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Non-thermal emission from Kepler's SNR

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Abstract: Nonlinear kinetic theory of cosmic ray (CR) acceleration in supernova remnants (SNRs) is used to investigate the properties of Kepler's SNR and, in particular, to predict the γ-ray spectrum expected from this SNR. Observations of the nonthermal radio and X-ray emission spectra as well as theoretical constraints for the total supernova (SN) explosion energy E_{sn} are used to constrain the astronomical and particle acceleration parameters of the system. Under the assumption that Kepler's SN is a type Ia SN we determine for any given explosion energy E_{sn} and source distance d the mass density of the ambient interstellar medium (ISM) from a fit to the observed SNR size and expansion speed. This makes it possible to make predictions for the expected γ-ray flux. Exploring the expected distance range we find that for a typical explosion energy $E_{sn} = 10^{51}$ erg the expected energy flux of TeV γ-rays varies from 2×10^{-11} to 10^{-13} erg/(cm^{2}s) when the distance changes from $d = 3.4$ kpc to 7 kpc. In all cases the γ-ray emission is dominated by π^0-decay γ-rays due to nuclear CRs. Therefore Kepler's SNR represents a very promising target for instruments like H.E.S.S., CANGAROO and GLAST. A non-detection of γ-rays would mean that the actual source distance is larger than 7 kpc.

Introduction

Kepler's supernova remnant (SNR) (G4.5+6.8) has been extensively observed throughout the electromagnetic spectrum (for a recent review, see [1] and references therein). At the same time the type of Kepler's SN has been debated over the years. Initially it was considered a type Ia SN, based on a study of the historical light curve of the SN [2]. More recently it was argued that the light curve does not contradict a type II-L SN [3], and [4, 5] proposed a bow-shock model in which a massive star, ejected from the Galactic plane, exploded into its own circumstellar medium. However, the thermal X-ray spectra, obtained more recently with ASCA [6], Chandra [7] and XMM [8], and corresponding theoretical modeling [9], favor a type Ia event. We take this as our starting point.

Within the so-called delayed-detonation model of a type Ia supernova explosions a typical range $E_{sn} = (1.3 - 1.6) \times 10^{51}$ erg was obtained [10]. The deflagration model has resulted in considerably lower mean energy releases $E_{sn} = (0.4 - 0.6) \times 10^{51}$ erg [11, 12]. In this situation we use below the value $E_{sn} = 10^{51}$ erg as a typical explosion energy for type Ia events. Since the value of E_{sn} strongly influences the SNR dynamics and in particular the expected γ-ray flux, we explore the range $E_{sn} = (0.5 - 2) \times 10^{51}$ erg, in order to demonstrate the sensitivity of the final results to the value of E_{sn}.

The most recent radio study of the distance to the SNR [13] leads to a lower limit of 4.8 ± 1.4 kpc and an upper limit of 6.4 kpc. Therefore we explore below the range $d = 3.4 - 7$ kpc.

We apply here the nonlinear kinetic theory of CR acceleration in SNRs [14, 15], as was successfully done for other individual SNRs (see [16] for a review), we use observations of the nonthermal radio and X-ray emission spectra to constrain the astronomical parameters as well as the particle acceleration parameters of the system, such as the interior magnetic field strength and the CR injection rates. We show that in all the cases considered the expected γ-ray flux is at a detectable level if the source distance is not larger than 7 kpc.

Table 1: Models Parameters

	d, kpc	E_{SN},10^{51}erg	N_H, cm^{-3}	σ	B_d, μG	K_{ep}, 10^{-4}	$F_\gamma^{pp}/F_\gamma^{IC}$
solid (Fig.1,2,4)	3.4	1.0	6.0	8.2	409	1.3	2403
dashed (Fig.1,2.3,4)	4.8	1.0	3.0	6.9	482	1.3	1058
dot-dash (Fig.1,2,4)	6.4	1.0	0.7	5.6	563	1.3	301
dotted (Fig.1,2,4)	7.0	1.0	0.4	5.3	534	1.8	137
solid (Fig.3)	4.8	0.5	1.4	6.3	441	2.8	175
dot-dash (Fig.3)	4.8	1.5	3.7	7.1	494	0.93	2128
dotted (Fig.3)	4.8	2.0	4.0	7.1	500	0.74	3080

Results and discussion

For any given pair of values E_{sn} and d we find the density of the ambient interstellar medium (ISM) from a fit to the observed SNR size and expansion speed [17]. This makes it possible to make quite definite predictions for the cosmic ray (CR) and γ-ray production in this SNR.

