Electron-Ion Equilibration from Proper Motions Studies of two Balmer-Dominated SNRs

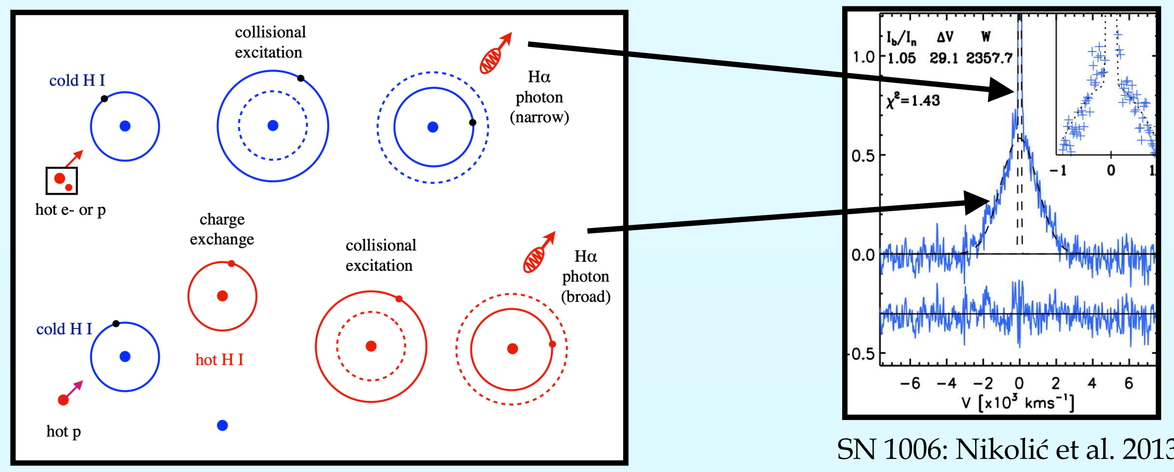
Parviz Ghavamian[1], Sladjana Knežević[2], Rino Bandiera[3] and Giovanni Morlino[3]

1: Towson University, Maryland, USA; 2: Astronomical Observatory of Belgrade, Serbia; 3: INAF/Observatorio Astrofisico di Arcetri, Firenze, Italy

Balmer-dominated supernova remnants at known distance (SNR 0509-67.5 and SNR 0519-69.0 in the LMC) present one of the rare opportunities to study the physics of high velocity collisionless shocks. We have combined proper motion measurements from archival HST and MUSE observations to study the electron-ion equilibration and cosmic ray acceleration of both SNRs. The HST proper motions in both objects extend over at least 10 years, providing excellent constraints on shock speeds. On the other hand from the MUSE data we have simultaneously measured broad and narrow Hα FWHM, as well as barycenter velocity and broad-to-narrow flux ratio at numerous locations along both SNR rims. We find that while many shock positions in both SNRs show $T_e/T_p \lesssim 0.1$, many others show Hα FWHM that are too low for even full equilibration, a result which may be caused by the interplay between pattern speed from proper motions and projection effects from oblique shocks (induced, e.g., by density inhomogeneities in the ISM). In addition, E-W gradients in narrow component centroid and line width in SNR 0509-67.5 may indicate the presence of a third, intermediate line component from a fast neutral precursor. Finally, we have detected Hα emission extending well ahead of the SE and NW rims of SNR 0509-67.5, the origin of which may lie in either a photoionization or cosmic ray precursor.

Introduction

Balmer-dominated filaments mark the shock transitions of collisionless shocks in partially neutral ISM. The optical spectra of these shocks consists of two collisionally excited Balmer line components[7] :



SN 1006: Nikolić et al. 2013

1. **Narrow Line (NL):** collisional excitation of cold H I, with contributions from both the postshock gas and preshock (precursor)

2. **Broad Line (BL):** postshock collisional excitation of hot H I neutrals generated by charge exchange. The broad line FWHM (W_{BL}) is sensitive to the shock speed (V_{SH}) and electron-ion temperature equilibration ($\beta \equiv T_e/T_p$) due to collisionless heating processes at the shock transition[7].

