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

H. J. VÖLK[1], E. G. BEREZHKO[2], L. T. KSENOFONTOV[2]
[1]*Max Planck Institut für Kernphysik, Postfach 103980, D-69029 Heidelberg, Germany*
[1]*Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy, 31 Lenin Ave., 677980 Yakutsk, Russia*
ksenofon@ikfia.ysn.ru

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.

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. [4] for reviews. Kinetic nonlinear theory of diffusive CR acceleration in SNRs [3, 5] couples the gas dynamics of the explosion with the particle acceleration. Therefore in a spherically symmetric approach it is able to predict 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 nonthermal radiation. Applied to individual SNRs (see [2] for review) the 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 nonthermal 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. 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 [11].

This theory has been applied in detail to Tycho's SNR, in order to compare results with the existing data [13, 11]. 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 $B_d \approx 300\ \mu$G 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 $5\ \mu$G 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 [9, 1], the existing ISM magnetic field can indeed be significantly amplified at a strong shock by CR streaming instabilities.

Using *Chandra* X-ray observations [15] 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 $R_{\rm c}/R_{\rm s} = 0.93$ 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 $R_{\rm c}/R_{\rm s}$, which are the unchanged part of our earlier considerations [13, 11], 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 $R_{\rm c}/R_{\rm s}$. We shall extend them by taking the effects of the Rayleigh-Taylor (R-T) instability of the CD into account.

Results and Discussion

Fig.1 and partly Fig.2 show the calculations of shock and CD related quantities [13, 11]. 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 $B_{\rm d} = 240\ \mu$G and $B_{\rm d} = 360\ \mu$G 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 $B_{\rm d} = 240\ \mu$G. In turn $\sigma = 5.2$, $\sigma_s = 3.6$, for $B_{\rm d} = 360\ \mu$G.

Therefore, as can be seen from Fig.2, including CR acceleration at the outer blast wave, the calculated value of the ratio $R_{\rm c}/R_{\rm s}$ for $B_{\rm d} = 360\ \mu$G is slightly lower than for $B_{\rm d} = 240\ \mu$G. At the current epoch we have $R_{\rm c}/R_{\rm s} \approx 0.90$ which is lower than the value $R_{\rm c}/R_{\rm s} = 0.93$ inferred from the observations. Qualitatively our result goes in the same direction as calculations by [6] which modeled SNRs with a uniform specific heat ratio $\gamma_{\rm eff} < 5/3$, for the circumstellar medium and the ejecta material alike.

The observationally inferred and the theoretically calculated ratios $R_{\rm c}/R_{\rm s}$ require two comments.

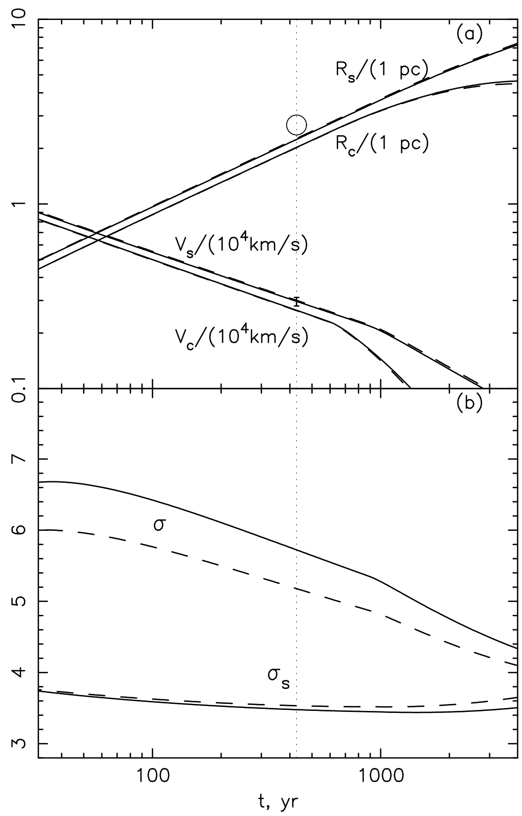

Figure 1: (a) Shock radius $R_{\rm s}$, contact discontinuity radius $R_{\rm c}$, shock speed $V_{\rm s}$, and contact discontinuity speed $V_{\rm c}$, for Tycho's SNR as functions of time, including particle acceleration; (b) total shock (σ) and subshock ($\sigma_{\rm s}$) compression ratios. The *dotted vertical line* marks the current epoch. The *solid and dashed lines* correspond to the internal magnetic field strength $B_{\rm d} = 240\ \mu$G and $B_{\rm d} = 360\ \mu$G, respectively. The observed mean size and speed of the shock, as determined by radio measurements [10], are shown as well.

