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Emission of Kepler's Supernova Remnant Produced by Accelerated Cosmic Rays

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The nonlinear kinetic model of cosmic ray acceleration in supernova remnants (SNRs) is used to describe the properties of the Kepler's SNR. The calculated expansion law and the radio and X-ray emission produced by the accelerated cosmic rays in Kepler's SNR agree quite well with the observations. A rather large interior magnetic field about 200 μG is required to give a good fit for the radio and X-ray synchrotron emission. The predicted TeV gamma-ray emission, which is of hadronic origin, is expected at a detectable level.

1. Introduction

Kepler's SNR is a result of a bright supernova (SN) in our Galaxy that exploded in 1604. This SNR, located at the distance $d \approx 4.8$ kpc, has been extensively observed throughout the electromagnetic spectrum. At the same time the type of Kepler's SN remains uncertain. Initially it was considered as a type Ia SN. Lately some authors (e.g. [1]) discuss the possibility that it may be a type II SN. We apply here the nonlinear kinetic theory of diffusive CR acceleration in SNRs [2, 3] in order to study the nonthermal emission, produced in Kepler's SNR by accelerated CRs. One of the aims of our study is to find the gamma-ray flux expected from this remnant.

2. Results and discussion

A SN explosion ejects a shell of matter with total energy E_{sn} and mass M_{ej}. During an initial period the shell material has a broad distribution in velocity v. The fastest part of these ejecta is described by a power law $dM_{ej}/dv \propto v^{2-k}$. The interaction of the ejecta with the interstellar medium (ISM) creates a strong shock there which accelerates particles diffusively.

Since the type of Kepler's SN is not known very well we consider two possibilities, type Ia and type II. In the first case we use in our calculations parameters that are typical for type Ia SNe: ejected mass $M_{ej} = 1.4 M_{\odot}$, $k = 7$, and a uniform ambient ISM. A SN explosion energy $E_{sn} = 4 \times 10^{50}$ erg, and a hydrogen number density $N_H = 0.5$ cm^{-3} which determines the ISM density $\rho_0 = 1.4 m_p N_H$, were chosen to fit the size R_s and the expansion speed V_s at the current evolutionary epoch $t_c = 400$ yr. As shown in Fig.1 the current evolutionary phase of Kepler's SNR corresponds to the free expansion phase. The adopted proton injection rate $\eta = 10^{-3}$ provides significant shock modification, characterized by a total shock compression ratio $\sigma \approx 5.5$ and a subshock compression ratio $\sigma_s \approx 3.1$ (see Fig.2). About 5% of the explosion energy has already transfered into CR energy up to now.

The calculated synchrotron flux is shown in Fig.3 together with the observed values at radio and X-ray frequencies. At radio frequencies the synchrotron spectrum $S_\nu \propto \nu^{-\alpha}$ has the spectral index $\alpha = 0.67$ which deviates significantly from the value $\alpha = 0.5$ that corresponds to an unmodified strong shock. The adopted proton injection rate $\eta = 10^{-3}$ gives the required shock modification. The electron-to-proton ratio $K_{ep} = 5 \times 10^{-4}$

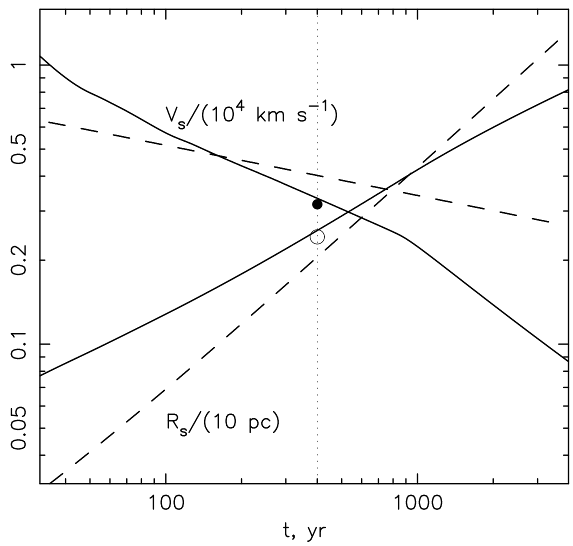

Figure 1. Shock speed V_s and shock radius R_s as functions of time. The experimental values of R_s and V_s [8] at the current epoch, corresponding to the vertical dotted line, are shown. *Solid and dashed lines* correspond to the type Ia and type II SN models, respectively.

