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Evolution of Ejecta Wakes in Supernova Remnants

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Background

Type Ia supernovae result from accretion onto a white dwarf from a binary companion, resulting in a collision between the supernova ejecta and the donor. The effects of this collision on the donor and on the early light curve have received much study, though **the collision also carves out a low-density wake in the ejecta.**. This provides one possible mechanism for the asymmetries observed in many type Ia supernova remnants such as SN 1572, SN 1604, and Cassiopeia A, though interaction with circumstellar material and nonuniformities in the ISM can produce similar effects.

Although any type of supernova may occur in a binary, **SNIa are of particular interest because the donor must be Roche lobe-filling,** guaranteeing that it subtends a large solid angle and thus collides with much of the ejecta. SNIa have also been proposed as a formation channel for the small population of hypervelocity white dwarfs observed by Gaia, one of which has been traced back to a supernova remnant.

Numerical Setup

Because of the large range of spatial scales involved in the evolution of supernova ejecta, our numerical modeling proceeds in several stages.

Collision with Donor ($t = 0$ to 1000 s):

We first model the collision of the ejecta with the donor on a static grid using Athena++, placing the donor at an orbital separation consistent with a Roche-lobe filling hot subdwarf helium star. Because we are interested in the ejecta structure rather than the fate of the donor, **we treat the donor as a rigid sphere** and enforce reflective boundary conditions at its surface. Based on (Wong et al., submitted to ApJ), the initial ejecta profile is taken to be

$$\rho(v,t) = \frac{M_{ej}}{(v_0 t\sqrt{\pi})^3}\exp(-v^2/v_0^2), \tag{1}$$

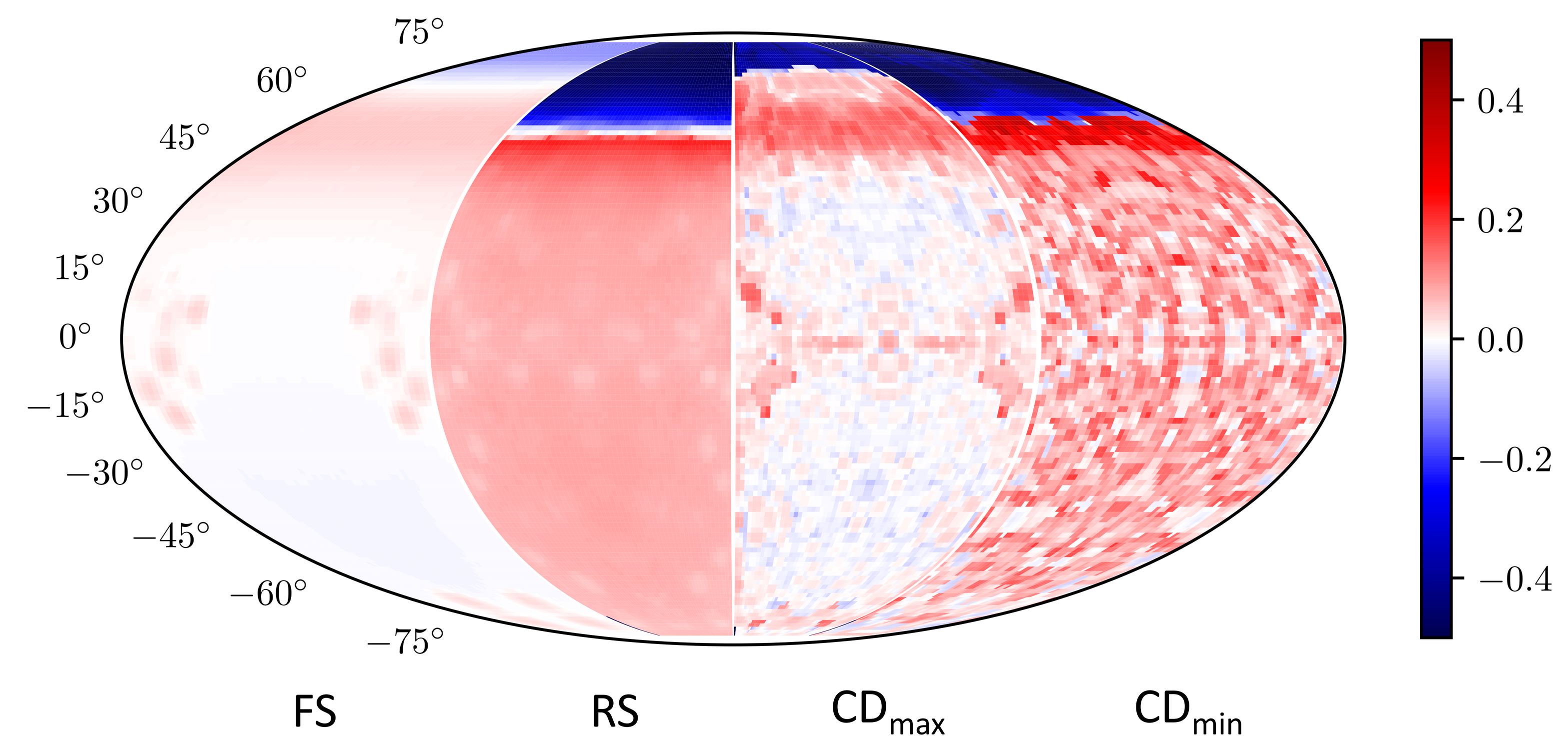
with uniform entropy. As the initially gas-pressure dominated ejecta may become radiation-pressure dominated after colliding with the donor, we use an equation of state which spans both regimes.