First of all, projecting a highly structured shell onto the plane of the sky tends to favor protruding parts of the shell. Therefore the average radius *measured* in this projection is an overestimate of the true average radius. Analysing the amount of bias from the projection for the shock and CD radii [15] found a corrected "true" value $R_{\rm c}/R_{\rm s} = 0.93$ which is lower than their actually measured "projected average" value $R_\mathrm{c}/R_\mathrm{s} = 0.96$, as a result of this geometrical effect.

Secondly, starting from a spherically symmetric *calculation* of the CD radius, as we do, one has to take into account that the actual CD is subject to the R-T instability. In the nonlinear regime it leads to effective mixing of the ejecta and swept-up ISM material with "fingers" of the ejecta on top of this mixing region, which extend farther into the shocked gas than the radius R_c predicted when assuming spherical symmetry e.g. [7, 8, 6, 14]. Therefore our ratio $R_\mathrm{c}/R_\mathrm{s} = 0.90$, calculated within the spherically symmetric approach, has to be corrected for this effect in order to compare it with the measured value $R_\mathrm{c}/R_\mathrm{s} = 0.93$. In the case when all the fingers have length l and occupy half of the CD surface, one would have a mean CD size $R'_c \approx R_c + 0.5l$ which has to be compared with $0.93R_\mathrm{s}$. According to the numerical modelling of [14], albeit without particle acceleration, the R-T instability allows fingers of ejecta to protrude beyond the spherically symmetric CD radius by 10%. The longest fingers of size $l \approx 0.1R_c$ occupy less than 50% of the CD surface. However, in projection they stick out of the mixing region, whose thickness is roughly $0.5l$. This leads to a rough estimate of the corrected CD radius $R'_c = 1.05R_c$ which has to be compared with the experimentally estimated value.

Note, that in an ideal case, when no factors exist which make the considered shells highly structured and therefore these shells are purely spherical, there would be no need for the first correction for the projection effect. Let us assume nevertheless that the R-T instability exists and, for the sake of argument, efficiently mixes the ejecta and swept-up ISM materials without breaking the spherical symmetry of the system. Since the R-T instability effectively brings ejecta matter towards larger radial distances, one has to make the second correction for the CD radius as calculated in a spherically symmetric approach in order to compare it with the experimentally measured value. This is what we do here, making a rough estimate of the corrected CD radius $R'_c = 1.05R_\mathrm{c}^\mathrm{1D}$. We would like to add that at radial distances $r < R'_c = 1.05R_\mathrm{c}^\mathrm{1D}$, according to the results of [6], the ejecta mass fraction is larger than 0.3. Our estimate for R'_c appears therefore quite reasonable also from such a point of view.

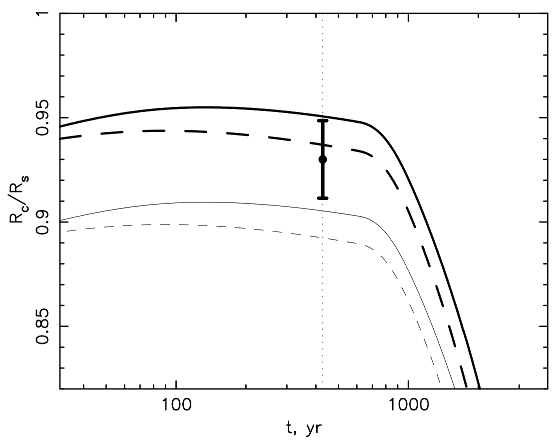

Figure 2: The ratio $R_\mathrm{c}/R_\mathrm{s}$ of the radii of the contact discontinuity and the forward shock as a function of time. *Solid and dashed* lines correspond to the same two cases as in Fig.1. *Thin* lines represent the values calculated in the spherically symmetric model, whereas the *thick* lines show the values $R'_\mathrm{c}/R_\mathrm{s}$ which contain the correction for the effect produced by the R-T instability. The value inferred from the observations is taken from [15].