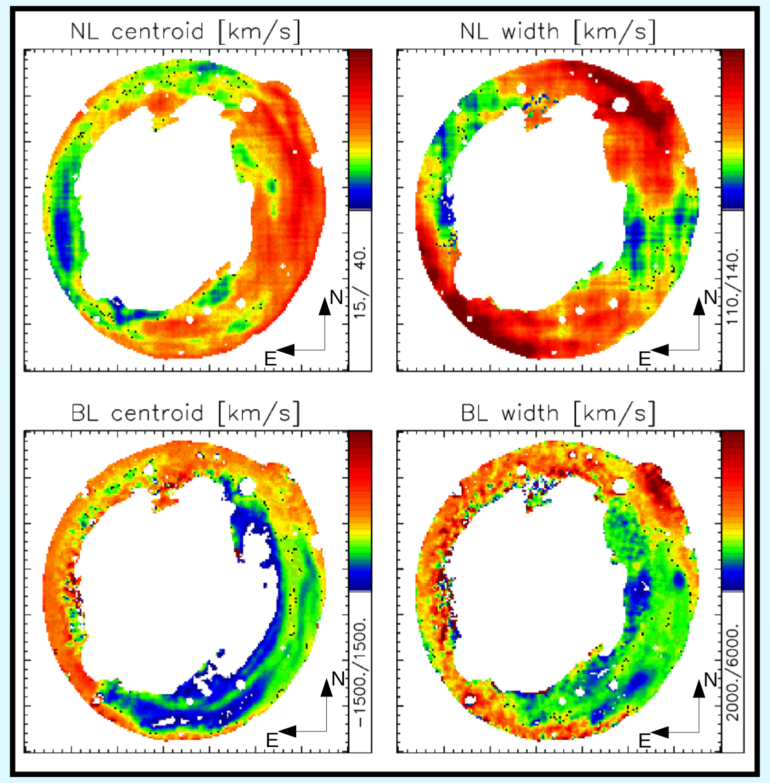
In principle, W_{BL} and V_{SH} can also be used to estimate the efficiency of cosmic ray (CR) shock acceleration, ε_{CR} ($\equiv P_{CR}/\rho V_{SH}^2$)[2,4,5]. At a given V_{SH}, the thermal energy channeled into CRs reduces the thermal proton temperature, which also lowers W_{BL} by a predictable amount (and also raises β, since a lowered temperature causes more rapid electron-ion equilibration).