Homologous Evolution ($t = 1000$ s to 10 yr):

After $t \sim 15$ min, pressure gradients have dropped to the point that the ejecta can be considered homologous. **Its subsequent evolution can then be computed trivially** until several years after the supernova when significant mass is swept up from the ISM. During this time, radioactive heating from ^{56}Ni plays a large role in the energetics and light curve of these transients. However, we can safely neglect such effects since the internal energy of the ejecta will be negligible by the remnant phase and will be reset by the reverse shock.

Remnant Phase ($t = 10$ to 3000 yr):

The evolution through the remnant phase is computed using the 3-D moving-mesh code Sprout. Sprout uses a uniformly-expanding Cartesian grid, which allows us to **follow the evolution of the SNR over several orders of magnitude** in time. This also minimizes advection errors and removes the need to remap the fluid onto larger grids, which is an inherently diffusive process. The speed of mesh expansion is set such that it locally matches that of the fastest-moving fluid parcel, though we exempt the wake from this condition because of the large fluid velocities created by the reverse shock convergence. Certain points on the forward shock experience Carbuncle instabilities, which are numerical instabilities which can form at grid-aligned shocks and slightly deform the forward shock.



Mollweide projection showing radial positions of the shocks as well as the minimum and maximum extent of the contact discontinuity at $t = 408$ yr. All radii are fractional with respect to their mean values. Here the wake is aligned with the north pole at $\theta = 90°$. The effects of Carbuncle instabilities can be seen along the equatorial plane. For comparison, a density slice is shown at the same epoch in the second panel from the left of the bottom figure.

Shock Trajectories

Forward Shock:

The theory of nonradiative SNRs developed by Truelove & McKee (1999) predicts the evolution of both shocks given several assumptions about the ratio of shock radii l_{ED} and the ratio of post-shock pressures ϕ_{ED}. Adapting this to our Gaussian profile (1), we obtain an implicit result for the forward shock radius R_{FS}:

$$\left(\frac{R_{FS}}{R_{ch}}\right)^{3/2} = \frac{1}{2^{1/4}\pi^{3/4}}\sqrt{\frac{l_{ED}}{\phi_{ED}}}\left[\Gamma\left(\frac{3}{4},\frac{3}{8}\frac{(R_{FS}/R_{ch})^2}{(t/t_{ch})^2 l_{ED}^2}\right) - \Gamma\left(\frac{3}{4},\frac{3}{4\alpha}\right)\right]. \tag{2}$$

This describes the forward shock for the unperturbed ejecta, but because of the low density of the wake the forward shock is significantly slowed by the ISM. **Gas from the edge of the wake then flows in to fill this vacuum,** and by $t \sim 1000$ yrs the forward shock is once again spherical and described by (2).

