Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 41 (2008) 473–476
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

New evidence for strong non-thermal effects in Tycho's supernova remnant

H.J. Völk [a], E.G. Berezhko [b], L.T. Ksenofontov [b,*]

[a] Max Planck Institut für Kernphysik, Postfach 103980, D-69029 Heidelberg, Germany
[b] Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy, 31 Lenin Avenue, 677980 Yakutsk, Russia

Received 1 November 2006; received in revised form 24 July 2007; accepted 1 August 2007

Abstract

For the case of Tycho's supernova remnant (SNR), we present the relation between the blast wave and contact discontinuity radii calculated within the nonlinear kinetic theory of cosmic ray (CR) acceleration in SNRs. It is demonstrated that these radii are confirmed by recently published Chandra measurements which show that the observed contact discontinuity radius is very close to the shock radius. Therefore a consistent explanation of these observations can be given in terms of efficient CR acceleration which makes the medium more compressible.

Keywords: ISM; Cosmic rays; Acceleration of particles; Shock waves; Supernovae individual (Tycho's SNR); Radiation mechanisms: non-thermal; Gamma-rays: theory

1. Introduction

Cosmic rays (CRs) are widely expected to be produced in SNRs by the diffusive shock acceleration process at the outer blast wave see e.g., Drury, 1983; Völk et al., 1984; Blandford and Eichler, 1987; Berezhko and Krymsky, 1988; Jones and Ellison, 1991; Malkov and Drury, 2001, for reviews. Kinetic nonlinear theory of diffusive CR acceleration in SNRs (Berezhko et al., 1996; Berezhko and Völk, 1997) couples the gas dynamics of the explosion with the particle acceleration. A numerical solution of the fully time-dependent equations is possible under the assumption of spherical symmetry. It describes the evolution of gas density, pressure, mass velocity, as well as the positions of the forward shock and the contact discontinuity, together with the energy spectrum and the spatial distribution of CR nuclei and electrons at any given evolutionary epoch t, including the properties of the non-thermal radiation. Applied to individual SNRs (Berezhko et al., 2002, 2003a,b; Völk et al., 2002, 2005) this theory was able to explain the observed SNR properties and to determine the extent of magnetic field amplification which leads to the concentration of the highest-energy electrons in a very thin shell just behind the shock.

Recent observations with the *Chandra* and *XMM-Newton* X-ray telescopes in space have confirmed earlier detections of non-thermal continuum emission in hard X-rays from young shell-type SNRs. With *Chandra* it became even possible to resolve spatial scales down to the arcsec extension of individual dynamical structures like shocks (Vink and Laming, 2003; Long et al., 2003; Bamba et al., 2003). The filamentary hard X-ray structures are the result of strong synchrotron losses of the emitting multi-TeV electrons in amplified magnetic fields downstream of the outer accelerating SNR shock (Vink and Laming, 2003; Berezhko et al., 2003a; Berezhko and Völk, 2004; Völk et al., 2005). Such observational results gain their qualitative significance through the fact that these effective magnetic fields and morphologies turned out to be exactly the same as predicted from acceleration theory.

This theory has been applied in detail to Tycho's SNR, in order to compare results with the existing data (Völk

* Corresponding author. Tel.: +7 4112 390454.
E-mail address: ksenofon@ikfia.ysn.ru (L.T. Ksenofontov).

0273-1177/$30 © 2007 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2007.08.001

et al., 2002, 2005). We have used a stellar ejecta mass $M_{ej} = 1.4 M_{\odot}$, distance $d = 2.3$ kpc, and interstellar medium (ISM) number density $N_H = 0.5$ H-atoms cm^{-3}. For these parameters a total hydrodynamic explosion energy $E_{sn} = 0.27 \times 10^{51}$ erg was derived to fit the observed size R_s and expansion speed V_s. A rather high downstream magnetic field strength $B_d \approx 300$ μG and a proton injection rate $\eta = 3 \times 10^{-4}$ are needed to reproduce the observed steep and concave radio spectrum and to ensure a smooth cutoff of the synchrotron emission in the X-ray region. We believe that the required strength of the magnetic field, that is significantly higher than the MHD compression of a 5 μG ISM field, has to be attributed to nonlinear field amplification at the SN shock by the process of CR acceleration itself. According to plasma physical considerations (Lucek and Bell, 2000; Bell and Lucek, 2001; Bell, 2004), the existing ISM magnetic field can indeed be significantly amplified at a strong shock by CR streaming instabilities.

Using *Chandra* X-ray observations Warren et al. (2005) have recently estimated the ratio between the radius R_c of the contact discontinuity (CD), separating the swept-up ISM and the ejecta material, and the radius R_s of the forward shock. The inferred large mean value $R_c/R_s = 0.93$ of this ratio was interpreted as evidence for efficient CR acceleration, which makes the medium between those two discontinuities more compressible.

