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Powerful Diagnostics of Cosmic-Ray Modified Shock by Hα Polarimetry*

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We show that polarimetry of Hα emission in sunpernova remnant shocks can be a powerful diagnostic of cosmic-ray modified shocks (CRMSs). Solving the radiative line transfer problem for collisionless shocks propagating into a partially ionized medium, we find the directions of the linearly polarized Hα strongly dependent on the existence of shock modification; the direction is parallel to the direction of shock travel for the case of the CRMS, while the direction is perpendicular for the case of no modification.

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1. Introduction

The acceleration of non-thermal particles in collisionless shocks, especially in supernova remnant shocks, is a long standing problem for revealing the origin of Galactic cosmic-rays (CRs). In the most reliable scenario, the Galactic CRs originate in the diffusive shock acceleration mechanism, and the pressure of accelerated CRs should be large, comparable to the ram pressure of upstream background protons, to realize the maximum energy of Galactic CRs of order 3 PeV. If this is the case, the upstream plasma is decelerated "before" entering the shock front (measured in the shock rest frame). This is called a CR modified shock and is one of the essential predictions for collisionless shocks efficiently accelerating CRs. Nevertheless, this modification has not yet been observed. In numerical simulations, the inferred degree of velocity modification is only at the 10 percent level. Thus, we must examine this 10 percent modification of plasma located at a distance of kpc scale. We have found that the polarimetry of Hα emission at supernova remnants is a potentially powerful tool to quantify the velocity modification: the polarization direction of Hα is parallel to the shock normal vector in the modified shock case, while the direction is perpendicular without modification. Note that although observations of Hα in supernova remnants have been done in past decades, linearly polarized Hα has recently been discovered by [10]. We have also found that among the observables we calculated, only the polarization direction responds sensitively to the velocity modification (5 percent in our model). Therefore, the polarimetry of Hα will be a unique diagnostic of CR modified shocks and will bring new insights to particle acceleration physics in collisionless shocks.

2. Model

The polarization direction of scattered Hα is determined by the incident direction of the Lyβ photon that is eventually absorbed. The Lyβ photons originate from collisions between hydrogen atoms and electrons in the downstream region or at the shock precursor where the electrons are heated due to the CRs [8]. If the upstream protons interact with CRs coming from the shock, they accelerate toward the far upstream region. Subsequently, they collide with neutral hydrogen atoms in the shock precursor region. These collisions are dominated by the charge-exchange reaction (H+p$\rightarrow$p+H). Thus, a fraction of hydrogen atoms in the upstream region has the same velocity profile as the accelerated protons. These hydrogen atoms resulting from this charge-exchange reaction "see" Doppler-shifted Lyβ, and they no longer absorb the Lyβ traveling along the shock propagation direction. Hence, the polarization "direction" depends sensitively on whether the CR pressure works on the background protons.

We estimate the polarization of Hα from the upstream region of SNR shocks with fixed shock velocity, $V_{\rm sh}$ = 4000 km s^{-1}, far upstream temperature, T_0 = 6000 K, and preshock proton fraction, χ_0 = 0.5, for the following three cases: (i) no particles leaking to the upstream region, (ii) an electron heating precursor with temperature of 10^6 K but no velocity modifications, (iii) in addition to the electron heating precursor, there are decelerated protons, but with no proton heating. We assume that the velocity modification is 5 per cent of $V_{\rm sh}$ (i.e. 200 km s^{-1}) and that the downstream values are given by usual the Rankine-Hugoniot relations for simplicity. Note that the downstream electron temperature is fixed at 10 per cent of proton temperature ($T_{\rm e} \simeq$ 3 keV).

