm inj} p_{th,2}$, with $p_{th,2}$ the typical thermal momentum downstream, start the acceleration process.

A crucial role in our model is played by the magnetic field amplification induced by the super-Alfvénic streaming of relativistic particles upstream of the shock. We model this *resonant* magnetic amplification as in Caprioli et al. (2009), by assuming that saturation is achieved when $P_w \simeq P_{cr}/2M_A$, where P_w and P_{cr} are the pressure in Alfvén waves and in CRs, respectively, and M_A is the Alfvénic Mach number. The large magnetic fields predicted by the resonant amplification have two main consequences: 1) the magnetic pressure upstream becomes comparable to, or even larger than, the thermal plasma pressure and, reducing the compressibility of the plasma, affects the prediction for the shock compression factor. 2) When the magnetic field is amplified the velocity of the scattering centers, which is generally neglected with respect to the shock speed, could be significantly enhanced (Vladimirov et al. 2006; Caprioli et al. 2009). When this occurs, the total compression factor felt by accelerated particles may be appreciably reduced and, in turn, the spectra of accelerated particles may be considerably softer. We explicitly include this effects assuming that the scattering centers moves with a speed equal to the Alfvén speed in the amplified magnetic field. In addition we also introduce the non-linear Landau damping of the magnetic field in the downstream according to Ptuskin & Zirakasvhili (2003).

Once the magnetic field structure is known, we can compute the spectrum of accelerated electrons at the shock, which is assumed to be proportional to the proton spectrum $f_e(p) = K_{ep} f_p(p)$, up to a maximum momentum $p_{e,\max}$ determined by the synchrotron losses in the amplified magnetic field, where the spectrum presents a squared exponential cut-off $\propto \exp[-(p/p_{e,\max})^2]$. The evolution of the electron and proton spectrum downstream of the shock is computed taking into account adiabatic losses for protons and adiabatic and synchrotron losses for electrons.

3. Results

In order to fit the emission observed from Tycho, we consider the following processes: 1) synchrotron emission of relativistic electrons; 2) thermal and non-thermal electron bremsstrahlung; 3) inverse Compton scattering

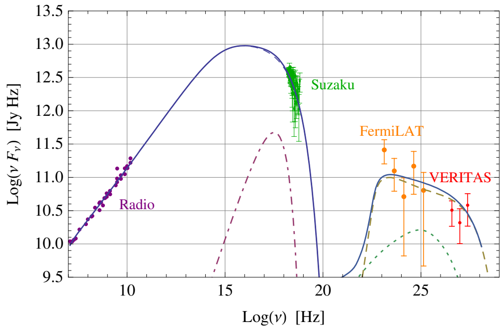

Fig. 1. Spatially integrated spectral energy distribution of Tycho. The curves show synchrotron emission (thin dashed), thermal electron bremsstrahlung (dot-dashed), pion decay (thick dashed) and ICS (dotted) as calculated within our model (see text for details). The total sum is showed by the solid curve. The experimental data are, respectively: radio from Reynolds & Ellison (1992); X-rays from *Suzaku* (courtesy of Toru Tamagawa) , GeV gamma-rays from Fermi-LAT (Giordano et al. 2011) and TeV gamma-rays from VERITAS Acciari et al. (2011). Both Fermi-LAT and VERITAS data include only statistical error at 1 σ.

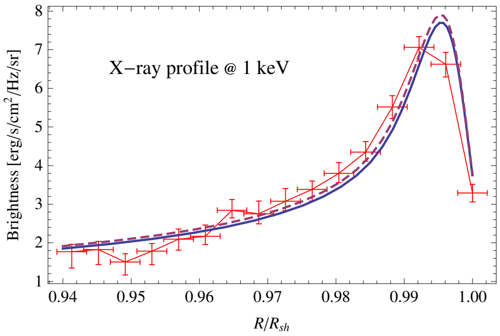

Fig. 2. Projected X-ray emission at 1 keV. The *Chandra* data points are from Cassam-Chenaï et al. (2007) (see their Fig. 15). The solid line shows the projected radial profile of synchrotron emission convolved with the Chandra point spread function (assumed to be 0.5 arcsec).

(ICS) of electrons on CMB, local IR dust emission and Galactic IR+optical light; 4) photons due to the decay of neutral pions produced in hadronic collisions.

