Investigating the Asymmetry of the Magnetic Field Profile of "Simple" Magnetic Ejecta through an Expansion-Modified Flux Rope Model

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Abstract

Magnetic clouds (MCs) are most often fitted with flux rope models which are static and have typically a symmetric magnetic field profile. However, spacecraft measurements near 1au show that MCs usually expand when propagating away from the Sun and that their magnetic field profile is asymmetric. Both effects are expected to be related since expansion has been shown to result in a shift of the peak of the magnetic field towards the front of the MC. In this study, we investigate the effects of expansion on the asymmetry of the total magnetic field strength profile inside MCs. We restrict our study to the simplest events, i.e. those which are crossed close to the nose of the MC. From a list of 25 such "simple" events, we compare the fitting results of a specific expanding Lundquist model with the classical force-free circular cross-section static Lundquist model. We quantify the goodness of the fits by the χ^2 of the total magnetic field and identify three types of MCs: (i) those with little expansion, well fitted by both models, (ii) those with moderate expansion, well fitted by the expanding model but not by a static model and (iii) those with expansion, cannot explain the asymmetry of the magnetic field. We find that the assumption of self-similar expansion cannot explain the measured asymmetry in the magnetic field profile of some of these MEs. We discuss our results in terms of understanding of the CME magnetic field and its evolution from the Sun to Earth.

Methodology

Lundquist Solution:

$$\begin{cases} B_r = 0 \\ B_\phi = H B_0 J_1(\alpha r) \\ B_z = B_0 J_0(\alpha r) \end{cases}$$

J_0 and J_1 are the Bessel functions of order 0 and 1, and H = ±1 is the sign of the helicity.

Using Lundquist model on the magnetic field components, the following parameters are outputs: the orientation (latitude angle, θ, and longitude angle, ϕ), impact parameter, B_0 (magnitude field magnitude on the axis), helicity (H), and α.

Expanding Lundquist Solution:

$$\begin{cases} B_r = 0 \\ B_\phi = (\frac{B_0}{\tau}) J_1(\alpha r/\tau) \\ B_z = (B_0/\tau^2) J_0(\alpha r/\tau) \end{cases}$$

τ is defined as $\tau=(t+t_0)/t_0$ and t_0 is the duration the structure has been expanding self-similarly before the ME encounters the spacecraft. And t_0 is obtained from fitting the velocity profile.

Outputs of the Expanding Model (Exp-Lundquist): the orientation (latitude angle, θ, and longitude angle, ϕ), impact parameter, B_0 (magnitude field strength on the axis), helicity (H), and α.

- We fit 25 MEs by two models (Lundquist and Exp-Lundquist).
- We examine if the expansion model can get better fitting.
- We discuss if the shift of the magnetic field peak towards the front is due to expansion.
- We investigate whether or not expansion is self-similar.

Conclusions

- Both models fit the three magnetic field components very well (close χ^2 numbers of **B** components).
- Exp-Lundquist model returns smaller value of the χ^2_{Btotal}.
- We define a threshold of χ^2_{Btotal} of 0.035 and classify these 25 MEs into 3 types: (j) MEs well fitted by both models (12 events) for which both the static and expanding fitting models return a χ^2 below the threshold; (ii) MEs well fitted by the Exp-Lundquist model but not the static Lundquist model (3 events); (iii) MEs not adequately fitted by either model (10 events).
- MEs with very small asymmetry (Type 1) of the magnetic field profile can be well fitted by a static force-free model.
- Events with moderate asymmetry (Type 2, DiP ~ 0.4-0.45, e.g.) can be well fitted by a force-free model with self-similar expansion.
- Events with larger asymmetry (Type 3), the expansion alone cannot explain the entire asymmetry.

