On the hadronic γ-ray emission from Tycho's Supernova Remnant†

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Abstract. Tycho is one of nearly a dozen Galactic supernova remnants which are suggested to emit hadronic γ-ray emission. Among them, however, it is the only one in which the hadronic emission is proposed to arise from the interaction with low-density ambient medium. Based on the multi-band observations, we suggest that Tycho is encountering dense cloud at the northeastern boundary. The γ-ray emissions can be explained by hadronic process with self-consistent parameters, such as a modest energy conversion efficiency. In this SNR-cloud association scenario, the distance can be estimated as $\sim$2.5 kpc.

Keywords. supernova remnants, ISM: individual (Tycho), radiation mechanisms: non-thermal

1. Introduction

Hadronic γ-ray emission from supernova remnants (SNRs) is an important tool to test shock acceleration of cosmic ray (CR) protons. For Tycho's SNR which is suggested evolving in a tenuous medium, an energy conversion efficiency 10–15% was invoked (e.g., Tang *et al.* 2011; Giordano *et al.* 2012; Morlino & Caprioli 2012). Although it is suggested that Tycho is a naked Ia SNR without any dense cloud (Tian & Leahy 2011), there seem to be signs and evidence in multiband showing the presence of dense clouds from the north to the east, which could be the target for bombardment of the accelerated protons and would thus reduce the needed converted energy. Constraints from γ-ray observation suggest that Cas A, another historical SNR, has only transferred a minor fraction ($\leqslant$ 2%) of the total kinetic energy to the accelerated particles (e.g., Araya & Cui 2010). Moreover, under the Bohm limit assumption, the conversion factor no more than 1.3% is predicted in kinetic models for an SNR at the Tycho's age, evolving in a pre-shock medium of density $\sim 0.3\,\mathrm{cm}^{-3}$ (Berezhko & Völk 1997). Therefore, the fraction of order $\sim$1% at Tycho's age deserves serious consideration.

2. Hadronic Gamma-ray emission

We assume that the energy spectrum of the accelerated particles (electrons and protons) is prescribed by a power law with high-energy cutoff. Some basic parameters are adopted as: distance 2.5 kpc, spectral index 2.3, explosion energy 6×10^{50} erg (Hughes 2000), the average downstream magnetic field $320\,\mu$G and the energy conversion efficiency $\eta \sim 10^{-2}$. By fitting the radio–γ-ray data (see the left panel in Fig. 1), we get
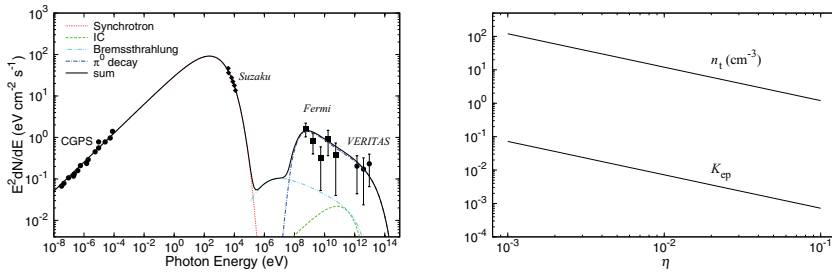
Figure 1. Left: Broadband SED of Tycho's SNR with the observed data in radio (Kothes *et al.* 2006), X-rays (Tamagawa *et al.* 2009) and γ-rays (*Fermi*: Giordano *et al.* 2012; *VERITAS*: Acciari *et al.* 2011). Right: Functional dependence of parameters K_{ep} and n_t on η.

the electron to proton number ratio $K_{ep} \sim 0.7 \times 10^{-2}$ and the average density of the target protons $n_t \sim 12$ cm^{-3} (see the right panel in Fig. 1 for functional dependence of n_t and K_{ep} on η). Considering the shock compression ratio, the average pre-shock proton density is in the range ~ 4–12 cm^{-3}, which is much larger than the reported gas density ~ 0.3 cm^{-3}. This discrepancy can be reconciled if Tycho is encountering an intercloud medium. Indeed, there are some multi-band observational evidence of the presence of the surrounding dense medium from the north to the east: the expansion rate measured in Radio (Reynoso *et al.* 1997) and X-rays (Katsuda *et al.* 2010), CO-line observations (Lee *et al.* 2004; Cai *et al.* 2009; Xu *et al.* 2011), and infrared observations (Ishihara *et al.* 2010; Gomez *et al.* 2012).

The SNR-cloud association can be used to estimate the distance to Tycho's SNR. Due to the spiral shock, the local standard of rest velocity of the associated clouds allows two distances in two armed spiral shock model (Roberts 1972) for the longitude 120°. In combination with the line-of-sight HI absorption (Tian & Leahy 2011), the distance is determined to be $\sim$2.5 kpc.

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