

## Unfolding of the vortical amplification of the magnetic field at inward shocks of Supernova remnant Cassiopeia A

F. Fraschetti,<sup>a,b,\*</sup> S. Katsuda,<sup>c</sup> T. Sato,<sup>d</sup> J. Giacalone<sup>b</sup> and J. R. Jokipii<sup>b</sup>

<sup>a</sup>Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, 02138, USA

<sup>b</sup>Lunar & Planetary Laboratory, Department of Planetary Sciences, University of Arizona, Tucson, AZ 85721, USA

<sup>c</sup>Graduate School of Science and Engineering, Saitama University, 255 Shimo-Ohkubo, Sakura, Saitama 338-8570, Japan

<sup>d</sup>RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

E-mail: [federico.fraschetti@cfa.harvard.edu](mailto:federico.fraschetti@cfa.harvard.edu)

We present an interpretation of the time variability of the X-ray flux reported from a 15 years multi-epoch observational campaign of the supernova remnant Cassiopeia A by *Chandra*. The increase of the [4.2 – 6] keV non-thermal flux up to 50% is shown quantitatively to trace the growth of the magnetic field due to vortical amplification mechanism at inward shocks colliding with inner overdensities. The fast synchrotron cooling as compared with shock-acceleration time scale qualitatively explains the subsequent flux decrease.

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\*Presenter

## 1. Introduction

The year time-scale variability in the  $X$ -ray filaments and knots of the supernova remnant Cassiopeia A was associated [1] with a fast synchrotron cooling in strong magnetic field; a decline of the  $X$ -ray flux between 2000 and 2010 was observed with *Chandra* in the entire remnant's western limb [2]. High spatial resolution multi-epoch observations of Cassiopeia A have shown unprecedented evidence of an increase followed by a decrease of  $X$ -ray flux ([4.2 – 6] keV band) up to 50% in six distinct regions approximately  $10'' \times 10''$  or  $15'' \times 15''$  in size located on the west side and toward the center of the remnant [3]; such observations cover a time period of 15 years (from 2000 to 2014). The location of these regions is consistent with a high speed shock observed to move inward. Due to the young age of the remnant, such a shock is unlikely to correspond to the reverse shock, that would move outward at such evolution stage, and plausibly originated as a reflection from the collision of the forward shock with an interstellar medium molecular cloud; such a scenario was modelled in an earlier work [4]. As a result of such reflection, the inward shock surface is likely to be corrugated to the scale of the molecular cloud.

In [5] overdensity clumps within the expanding plasma of Cassiopeia A were shown to lead to the [4.2 – 6] keV flux increase via magnetic field amplification through vorticity generation, after crossing by the reflection inward shock. Such a process was investigated numerically [6, 7], analytically [8] and in laboratory experiments [9]. Figure 1 shows a cartoon illustration of the scenario proposed in [5]: the corrugated inward shock travels through the shocked layer and therein collides with density clumps, generates vorticity and amplifies the magnetic field in the downstream medium.

The induction equation for  $B$  was solved in [8] to determine the MHD jump conditions at corrugated shock fronts; the vorticity generated behind the shock is related to  $B$  via the small-scale dynamo process [10] leading to

$$\left(\frac{B}{B_0}\right)^2(t) = \frac{e^{2t/\tau}}{1 - \alpha\tau(1 - e^{2t/\tau})v_A^2/2}, \quad (1)$$

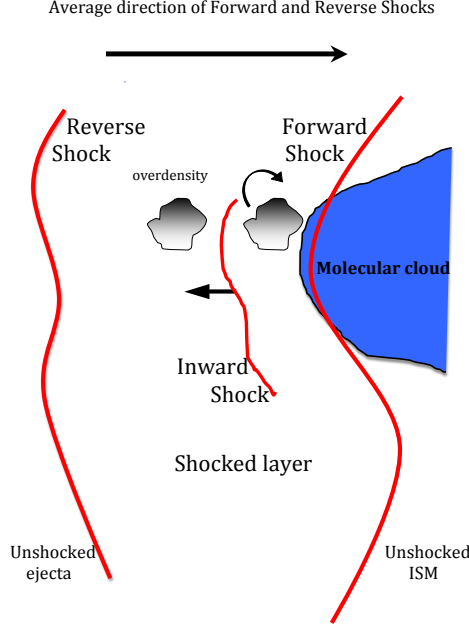
where  $B_0$  is the upstream seed magnetic strength and

$$\tau = \frac{r}{r-1} \frac{1}{C_r} \frac{R_c \ell_F}{R_c + \ell_F} \quad (2)$$

is the growth time-scale determined by the shock compression  $r$ , the curvature radius of the ripples on the forward shock surface  $R_c$  that is expected to be comparable with the size of the overdensity clumps, the thickness of the outer clump layer where the density gradient is non-vanishing  $\ell_F$  (corresponding to the Field length in the ISM) and the shock speed in the upstream frame  $C_r$ ;  $\alpha \sim 1/R_c C_r$  describes the field back-reaction to the whirling of the fluid and  $v_A$  is the seed field Alfvén speed. As calculated in detail in [8], the  $B$ -amplification occurs within the outer layer of thickness  $\ell_F$ .

## 2. Flux increase

The main assumption is that the time-variation of the non-thermal emission (assumed to be synchrotron radiation by energetic electrons) is due to the time-variation of the magnetic field  $B(t)$ .