Examples

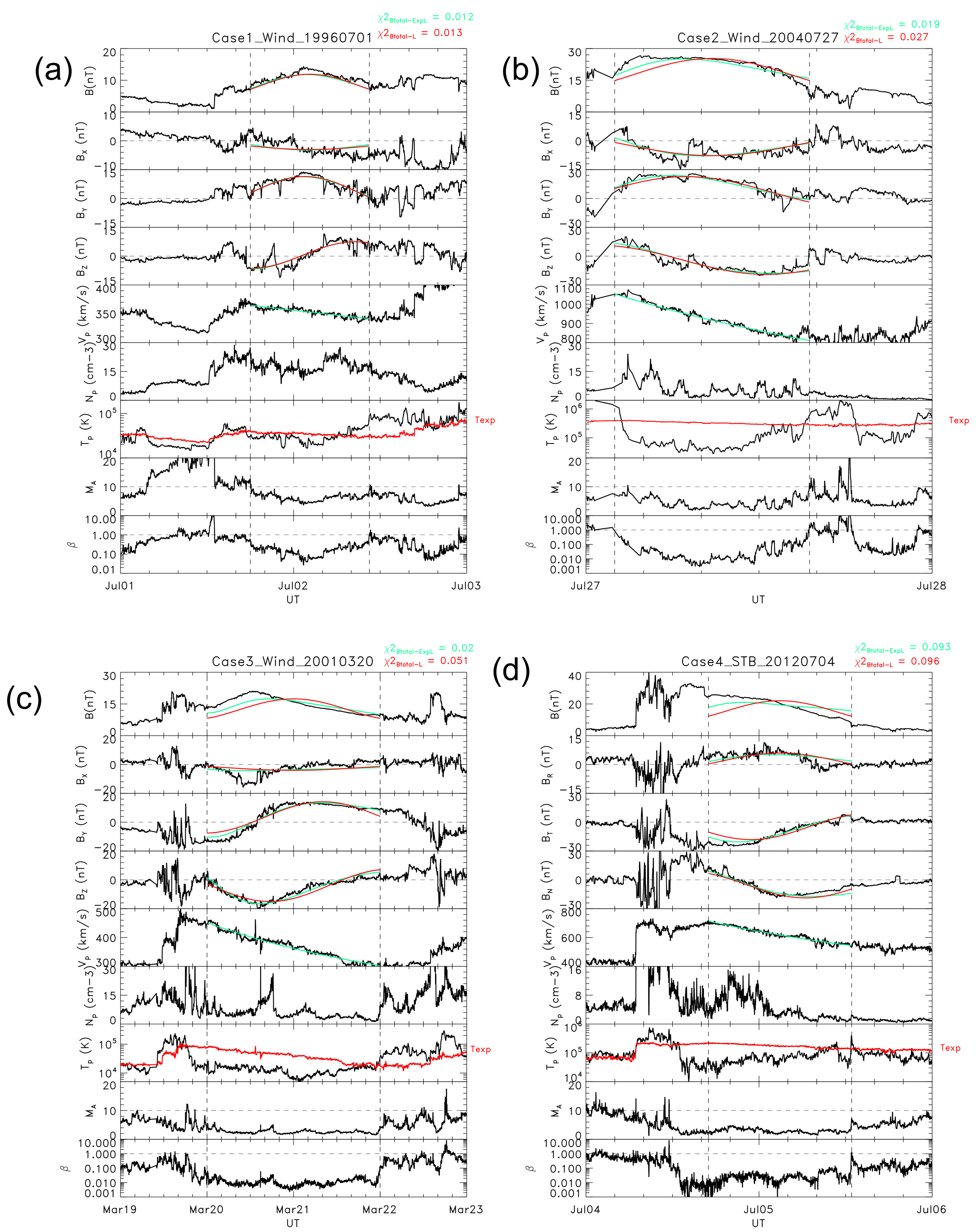

Figure 1: 4 typical MCs. (a) Wind – 19960701. (b) Wind – 20040727. (c) Wind – 20010320. (d) STB – 20120704. The panels from the top to bottom are: (i) B_{total}; (ii) three **B** components; (iii) V_p; (iv) N_p; (v) T_p; (vi) M_A; (vii) β_p.

- Our results indicate that the shift of the magnetic field peak towards the front is only partially due to expansion.
- We conclude that the assumption of self-similar expansion is not correct for most events as a self-similar expanding force-free field model is not able to fit the observed asymmetry of the magnetic field profile.