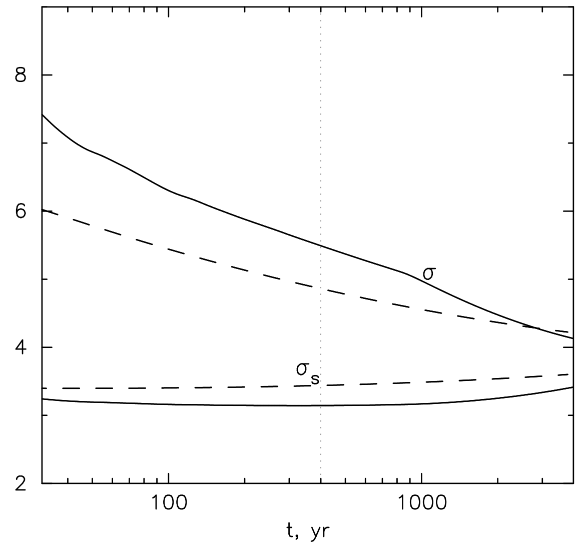

Figure 2. Overall compression ratio σ and subshock compression ratio σ_s as a function of time, for the same cases as in Fig.1.

and an interior magnetic field strength $B = 380$ μG provide a good fit for the experimental data in the radio and X-ray ranges.

Note that the interior magnetic field $B = 380$ μG, derived here from the fit of the *overall* synchrotron spectrum, is higher than the value $B = 215$ μG, determined from the observed spatial fine structure of the synchrotron emission [4]. Such a high interior magnetic field is the result of field amplification by the nonlinear CR backreaction on the acceleration process [5, 6]. It was established that such strong field amplification takes place in all young Galactic SNRs which have known filamentary structures in the nonthermal X-ray emission [4].

In Fig.4 we represent the gamma-ray spectrum of Kepler's SNR expected at the current epoch. It is mainly produced by the CR proton component in hadronic collisions with background gas nuclei, leading to π^0-production and subsequent decay into two gamma-quanta. The integral gamma-ray spectrum is expected to be rather hard, $F_\gamma \propto \epsilon_\gamma^{-1.8}$, within the energy range from 1 GeV to 1 TeV. At TeV-energies the expected energy flux is $\epsilon_\gamma F_\gamma \approx 2 \times 10^{-13}$ erg/(cm^{2}s), which can be detected by a modern ground based stereoscopic system of Cherenkov telescopes, like H.E.S.S.

As the second possibility for Kepler's SN we consider a type II SN with a massive progenitor star that emits an intense wind which strongly modifies the circumstellar medium (CSM). Following Borkowski et al. [1] we adopt here a mass-loss rate of the progenitor star $\dot{M} = 5 \times 10^{-5} M_\odot$ yr^{-1}, a stellar wind speed $V_w = 15$ km/s, a supernova explosion energy $E_{sn} = 5 \times 10^{50}$ erg, an ejecta mass $M_{ej} = 5M_\odot$, and $k = 7$.

The stellar wind surrounding the progenitor star has a density distribution $\rho_0 = \dot{M}/(4\pi r^2 V_w)$ in radius r. According to the model developed by Borkowski et al. [1], besides the free stellar wind the CSM includes a dense shell formed in the interaction of the wind with the surrounding ISM. As a result the assumed fast movement of the SN progenitor star the shell has a strongly asymmetric shape and approaches the progenitor

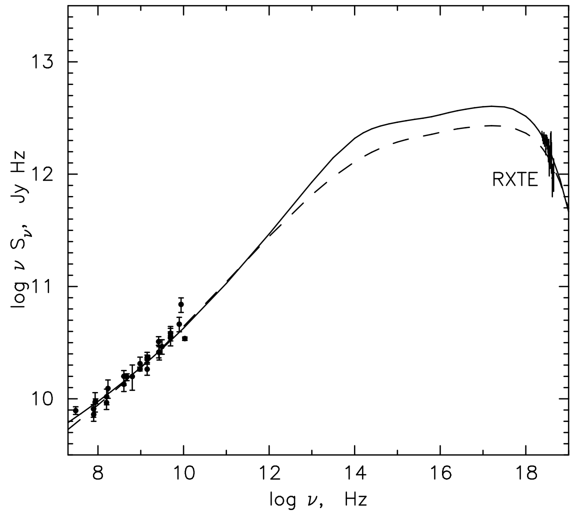

Figure 3. Calculated energy flux of synchrotron emission as a function of frequency for the same cases as in Fig. 1. The observed non-thermal X-ray [7] and radio emission [9] flux values are also shown.

