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

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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. [1] for reviews). Kinetic nonlinear theory of diffusive CR acceleration in SNRs [2, 3] 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 [4] 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 \textit{Chandra} and \textit{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 \textit{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 [5]. This theory has been applied in detail to Tycho’s SNR, in order to compare results with the existing data [6, 5]. 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 \( \text{cm}^{-3} \). For these parameters a total hydrodynamic explosion energy \( E_{sn} = 0.27 \times 10^{51} \text{ erg} \) was derived to fit the observed size \( R_s \) and expansion speed \( V_s \). A rather high downstream magnetic field strength \( B_d \approx 300 \mu \text{G} \) 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 \( \mu \text{G} \) 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 [7, 8], the existing ISM magnetic field can indeed be significantly amplified at a strong shock by CR streaming instabilities.

Using \textit{Chandra} X-ray observations [9] 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

\( \text{(CD), separating the swept-up ISM and the ejecta material, and the radius} \ R_s \text{ of the forward shock. The inferred large} \)
mean value \( R_c/R_s = 0.93 \) of this ratio was inter-
preted as evidence for efficient CR acceleration, which makes the medium between those two dis-
continuities more compressible.

Here we present the calculations of the mean ratio \( R_c/R_s \), which are the unchanged part of our earlier
considerations [6, 5], 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 con-
cern 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.

Results and Discussion

Fig.1 and partly Fig.2 show the calculations of shock and CD related quantities [6, 5]. The cal-
culated 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 \( B_d = 240 \) \( \mu \)G and \( B_d = 360 \) \( \mu \)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 \( B_d = 240 \) \( \mu \)G. In turn \( \sigma = 5.2 \), \( \sigma_s = 3.6 \), for \( B_d = 360 \) \( \mu \)G.

Therefore, as can be seen from Fig.2, including CR acceleration at the outer blast wave, the cal-
culated value of the ratio \( R_c/R_s \) for \( B_d = 360 \) \( \mu \)G is slightly lower than for \( B_d = 240 \) \( \mu \)G. 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 [13] which
modeled SNRs with a uniform specific heat ratio \( \gamma_{\text{eff}} < 5/3 \), for the circumstellar medium and the
ejecta material alike.

The observationally inferred and the theoretically calculated ratios \( R_c/R_s \) require two comments.

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 [9] found
a corrected "true" value \( R_c/R_s = 0.93 \) which is lower than their actually measured "projected av-
verage” value $R_c/R_n = 0.96$, 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. [11, 12, 13, 14]. Therefore our ratio $R_c/R_n = 0.90$, calculated within the spherically symmetric approach, has to be corrected for this effect in order to compare it with the measured value $R_c/R_n = 0.93$. 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 $0.93R_c$. 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 $R'_c = 1.05R_{c,1D}$. We would like to add that at radial distances $r < R'_c = 1.05R_{c,1D}$, according to the results of [13], 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.

The comparison of the corrected values $R'_c/R_n$, according to our calculations with this experimentally estimated value $R_c/R_n = 0.93$ (in Fig.2 we present that value with 2% uncertainties, according to [9]) shows quite good agreement (see Fig.2) even if one takes into account some uncertainty in the quantitative determination of our correction factor $R'_c/R_c$, 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 [9]. We have discussed this observation elsewhere [15]. This irregularity is probably a consequence of the magnetic field structure in the circumstellar medium. But to lowest order the mean ratio $R_c/R_n$ 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

![Figure 2: The ratio $R'_c/R_n$ 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 $R'_c/R_n$ which contain the correction for the effect produced by the R-T instability. The value inferred from the observations is taken from [9].](image-url)
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.

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