Results

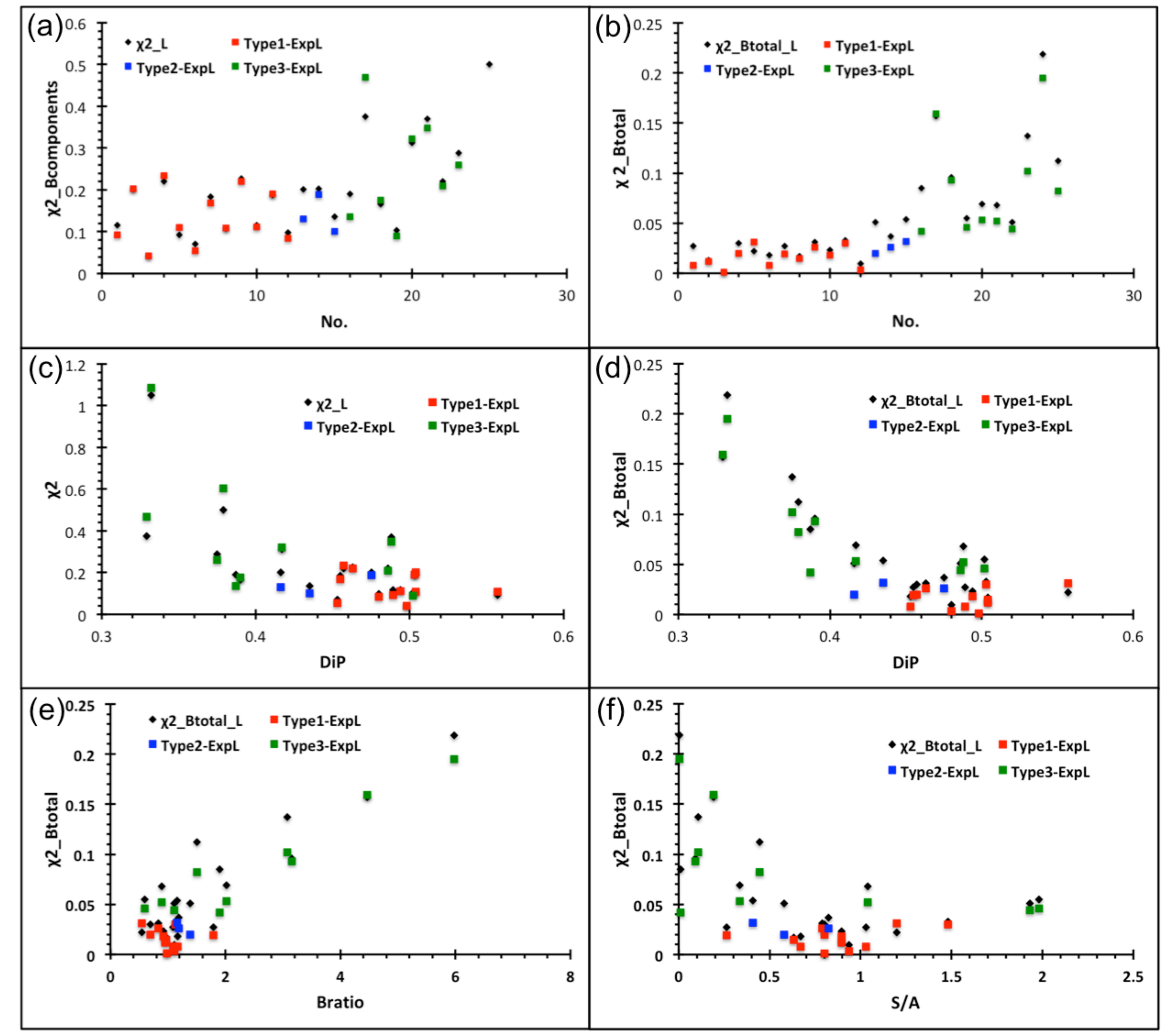

Figure 2. The scatter distributions of the χ^2 values of two models. (a) Normalized χ^2 of **B** components; (b) normalized χ^2_{Btotal}; (c) DiP vs. normalized χ^2 of **B** components; (d) DiP vs. normalized χ^2_{Btotal}; (e) B_{ratio} vs. normalized χ^2_{Btotal}; (f) S/A vs. normalized χ^2_{Btotal}.