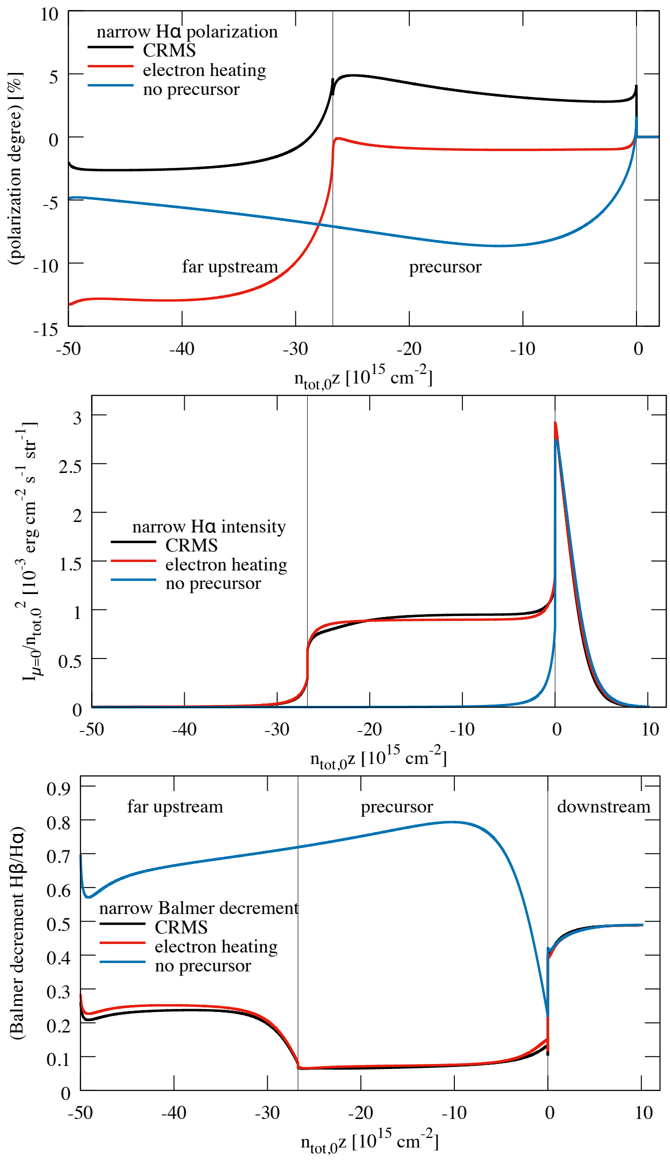

Figure 1: The polarization degree of Hα (top panel), surface brightness of Hα (middle), and brightness ratio of Hα to Hβ (bottom panel). The blue, red and black lines show the cases (i) no energetic particles, (ii) heated electrons in the upstream region but no shock modification, and (iii) the CRMS with the electron heating precursor. The parameter $n_{\text{tot},0}$ is the total number density of the far upstream region.

For the radiation transfer problem ([11]), we set two free escape boundaries for photons upstream and downstream of the shock. The shock direction of travel is along the z-axis, and the shock surface corresponds to the $x - y$ plane. The plasma consists of protons, electrons and hydrogen atoms. Note that bremsstrahlung radiation, emission from the SNR ejecta and any other external radiation sources are neglected. The excitation of levels in the hydrogen atom is considered up to 4f. To evaluate the Stokes Q of Hα, we consider the polarization in the Rayleigh scattering regime, following [5] and [3] (see, [12] for details).

The top panel of Figure 1 shows the results of the polarization degree (ratio of Sokes Q to I). Here we define that negative (positive) Stokes Q means the direction of polarization is perpendicular (parallel) to the shock direction of travel. In the no precursor case (i), the polarization degree is positive ($\simeq 2$ per cent) in the region close to the shock front where the optical depth of Lyβ is small. Then, the polarization becomes negative at optical depth ~ 1. Since the Lyβ radiated from the downstream region in the direction along the z-axis is not so attenuated compared to that radiated along the x or y direction, the 'photon beam' is elongated along the z-axis, giving a negative polarization in the region distant from the shock. Note that the polarization at $z \simeq -5 \times 10^{16}$ cm is affected by the photon free escape boundary. On the other hand, in the simple electron heating precursor case (ii), the polarization degree is modest ($\simeq -1$ per cent) in the precursor region. This is because the electron heating precursor with no velocity modification yields a uniform, isotropically emitting medium whose polarization property is shown in Figure 1. Note that the polarization degree in front of the shock is $\simeq 1$ per cent in this case (the plots in Figure 1 are overlapped). In the modified shock case (iii), the polarization is positive with a degree of $\simeq 5$ per cent. The degree of attenuation of Lyβ photons radiated in the z-axis depends on whether the decelerated/non-decelerated atoms emit/absorb them, while the photons radiated in the x or y axis are attenuated by the both populations of atoms. Thus, the photons traveling along the z-axis are efficiently attenuated resulting in positive polarization.