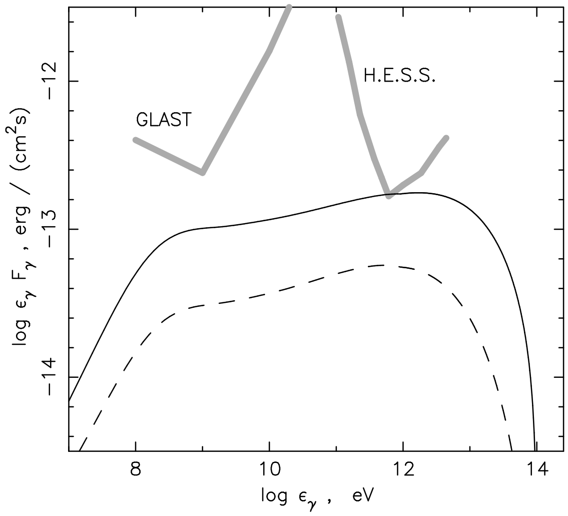

Figure 4. Total (π^0-decay + IC) integral γ-ray energy fluxes as a function of γ-ray energy for the same cases as in Fig. 1. The GLAST sensitivity and the H.E.S.S. sensitivity for a 5σ detection in 50 hours are shown.

closest in the direction of its motion. Since the SN shock has already reached the shell, there are two major effects due to the shell. First, it makes the SNR slightly asymmetric. Secondly, since the shell is much denser than the free stellar wind at the same distance, the acceleration of CRs and their nonthermal emission is more intense in the swept up shell region.

Due to its asymmetry the shell can not be incorporated into our spherically symmetric model. For simplicity we neglect it and consider the evolution of the SN shock in the free stellar wind only. Due to this simplification we underestimate the CR and gamma-ray production.

Since the nonlinear magnetic field amplification is produced by the CR pressure P_c, $B \propto \sqrt{P_c}$ [5]. Since $P_c \propto \rho_0 V_s^2$ we adopt here the magnetic field strength $B \propto \sqrt{\rho_0 V_s^2}$. The magnetic field strength $B(t)$ becomes fully determined when we derive its appropriate value at the current evolutionary epoch $t = t_c$ from the fit of the observed synchrotron emission.

From Fig.1 we see that the observed SNR size and expansion speed are less perfectly reproduced by our theory compared with the previous case. Partly this can be considered as an indication that the free stellar wind does not sufficiently represent the actual CSM.

The adopted proton injection rate $\eta = 6 \times 10^{-4}$ gives significant shock modification, characterized by a total shock compression ratio $\sigma \approx 4.8$ and a subshock compression ratio $\sigma_s \approx 3.5$ (see Fig.2). About 3% of the explosion energy has already transfered into CR energy.

As in the previous case the theory reproduces the observed synchrotron spectrum of Kepler's SNR very well (see Fig.3). It is achieved for a proton injection rate $\eta = 6 \times 10^{-4}$, an electron-to-proton ratio $K_{ep} = 10^{-3}$, and a downstream magnetic field $B = 430\ \mu$G which is comparable with the previous case.

The shape of the gamma-ray spectrum, given in Fig.4, is very similar to that corresponding to the type Ia case, whereas its amplitude is a factor of 3 lower. Since the mass of the swept-up shell is comparable with the mass of the swept-up wind [1], the actual gamma-ray flux is expected to be a factor of about two larger than given in Fig.4 by the dashed line.

3. Summary

Our consideration of CR acceleration and nonthermal emission in Kepler's SNR demonstrates that spherically symmetric nonlinear kinetic theory reproduces the SNR dynamics and the properties of its nonthermal radiation in a very satisfactory way when Kepler's SN is treated as a type Ia SN. This is clearly less so in our crude model for a type II SN.

A most important result is that the predicted gamma-ray spectrum of Kepler's SNR is not very sensitive to the models for the SN event, at least for the approximation for the core collapse event we have used. The gamma-ray energy flux expected at TeV-energies $\epsilon_\gamma F_\gamma \approx (1-3)\times 10^{-13}$ erg/(cm^{2}s) is near the sensitivity limit of a telescope system like H.E.S.S. We estimate an observation time of 50 to 100 hours for the detection of Kepler's SNR with such an instrument.

4. Acknowledgements

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References

[1] K.J. Borkowski, C.L. Sarazin, J.M. Blondin, ApJ 429, 710 (1992).
[2] E.G. Berezhko, V.K. Elshin, L.T. Ksenofontov, JETP 82, 1 (1996).
[3] E.G. Berezhko, H.J. Völk, Astropart. Phys. 7, 183 (1997).
[4] H.J. Völk, E.G. Berezhko, L.T. Ksenofontov, A&A 433, 229 (2005).
[5] A.R. Bell, S.G. Lucek, MNRAS 321, 433 (2001).
[6] A.R. Bell, MNRAS 353, 550 (2004).
[7] G.E. Allen, E.V. Gotthelf, R. Petre, Proc. 26th ICRC, Salt Lake City, Vol.3, p.480 (1999).
[8] J.R. Dickel, R. Sault, R.G. Arendt, Y. Matsui, K.T. Korista, ApJ 330, 254 (1988).
[9] S.P. Reynolds, D.C. Ellison, ApJ 399, L75 (1992).