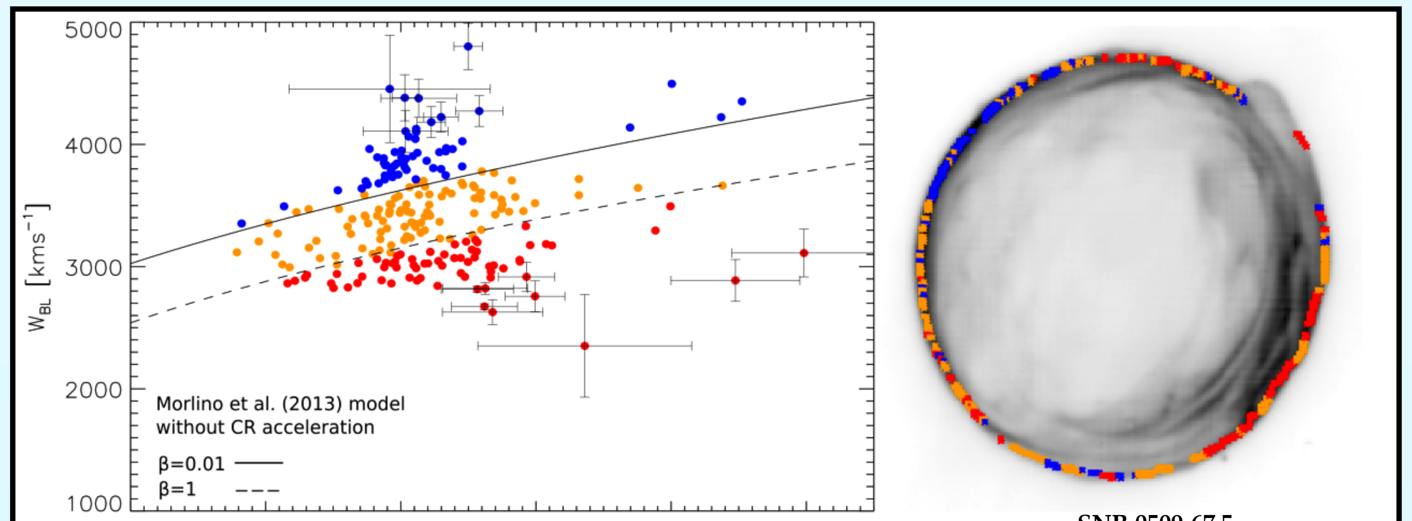
VLT/MUSE Data

Both SNRs are at a known distance (in the LMC, D = 50 kpc), hence are highly suited for shock physics studies. For example, owing to its young age (~300 yrs)[8] and very high shock speeds (~ 6000 km s^{-1})[1] , SNR 0509-67.5 is among the best candidates for the study of CR acceleration. In contrast, SNR 0519-69.0 is nearly twice that age[8] and presents a more distorted morphology, w/slower shocks (~ 1100 - 4000 km s^{-1}). X-ray analyses have indicated this is is likely due to interaction with a relic PN[9].

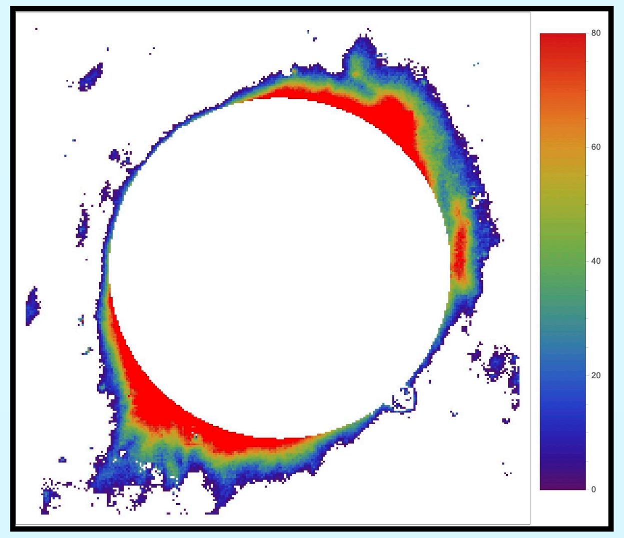
- IFU observations of both SNRs acquired with VLT Yepun/UT4 telescope (1' x 1' FOV; 0.2" pixel^{-1}; R ~ 3,000 (100 km s^{-1}))
- Depth: 24 hrs on 0509 with AO mode (PI: I. Seitenzahl: seeing ≤ 0.6") and 1.4 hrs (PI: B. Leibundgut; seeing ~ 0.9"). Both reduced datasets are available on the ESO Archive Science Portal.