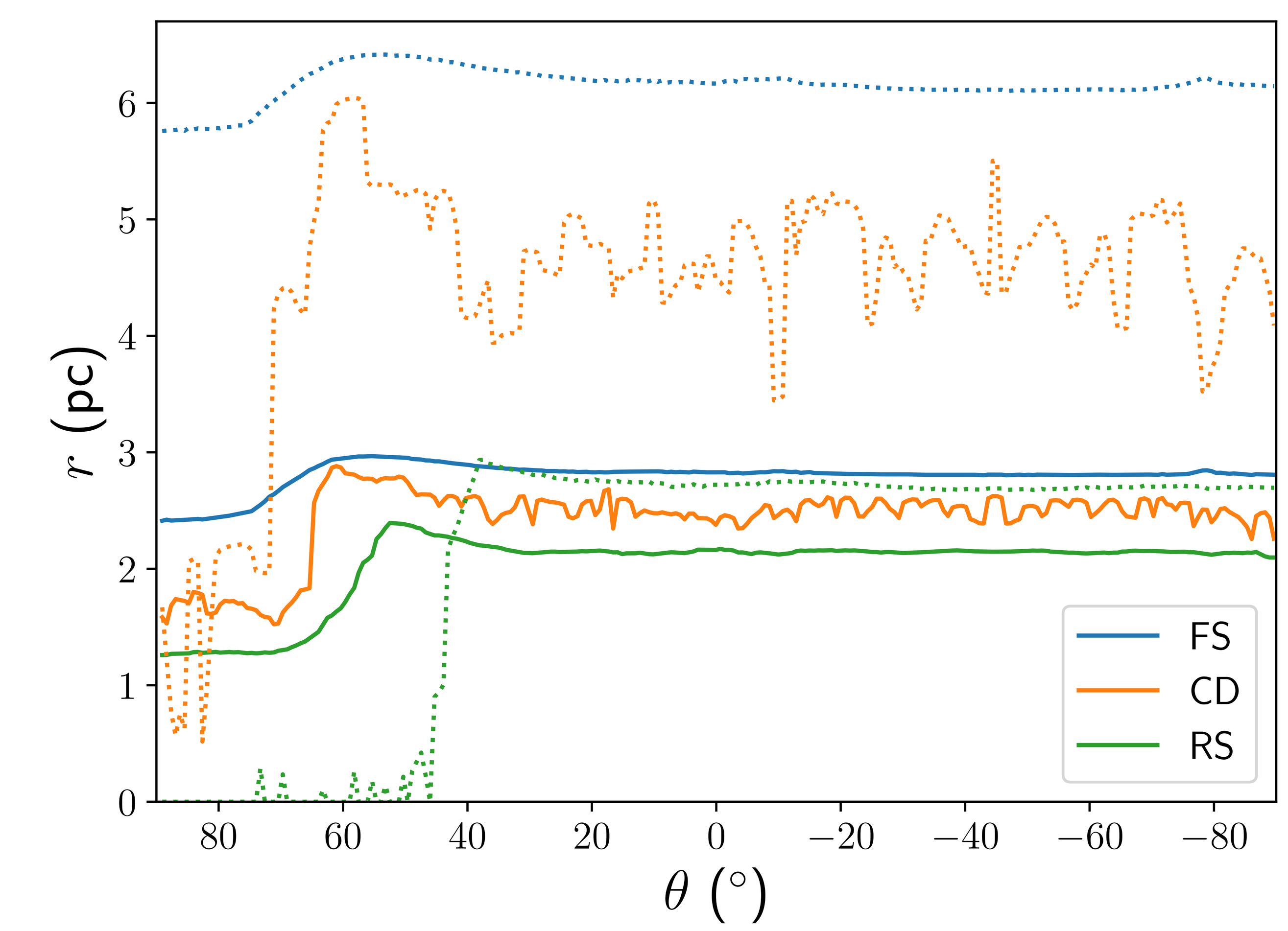
Reverse Shock:

The reverse shock is impeded far less within the wake than in the unperturbed ejecta, **reaching the center of the remnant in under a thousand years** and causing an off-center convergence of the reverse shock. This then leads to an asymmetrical bounce shock which drives ejecta into the wake at ≈ 10000 km/s, which is an order of magnitude greater than the forward shock velocity at this epoch.