The comparison of the corrected values $R'_\mathrm{c}/R_\mathrm{s}$, according to our calculations with this experimentally estimated value $R_\mathrm{c}/R_\mathrm{s} = 0.93$ (in Fig.2 we present that value with 2% uncertainties, according to [15]) shows quite good agreement (see Fig.2) even if one takes into account some uncertainty in the quantitative determination of our correction factor $R'_\mathrm{c}/R_\mathrm{c}$, which in our view lies in the range 1.03-1.07.

An additional peculiarity of Tycho's shock structure is the rather irregular behaviour of the radius of the forward shock around the edge of the visible SNR disk, as observed with Chandra [15]. We have discussed this observation elsewhere [12]. This irregularity is probably a consequence of the magnetic field structure in the circumstellar medium. But to lowest order the mean ratio $R_\mathrm{c}/R_\mathrm{s}$ should be independent of these fluctuations.

We conclude that a consistent explanation of the observations of the mean values of contact discontinuity and blast wave radius in Tycho's SNR can be given in terms of efficient CR acceleration at the blast wave which makes the medium more compressible. This is new evidence for strong nonthermal effects in this SNR.

EGB and LTK acknowledge the partial support by the Presidium of RAS (program No.16) and by the Russian Foundation for Basic Research (grant 07-02-00221) and the hospitality of the Max-Planck-Institut für Kernphysik, where part of this work was carried out.

References

[1] A. R. Bell and S. G. Lucek. Cosmic ray acceleration to very high energy through the non-linear amplification by cosmic rays of the seed magnetic field. *MNRAS*, 321:433–438, 2001.

[2] E. G. Berezhko. Gamma-ray astronomy and cosmic ray origin problem. *Advances in Space Research*, 35:1031–1040, 2005.

[3] E. G. Berezhko, V. K. Elshin, and L. T. Ksenofontov. Cosmic ray acceleration in supernova remnants. *J. Exp. Theor. Phys.*, 82:1–21, 1996.

[4] E. G. Berezhko and G. F. Krymsky. Acceleration of cosmic rays by shock waves. *Sov. Phys. Usp.*, 31:27–51, 1988.

[5] E. G. Berezhko and H. J. Völk. Kinetic theory of cosmic rays and gamma rays in supernova remnants. I. Uniform interstellar medium. *Astroparticle Physics*, 7:183–202, 1997.

[6] J. M. Blondin and D. C. Ellison. Rayleigh-Taylor Instabilities in Young Supernova Remnants Undergoing Efficient Particle Acceleration. *ApJ*, 560:244–253, 2001.

[7] R. A. Chevalier, J. M. Blondin, and R. T. Emmering. Hydrodynamic instabilities in supernova remnants - Self-similar driven waves. *ApJ*, 392:118–130, 1992.

[8] V. V. Dwarkadas. Interaction of Type IA Supernovae with Their Surroundings: The Exponential Profile in Two Dimensions. *ApJ*, 541:418–427, 2000.

[9] S. G. Lucek and A. R. Bell. Non-linear amplification of a magnetic field driven by cosmic ray streaming. *MNRAS*, 314:65–74, 2000.

[10] S. M. Tan and S. F. Gull. The expansion of Tycho's supernova remnant as determined by a new algorithm for comparing data. *MNRAS*, 216:949–970, 1985.

[11] H. J. Völk, E. G. Berezhko, and L. T. Ksenofontov. Magnetic field amplification in Tycho and other shell-type supernova remnants. *A&A*, 433:229–240, 2005.

[12] H. J. Völk, E. G. Berezhko, and L. T. Ksenofontov. *Astrophys. and Space Science*, 2007.

[13] H. J. Völk, E. G. Berezhko, L. T. Ksenofontov, and G. P. Rowell. The high energy gamma-ray emission expected from Tycho's supernova remnant. *A&A*, 396:649–656, 2002.

[14] C.-Y. Wang and R. A. Chevalier. Instabilities and Clumping in Type IA Supernova Remnants. *ApJ*, 549:1119–1134, 2001.

[15] J. S. Warren, J. P. Hughes, C. Badenes, et al. Cosmic-Ray Acceleration at the Forward Shock in Tycho's Supernova Remnant: Evidence from Chandra X-Ray Observations. *ApJ*, 634:376–389, 2005.