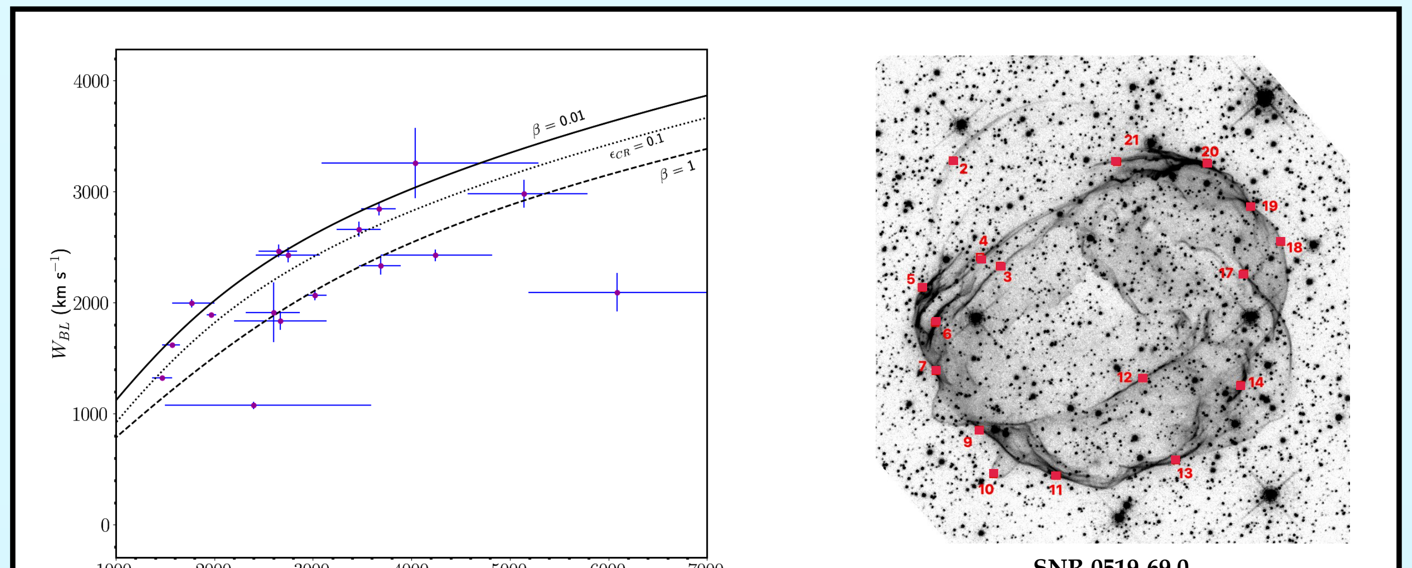
Analysis





SNR 0509-67.5
(MUSE Hα)





SNR 0519-69.0
(HST/ACS F658N)

- **Left panel - Top:** Hα line maps for SNR 0509-67.5, generated by double-gaussian line profile fits at each spaxel of the MUSE datacube after careful subtraction of stellar contamination. The narrow component (NL) and broad component (BL) fits (line flux, line width and line centroid) are color coded by value. **Bottom:** NL flux (the SNR is masked) in units of 10^{-20} ergs cm^{-2} s^{-1} pixel^{-1}. Note the faint diffuse Hα emission extending ahead of the NW and SE rims.
- **Right panel - Top:** BL widths (W_{BL}) vs shock velocities (V_{SH}) for SNR 0509-67.5. Broad line widths for 224 points along the rim of SNR 0509-67.5 are plotted along with corresponding proper motion shock velocities from HST data[1]. Curves of W_{BL} vs V_{SH} predicted by detailed kinetic models of Morlino et al. (2013) without cosmic ray feedback are overlaid, for the limits of <u>β = 0.01</u> (low electron-ion equilibration) to <u>β = 1</u> (full equilibration). **Bottom:** same plot for SNR 0519-69.0, but using the HST proper motion measurements of Williams et al. (2022). For comparison, the Morlino et al (2013) curves are reproduced, but with the additional curve correspond to 10% of shock energy lost to cosmic ray acceleration (ε_{CR} = 0.1, β ~ 0.1).

Results

- Contrary to expectation[7], many of the BL widths in both SNRs <u>fail</u> to align with low equilibrations (β ≤ 0.1) and instead fall <u>outside</u> the range of β allowed by the models for their corresponding shock speeds.
- Both SNRs have been shown to exhibit only moderate CR acceleration efficiency[5]. The Morlino et al. (2013) model results, modified to allow ε_{CR} ≤ 0.2 and β ~ 0.1 bring the solid black line curves slightly lower (e.g., see the dotted line for the SNR 0519-69.0 plot), but many points still fail to align with curves of low β.
- If we accept substantial random variations in β, it remains unexplained how this can occur between adjacent locations on the forward shock with similar values of V_{SH} (and likely preshock B- field orientation).
- Low W_{BL} values may be due to SNR propagation into an inhomogeneous ISM. Random density fluctuations from supernova-driven ISM turbulence[10] are expected on a scale ~ 1 pc and δρ/ρ ~ 0.3. In those cases the flow is not completely normal to the shock front within the over/under-dense regions, and V_{SH} depends on the normal component of the flow. This can lower the observed W_{BL}, so that the measured Hα proper motions reflect more the pattern speed than V_{SH}.
- Although prior studies[11] of the narrow components of these Balmer-dominated SNRs have shown W_{NL} ~ 30 - 50 km s^{-1}, the narrow component is marginally resolved in the MUSE observations of SNR 0509-67.5, where W_{NL} ~ 110 - 140 km s^{-1} (see the NL width map). This may be due to presence of a partially resolved intermediate width line[2,4], predicted to arise from a fast neutral precursor, (W_{IL} ~ 100 - 300 km s^{-1}). This may also explain the NL centroid shifts (see line map).
- We have uncovered a narrow line ridge of diffuse Hα emission extending ~ 1 pc ahead of the NW and SE rims of SNR 0509-67.5 (see left figure). The layer may be due to collisional excitation in a He II λ304 Å photoionization precursor (T ~ 12,000-15,000 K)[3].

References

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