In the wake, **theory correctly predicts the trajectory of the reverse shock provided the explosion energy and ejecta mass are effectively reduced** to reflect the lower density. However, in both the wake and in the unperturbed ejecta we find that the reverse shock quickly accelerates as it nears the center, causing theoretical predictions to overestimate the time at which the shock converges.

Contact Discontinuity

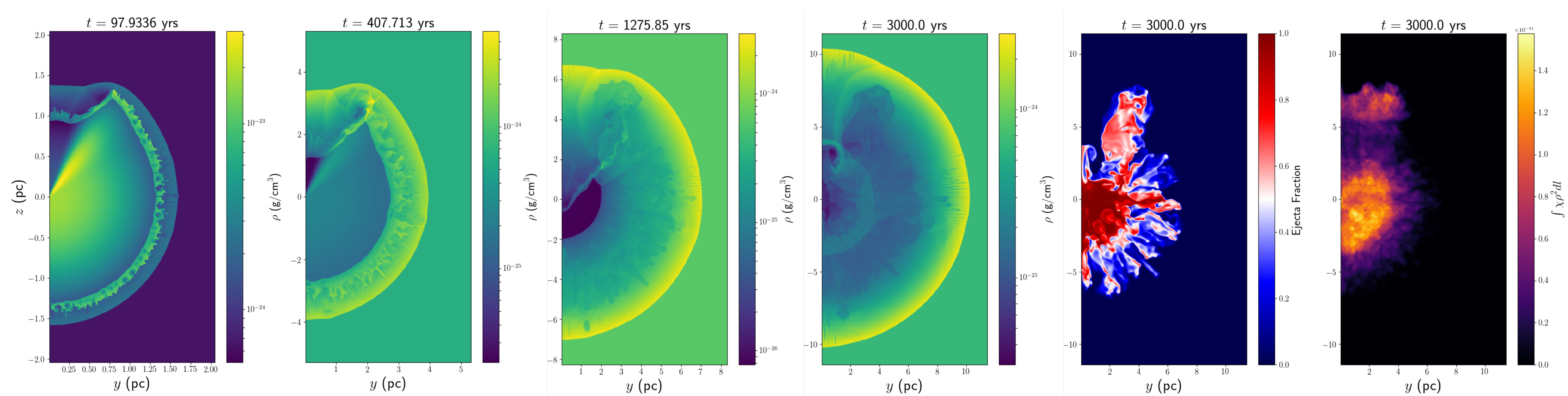
ISM material swept up by the forward shock is separated from supernova ejecta by the contact discontinuity, which deforms into long plumes due to Rayleigh-Taylor instabilities. **The instabilities are particularly strong at the edge of the wake,** where Rayleigh-Taylor plumes nearly reach the forward shock. This leaves a torus of ejecta material at the edge of the wake for thousands of years. On the other hand, within the wake **the reverse shock drags ISM material to near the center of the remnant.**



Radii of the shocks and contact surfaces at $t = 230$ yr (solid lines) and $t = 959$ yr (dotted lines). The center of the wake is at $\theta = 90°$, where the reverse shock has reached the center of the remnant at $t = 959$ yr. At both epochs, a Rayleigh-Taylor plume reaches nearly to the forward shock at the edge of the wake.

X-Ray Tomography

As supernova remnants are optically thin to X-rays, they provide an excellent probe of SNR morphology. Though the unshocked ejecta has cooled due to adiabatic expansion, **shock-heated gas is bright in X-rays due to thermal Bremstrahllung.** This emission is dominated by shocked ISM near the forward shock, though this can be distinguished from shocked ejecta – which displays far more asymmetry – as they differ spectroscopically. Using ρ^2 as a proxy for thermal emission, we define our emission measure to be $\int \chi\rho^2 dl$ along a line of sight, where χ is the ejecta mass fraction of the fluid. We only consider ejecta which has been heated by the reverse shock, which is characterized by high entropy. The result is shown in the rightmost panel of the bottom figure, where in the wake the emission extends several parsecs beyond that of the unperturbed ejecta.



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