The middle panel of Figure 1 shows the surface brightness profiles of the frequency-integrated Stokes I for the three cases. With the existence of a precursor, cases (ii) and (iii), the emission from the upstream region is bright and comparable to that from the downstream region. Thus, in an actual observation, the polarization of such a precursor emission is detectable. Indeed, [10] discovered the polarized H α with a polarization degree of 2.0 ± 0.4 per cent at SNR SN 1006. Note that precursor emissions have been reported in several cases in the literature ([6, 7, 9]) although their origin is still a matter of debate.

The bottom panel of Figure 1 is the ratio of the frequency-integrated Stokes I of Hβ to that of Hα. The ratio does not depend on the existence of a velocity modification, in other words, the net optical depth of the Lyman lines does not depend on the modification. The reason is that both decelerated and non-decelerated hydrogen atoms survive sufficiently in the precursor region for the absorption of Lyman lines. Thus, the polarimetry of Hα is a unique diagnostic for the velocity modification of shock that is one of the essential predictions for the collisionless shocks efficiently accelerating non-thermal particles.

In comparison to the case of 5 per cent modification, we additionally estimate the cases of 1 per cent ($\simeq 40$ km s^{-1}) and 2 per cent modification ($\simeq 80$ km s^{-1}). Figure 2 shows the polarization degree of Hα and the ionization structure of hydrogen. When the relative velocity between the accelerated protons and hydrogen atoms is small (1 per cent case), the decelerated hydrogen atoms are hardly generated in the precursor region. Thus, to constrain the velocity modification via Hα polarimetry, the length of the precursor should be larger than the characteristic length of the spatial distribution of the decelerated hydrogen atoms, $\chi_0 V_{\rm sh}/C_{\rm CX}(\Delta V_{\rm sh})$, where $C_{\rm CX}/n_{\rm p} \approx 4.59 \times 10^{-8}$ cm^3 s$^{-1}(\Delta V_{\rm sh}/200$ km s$^{-1})$ is the charge exchange rate and $\Delta V_{\rm sh}$ is the relative velocity of collision particles. For the case of 5 per cent modification, the precursor length is about $3\chi_0 V_{\rm sh}/C_{\rm CX}$ at which almost all hydrogen atoms undergo the charge exchange reaction (three times the e-folding length), while the length is about $0.6\chi_0 V_{\rm sh}/C_{\rm CX}$ for the 1 percent modification.

