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Using optical lines to study particle acceleration at supernova remnants

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Abstract

The shocks of several young supernova remnants (SNR) are often associated with very thin optical filaments dominated by Balmer emission resulting from charge-exchange and collisional excitation between neutral Hydrogen from the interstellar medium and shocked protons and electrons. Optical lines are a direct probe of the conditions at the shock, in particular the width of the narrow and broad components reflect the temperature upstream and downstream of the shock, respectively. When the shock accelerate efficiently non-thermal particles, the shock structure changes producing anomalous Balmer lines and it is possible to use their line shape and their spatial profile to check the efficiency of SNR shocks in accelerating cosmic rays. Here we illustrate the kinetic theory of shock acceleration in presence of neutrals with some applications to young SNRs. We show that in three cases (RCW 86, SNR 0509-67.5 and Tycho) anomalous Balmer lines can be explained assuming that a fraction of $\sim$ 10% of the total shock kinetic energy is converted into not thermal particles, while in one single case, the northwestern part of SN 1006, there is no evidence of efficient acceleration.

Keywords: cosmic-rays, particle acceleration, supernova remnants, Balmer lines

1. Introduction

In the context of supernova remnant (SNR) paradigm for the origin of cosmic rays (CR), particle acceleration takes place at shocks associated with the supernova explosion, and it is described by the non linear theory of diffusive shock acceleration (see [1] for a review). Energy and momentum conservation at the shock in the presence of accelerated particles leads to two straightforward conclusions: 1) since part of the energy is channeled into particle acceleration, the thermal energy (hence the temperature) of the downstream gas is expected to be lower than in the absence of CRs; 2) the dynamical reaction of CRs induces the formation of a precursor upstream of the shock, which results in a deviation of the CR spectrum from a simple power-law behavior. Optical spectra observed from so called Balmer dominated shocks can be used to test these predictions. In fact some young SNR shocks emit optical lines mainly consisting of Balmer Hα emission.

The first detection of bright Hα filaments around the remnants of Kepler, Tycho and the Cygnus Loop was reported by [2]. A peculiarity of this emission is the weakness of forbidden metal lines which implies an high temperature of the emitting region so that radiative cooling and recombination are unimportant. The interpretation of such optical emission remained a mystery up to the seminal works of [3, 4] who proposed that it can be produced by shocks propagating thorough a partially neutral gas. Their model was able to explain the intensity, spectrum and width of the filaments observed in Tycho's SNR, including the weakness of the forbidden metal lines. A peculiarity of Balmer dominated shocks, firstly reported by [4] for the Tycho's SNR, is that the Hα line is formed by two distinct components, a narrow line with a FWHM of few tens km/s and a broad line with a FWHM of the order of the shock speed. Similar optical profiles are now observed from a bunch of young SNRs both in the Galaxy and in the Large Mag-

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ellanic Cloud (for a review see [5]).

SNR shocks are collisionless and when they propagates in partially ionized medium, only ions are heated up and slowed down, while neutral atoms are unaffected to first approximation. However, when a velocity difference is established between ions and neutrals in the downstream of the shock, the processes of charge exchange (CE) and ionization are activated and this explain the existence of two distinct lines: the narrow line is emitted by direct excitation of neutral hydrogen after entering the shock front while the broad line results from the excitation of hot hydrogen population produced by CE of cold hydrogen with hot shocked protons. As a consequence, optical lines are a direct probe of the conditions at the shock, in particular the width of the narrow and broad components reflect the temperature upstream and downstream of the shock, respectively. Now, as already pointed out, if the shock accelerate particles efficiently, the shock's structure will be modified, altering the plasma temperature and inducing the formation of a CR precursor. Hence, Balmer emission could be used to provide an indirect measurement of the CR acceleration efficiency and even to gather information on the CR induced precursor.

The first clue that Balmer emission could provide evidence for the presence of accelerated particles was put forward as a possible way to explain the anomalous width of narrow Balmer lines reported for the first time by [6] and [7]: FWHM ranging from 30 to 50 km s^{-1} was detected for four SNRs in the LMC and for the Cygnus Loop, implying a pre-shock temperature around 25,000-50,000 K. Values in the same range have been reported afterwards for other SNRs (see, e.g.[8]). If this were the ISM equilibrium temperature there would be no atomic hydrogen, implying that the pre-shock hydrogen is heated by some form of shock precursor in a region that is sufficiently thin so that collisional ionization equilibrium cannot be established before the shock. Several explanations for this anomaly were proposed but only two of them was considered realistic: 1) the neutral-induced precursor and 2) the CR-induced precursor.

Let us comment the former possibility first. When fast, cold neutrals undergo CE interactions with the slower hot ions downstream of the shock, some fraction of the resulting hot neutrals can cross the shock and move upstream. The relative velocity between these hot neutrals and the upstream ions triggers the onset of CE and ionization interactions that lead to the heating and slowing down of the ionized component of the upstream fluid. The system then tends to develop a *neutral-induced* shock precursor, in which the fluid velocity gradually decreases, and even more important, the temperature of ions increases as a result of the energy and momentum deposition of returning neutrals. A first attempt at investigating the broadening of the narrow line component induced by the neutral precursor was made by [9], using a simplified Boltzmann equation for neutrals, but their calculation does not show any appreciable change of the narrow line width. This conclusion was confirmed by [10, 11], using a fully kinetic approach able to describe the interaction between neutrals and ions in a more accurate way. The physical reason is that the ionization length-scale of returning hot neutrals in the upstream is always smaller than the CE length-scale of incoming cold neutrals. Interestingly enough, [11] showed that the neutral precursor could produce a different signature, namely the presence of a third intermediate Balmer line due to hydrogen atoms that undergone charge exchange with warm protons in the neutral precursor.

The second and more promising possibilities to explain the anomalous width of narrow lines requires efficient particle acceleration which leads to the formation of a *CR-induced* precursor, where ionized plasma is heated before crossing the shock. If the precursor is large enough, CE can occur upstream leading to a broader narrow Balmer line. The first attempt to model this scenario was done by [12] using a two-fluid approach to treat ions and CRs but neglecting the dynamical role of neutrals. A different model was proposed by [13] where momentum and energy transfer between ions and neutrals is included, but the profile of the CR-precursor is assumed *a-priori* . Both works concluded that the observed width of 30-50 km s^{-1} can be explained using a low CR acceleration efficiency.

From the theoretical point of view, the main difficulty in describing the structure of a collisionless shock propagating in a partially ionized medium is that neutrals have no time to reach thermalization and cannot be treated as a fluid. Steps forward in relaxing the fluid assumption have been made by [14] and [15], even if these works neglect the modification induced by neutrals upstream of the shock. A more reliable interpretation of Balmer line profile requires an accurate description of the CR acceleration process where the mutual interplay between CRs, neutrals, ionized plasma and magnetic turbulence is simultaneously taken into account. Such an approach has been developed by [16] using a semi-analytical technique. This work showed that the main physical effect able to broaden the narrow line is the damping of magnetic turbulence in the CR precursor while the adiabatic compression alone is ineffective. Hence the observed widths are compatible