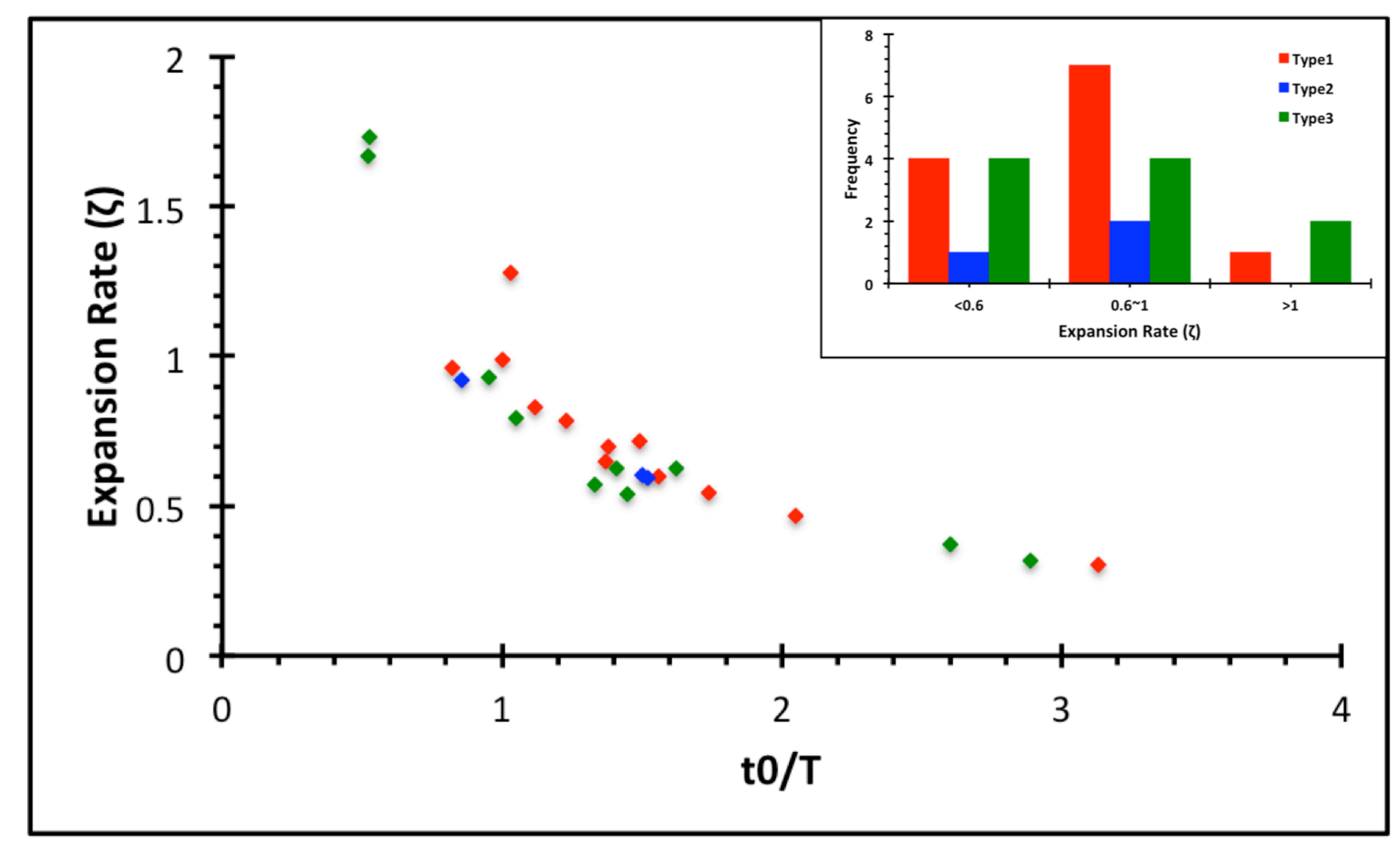

Figure 4. t_0/T vs. dimensionless expansion rate (ζ) of the Exp-Lundquist model and its distribution.

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