Different models parameters are listed in Table 1. The hydrogen number density N_H, which determines the ISM density $\rho_0 = 1.4 m_p N_H$, was chosen to fit the size R_s and the expansion speed V_s at the present age $t_c = 400$ yr (see Fig. 1a). Note, that on Fig. 1a experimental data and curves are scaled by factor $d/4.8$ kpc.

The adopted proton injection rate $\eta = 1.5 \times 10^{-3}$ leads to a significant shock modification, characterized by a total shock compression ratio $\sigma > 5$ and a subshock compression ratio $\sigma_s < 3$ in all cases (see Fig. 1b). Such a shock modification is needed to fit the observed steep radio spectrum and the smooth connection with its X-ray part (see below).

About 10% of the explosion energy has been transfered into CR energy up to now, which means that the CR energy content is $E_c = 0.1 E_{sn}$.

The calculated synchrotron fluxes are shown in Fig. 2 together with the observed values at radio and X-ray frequencies. At radio frequencies the synchrotron spectrum $S_\nu \propto \nu^{-\alpha}$ has spectral index $\alpha = 0.71$ [18]. It deviates significantly from the value $\alpha = 0.5$ that corresponds to an unmodified strong shock. The adopted proton injection rate $\eta = 1.5 \times 10^{-3}$ gives the required shock modification. The interior magnetic field strength B_d and the subsequent electron-to-proton ratio K_{ep} (see Table 1) give a good fit for the experimen-

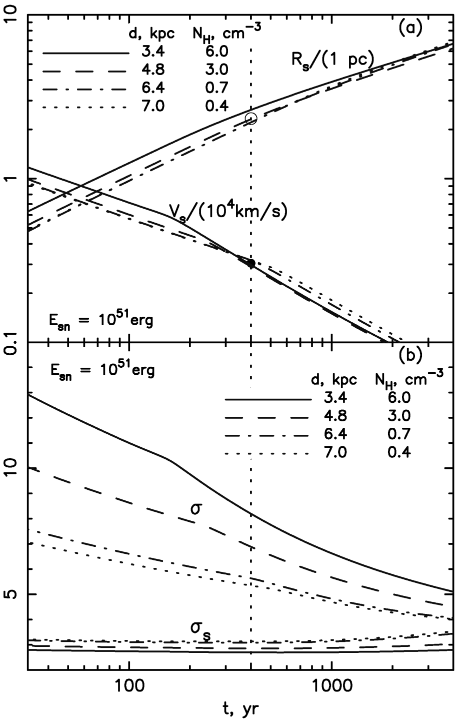

Figure 1: (a) Shock radius R_s and shock speed V_s as functions of time since explosion. The observed mean size and speed of the shock, as determined by radio measurements [17], are shown as well. Curves and experimental data are scaled by factor $d/4.8$ kpc; (b) total shock (σ) and subshock (σ_s) compression ratios. The dotted vertical line marks the current epoch t_c. Model parameters for different curves can be found in Table 1.

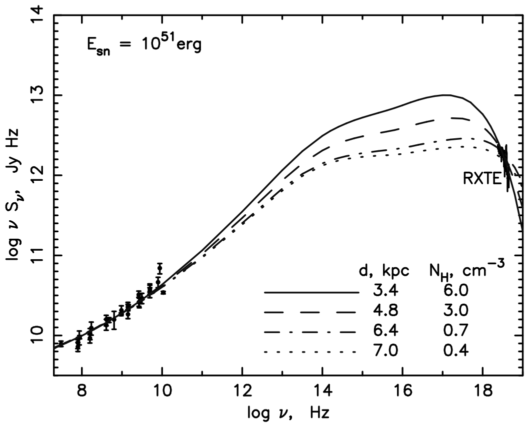

Figure 2: Calculated energy flux of synchrotron emission as a function of frequency for the same case as in Fig. 1. The observed non-thermal X-ray [22] and radio emission [23] flux values are also shown.