Here, we present the calculations of the mean ratio R_c/R_s, which are the unchanged part of our earlier considerations (Völk et al., 2002, 2005), and demonstrate that these results (which are in fact predictions) fit the above measurements very well. Since our calculations have been made in spherical symmetry they concern a priori an azimuthally averaged ratio R_c/R_s. We shall extend them by taking the effects of the Rayleigh–Taylor (R–T) instability of the CD into account.

2. Results and discussion

Fig. 1 and partly Fig. 2 show the calculations of shock and CD related quantities (Völk et al., 2002, 2005). The calculated shock as well as CD radii and speeds are given as a function of time for the two different cases of interior magnetic field strengths $B_d = 240$ μG and $B_d = 360$ μG considered, together with the azimuthally averaged experimental data available at the time. According to Fig. 1a Tycho is nearing the adiabatic phase. To fit the spectral shape of the observed radio emission one has to require a proton injection rate $\eta = 3 \times 10^{-4}$. This leads to a significant nonlinear modification of the shock at the current age of $t = 428$ yrs. A larger magnetic field lowers the Alfvénic Mach number and therefore leads to a decrease of the shock compression ratio, as seen in Fig. 1b. The result is a total compression ratio $\sigma = 5.7$ and a subshock compression ratio $\sigma_s = 3.5$ for $B_d = 240$ μG. In turn $\sigma = 5.2$, $\sigma_s = 3.6$, for $B_d = 360$ μG.

Therefore, as can be seen from Fig. 2, including CR acceleration at the outer blast wave, the calculated value of the ratio R_c/R_s for $B_d = 360$ μG is slightly lower than for $B_d = 240$ μG. At the current epoch we have $R_c/R_s \approx 0.90$ which is lower than the value $R_c/R_s = 0.93$ inferred from the observations. Qualitatively our result goes in the same direction as calculations by Blondin and Ellison (2001) which modeled SNRs with a uniform specific heat ratio $\gamma_{eff} < 5/3$, for the circumstellar medium and the ejecta material alike.

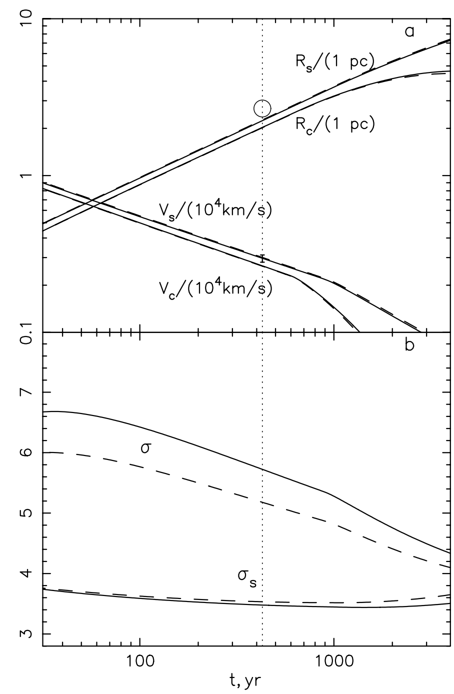

Fig. 1. (a) Shock radius R_s, contact discontinuity radius R_c, shock speed V_s, and contact discontinuity speed V_c, for Tycho's SNR as functions of time, including particle acceleration; (b) total shock (σ) and subshock (σ_s) compression ratios. The *dotted vertical line* marks the current epoch. The *solid and dashed lines* correspond to the internal magnetic field strength $B_d = 240$ μG and $B_d = 360$ μG, respectively. The observed mean size and speed of the shock, as determined by radio measurements (Tan and Gull, 1985), are shown as well.

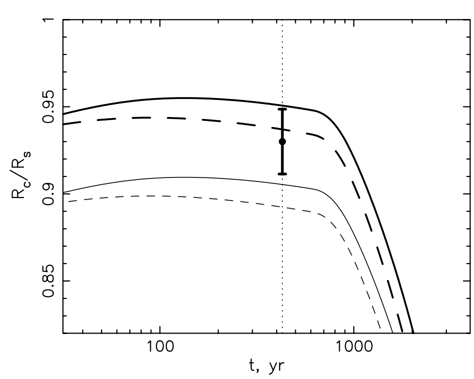

Fig. 2. The ratio R_c/R_s of the radii of the contact discontinuity and the forward shock as a function of time. *Solid and dashed* lines correspond to the same two cases as in Fig. 1. *Thin* lines represent the values calculated in the spherically symmetric model, whereas the *thick* lines show the values R'_c/R_s which contain the correction for the effect produced by the R–T instability. The value inferred from the observations is taken from Warren et al. (2005).