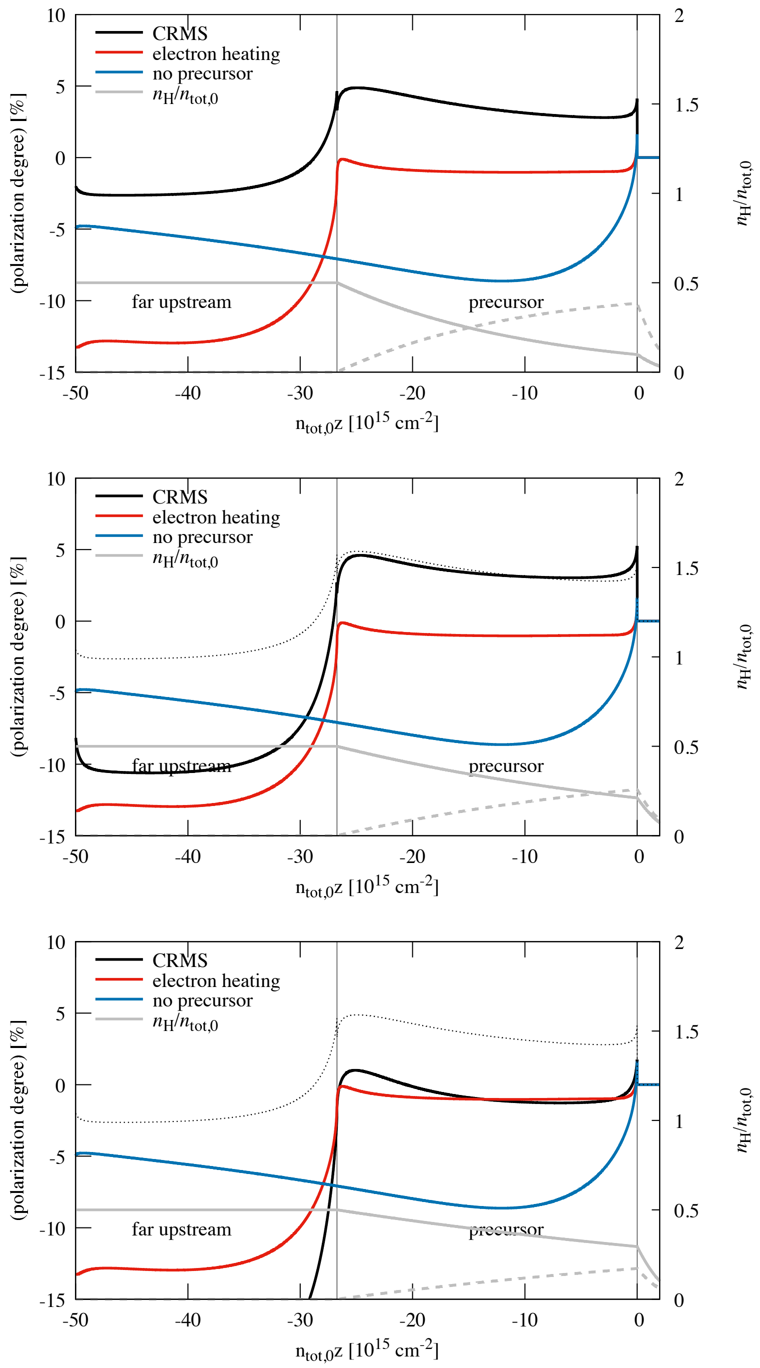

Figure 2: The polarization degree of Hα for 5 per cent velocity modification (top panel), 2 per cent (middle panel) and 1 per cent (bottom panel). The black dots represent the degree for the 5 per cent case. The blue, red and black lines show the cases where (i) there are no energetic particles, (ii)there are heated electrons in the upstream region but no shock modification, and (iii) the CRMS with the heating electron precursor. The gray solid line shows the number density of hydrogen atoms that have not experienced a charge-exchange reaction. The gray broken line shows the number density of hydrogen atoms that have experienced a charge-exchange reaction with the decelerated protons in the precursor region. The $n_{tot,0}$ is the total number density of the far upstream region.

The polarization signal from the precursor region is saturated with the modification of 2 per cent that corresponds to the length of about $1.2\chi_0 V_{\rm sh}/C_{\rm CX}$. Thus, the polarimetry of Hα can be useful to distinguish whether the shock modification is weak or not.

3. Summary

We have given an overview that polarimetry of H α can be a useful and unique diagnostic of a CR modified shock. The upstream H α is linearly polarized with a polarization degree of $\sim$ a few per cent. The polarization direction (angle) depends strongly on whether there is a velocity modification. For the case of no velocity modification, the polarization direction is parallel to the shock surface. On the other hand, if there are velocity modified hydrogen atoms generated by charge-exchange reactions with the decelerated upstream protons, the direction is perpendicular to the shock surface. Moreover, the upstream surface brightness of Hα is comparable to the downstream brightness. Furthermore, we have shown that even if the velocity modification is just 5 per cent of $V_{\rm sh}$, the polarization of Hα responds to the modification sensitively. Hence, polarimetry of upstream Hα may be realised that will constrain the modification of the shock due to the CR back reactions and bring new insights to particle acceleration in collisionless shocks.

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