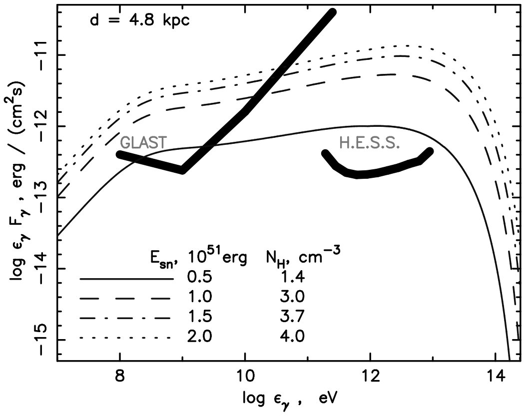

Figure 3: Total (π^0-decay + IC) integral γ-ray energy fluxes as a function of γ-ray energy for the source distance $d = 4.8$ kpc and four values of the SN explosion energy E_{sn}. For comparison, the respective sensitivities of GLAST [24], and H.E.S.S. [25], are shown.

tal data in the radio and X-ray ranges in all cases. Such a high interior magnetic field is the result of field amplification by the nonlinear CR backreaction on the acceleration process [19, 20]. It was recently established that such strong field amplification takes place in all young Galactic SNRs which have known filamentary structures in the nonthermal X-ray emission [21].

In Fig. 3 we present 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. This so-called hadronic γ-ray component exceeds the leptonic γ-ray component due to the Inverse Compton (IC) scattering off the cosmic microwave background by more than a factor of 10^3. The integral gamma-ray spectrum is expected to be very hard, $F_\gamma \propto \epsilon_\gamma^{-1.8}$, within the energy range from 1 GeV to almost 10 TeV. At $\epsilon_\gamma = 1$ TeV $\epsilon_\gamma F_\gamma \approx 5 \times 10^{-12}$ erg/(cm^{2}s) for $E_{sn} = 10^{51}$ erg. Since the SN explosion energy is not exactly known, we present in Fig. 3 also the results calculated for the three other values $E_{sn}/(10^{51}$ erg)=0.5, 1.5 and 2. We note that even at the lowest explosion energy $E_{sn} = 0.5 \times 10^{51}$ erg considered here, the expected γ-ray flux exceeds the sensitivity of the GLAST instrument at GeV energies and of the H.E.S.S. instrument at TeV energies. At TeV-energies the expected energy flux is $\epsilon_\gamma F_\gamma \approx 10^{-12}$ erg/(cm^{2}s) in the case $E_{sn} = 0.5 \times 10^{51}$ erg and an order of magnitude higher for $E_{sn} = 2 \times 10^{51}$ erg.

Since the source distance is not known very well, we performed our calculations for a range of distances $d = 3.4 - 7$ kpc in a similar way as it was done above for $d = 4.8$ kpc. In each case we achieve the same quality of fit of the observed SNR size, its expansion speed and the overall synchrotron emission spectrum. Therefore we present in Fig. 4 only the results of the γ-ray energy fluxes expected for the SN explosion energy $E_{sn} = 10^{51}$ erg and for four different distances from the range $d = 3.4 - 7$ kpc. It can be seen from Fig. 4 that Kepler's SNR is expected to be as bright a TeV γ-ray source as the Crab Nebula if the distance is as small as $d = 3.4$ kpc. The expected γ-ray flux goes down with increasing distance and comes to the minimum observable H.E.S.S. flux if the distance becomes as large as 7 kpc.

The γ-ray energy flux expected at TeV energies is $\epsilon_\gamma F_\gamma \approx (3 - 5) \times 10^{-12}$ erg/(cm^{2}s) if the distance is as small as $d = 4.8$ kpc. The flux is expected to be in a detectable range $\epsilon_\gamma F_\gamma > 10^{-13}$ erg/(cm^{2}s) at TeV energies if the distance does not exceed 7 kpc. If the upper limit for the source distance

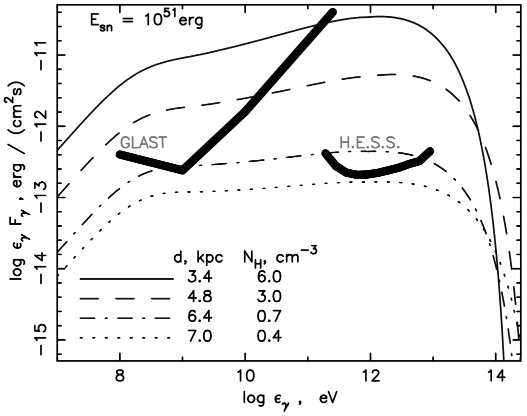

Figure 4: Same as in Fig. 3, but different curves correspond now to different source distances d with the explosion energy 10^{51} erg.

is indeed $d = 6.4$ kpc [13] – a conclusion that is confirmed by the consistency check of the interior magnetic field values obtained by two independent methods – we conclude that Kepler's SNR is a potentially bright γ-ray source in the sky.

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