In Fig. 1 we show our best fitting of the photon spectrum produced by the superposition of all the radiative processes outlined above, comparing it with the existing data. The overall agreement is quite good.

Our model actually has only three free parameters: the number density of the upstream medium, $n_0 = \rho_0/m_p$, the injection efficiency of protons, $\xi_{\rm inj}$, and the electron to proton normalization, K_{ep}. The values of n_0 and $\xi_{\rm inj}$ are simultaneously chosen in order to fit the gamma-ray emission detected by Fermi-LAT and VERITAS, in such a way that n_0 also allows us to reproduce the inferred position and velocity of the SNR forward shock. We get $n_0 = 0.3\,{\rm cm}^{-3}$ and $\xi_{\rm inj} = 3.7$. Finally, we fix the electron to proton ratio from the fit of the synchrotron emission. Very interestingly, a unique value $K_{ep} = 1.6 \times 10^{-3}$ allows us to fit both the X-ray data from *Suzaku* and the radio emission. The predicted photon spectral index in the radio band considered (10 to 1500 MHz) is 0.606.

In the X-ray band the synchrotron emission sums up with the emission due to thermal bremsstrahlung of shocked electrons. The electron temperature in the downstream, calculated taking into account only the heating due to Coulomb collisions with protons, results in a bremsstrahlung emission peaked around 1.2 keV which, at its maximum, contributes for about the 6 per cent of the total X-ray continuum emission only.

The projected X-ray emission profile, computed at 1 keV, is shown in Fig.2, where it is compared with the Chandra data in the region that Cassam-Chenaï et al. (2007) call *region W*. The solid curve represents the resulting radial profile, already convoluted with the Chandra PSF, and shows a remarkable agreement with the data. The sharp decrease of the emission behind the FS is due to the rapid synchrotron losses of the electrons in a magnetic field as large as $\sim 300\mu$G. In Fig. 2 we also plot the radial profile computed without magnetic damping (dashed line): it is clear that the non-linear Landau damping does not contribute to the determination of the filament thickness, because the typical damping length-scale is ~ 3 pc.

In the gamma-ray band the decay of neutral pions produced in hadronic collision is the dominant process. In particular, we predict a slope for accelerated protons $\propto E^{-2.2}$ which well accounts for Fermi-LAT and VERITAS detections within the experimental errors. The predicted proton spectrum shows a cut-off around $p_{\max} = 470$ TeV/c. In this respect, Tycho can be considered as a half-PeVatron at least, since there is no evidence of a cut-off in VERITAS data.

The ICS of relativistic electrons cannot explain the observed gamma-ray emission for two different reasons. First the strong magnetic field produced by the CR-induced streaming instability forces the number density of relativistic electrons to be too small to explain the gamma-ray emission as due to ICS on the ambient photons. Second, even if we arbitrarily reduced the magnetic field strength, enhancing at the same time the electron number density in order to fit the TeV gamma-rays with ICS emission, we could not account for the GeV gamma-rays because both the spectral slope and the flux would be incompatible with the recent Fermi-LAT observations.

Also the other competing leptonic process, namely the non-thermal bremsstrahlung, has to be ruled out, in that it provides a flux two order of magnitudes lower than the Fermi-LAT detection, and cannot be arbitrarily enhanced without over-predicting both the TeV and the X-ray emission.

4. Conclusions

Using the observed non-thermal spectrum, and in particular the recent detection of GeV emission by Fermi-LAT together with the TeV spectrum detected by VERITAS, we can infer that at Tycho's FS protons are accelerated up to energies as large as ~ 500 TeV, and that the total energy converted into CRs can be estimated to be about 12 per cent of the FS bulk kinetic energy. To reach this conclusion we investigated particle acceleration at the forward shock using a state-of-the-art semi-analytical NLDSA model including the dynamical reaction of the accelerated particles, the generation of magnetic fields as due to streaming instability excited by CRs, the dynamical reaction of these self-generated fields on the plasma and also the modification of the speed of the scattering centers (Alfvénic drift) induced by the magnetic field amplification. The last effect is of crucial importance because it produces a softening of the particle spectrum with respect to the standard prediction $\propto E^{-2}$, which allow us to fit both the radio and the gamma photon spectra. Our findings show, with unprecedented clarity, that the gamma-ray emission detected from Tycho cannot be of leptonic origin, therefore representing the first convincing evidence that in SNRs protons are accelerated up to energies as high as few hundreds TeV.

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