**Figure 1:** Cartoon illustration: the inward shock recedes into the shocked layer and crosses outward moving clumps. The arrows indicate the direction of the shocks motion in the observer frame.

For a differential energy distribution of the energetic electrons given by a simple power-law, it holds  $dN/d\gamma = N_0(\gamma/\gamma_0)^{-p}$ , where  $\gamma_0$  is the injection electron Lorentz factor and the index  $p$  is determined by the shock compression only, as predicted by the linear test-particle version of the diffusive shock acceleration model.

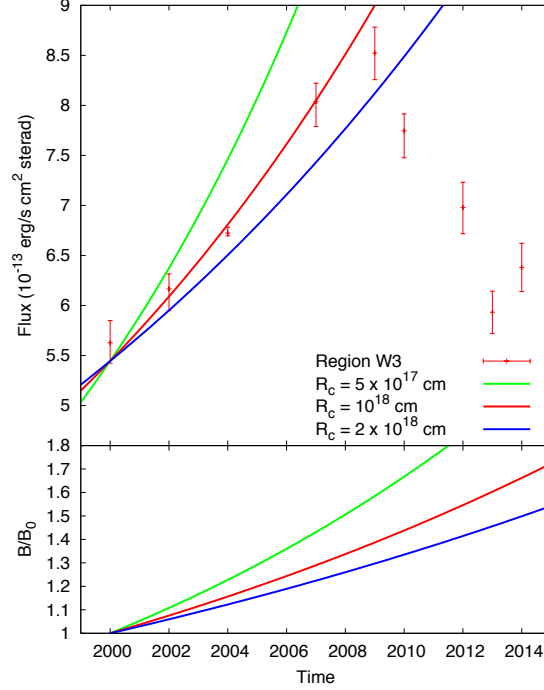
The total synchrotron flux at Earth from Cas A, located at distance  $d$ , namely  $\nu F_\nu$ , is found by folding the single electron isotropic power with  $dN/d\gamma$ . Assuming that the electron power is concentrated around the characteristic synchrotron energy  $\epsilon_s = 0.29(3eh\gamma^2 B)/(4\pi m_e c)$ , where  $e$  is the electron charge and  $h$  is the Planck constant, we recast the total flux observed at Earth as

$$\nu F_\nu(\epsilon, t) = \frac{1}{4\pi d^2} \frac{\sigma_T c}{12\pi} \frac{N_0}{\mathcal{A}} \gamma_0^p \epsilon^{-\frac{p-3}{2}} B(t)^{2+\frac{p-3}{2}} \quad (3)$$

where  $\sigma_T$  is the Thomson cross-section,  $c$  speed of light in vacuum and the constant  $\mathcal{A}$  is defined as  $\mathcal{A} = [0.29(3eh)/(4\pi m_e c)]^{-\frac{p-3}{2}}$ .

In [5] we reproduced (see Fig. 2, upper panel), the observed flux change in the range [4.2 – 6] keV compared with the theoretical prediction (from Eq.3) for  $\epsilon = 5$  keV,  $d = 3.4$  kpc and for distinct values of  $R_c$ . The model of the flux increase depends only on two fitting parameters,  $R_c$  and  $\ell_F$ . The best-fit values for the time-interval [2000 : 2009] are  $R_c = (1.00 \pm 0.16) \times 10^{18}$  cm and  $\ell_F = (7.03 \pm 0.76) \times 10^{17}$  cm. The error bars on  $R_c$  and  $\ell_F$  are likely dominated by the uncertainty on the exponential rise. In addition, the 2009 data-point belongs to the incipient decrease phase of the flux, hence is not accounted for by our analytic model.

The inward shocks are likely to be travelling into a hot plasma with electron temperature  $\sim 2$  keV (see also [11]), in equilibrium with ions: narrow lines in some bright knots indicate low ion



**Figure 2:** *Upper panel:* Theoretical synchrotron flux at  $\epsilon = 5$  keV as a function of time for distinct values of  $R_c$  compared with *Chandra* [4.2 – 6] keV observations; here  $\ell_F = 7.03 \times 10^{17}$  cm. The best fit is represented by the red line. *Lower panel:* Time-evolution of relative magnetic strength during the turbulent amplification for the three cases shown above, with the same color-labels.

temperature within the remnant [12]. For the W3 inward shock  $C_r = 6,500$  km/s in the shocked layer frame [table 3 in ref. 3]. Comparable best-fit values of  $R_c$  and  $\ell_F$  for the other inward shocks reported in [3] were found by [13].

### 3. Flux decrease

The time of the peak of  $\nu F_\nu^{[4.2-6] \text{ keV}}$ , occurring in  $\sim 2009$  for W3, was approximated by the ratio of the synchrotron cooling time scale,  $t_{cool}$ , to the acceleration time-scale,  $t_{acc}$ . For an electron emitting synchrotron radiation in an ambient downstream magnetic field  $B(t)$  at a typical photon energy  $\epsilon$ , it holds

$$t_{cool}(t) \simeq (55 \text{ yr}) \epsilon_{keV}^{-1/2} B_{0.1}(t)^{-3/2}. \quad (4)$$

At  $\epsilon_{keV} = \epsilon/1 \text{ keV} = 5$ , the value  $t_{cool} = 4$  yrs yields at a time  $t^* = 2009$  the field  $B_{0.1}(t^*) \simeq 3.4$ , in the expected range for Cassiopeia A, as discussed in Ref. [1]. The best-fit  $B$ -field (solid line in the lower panel in Fig. 2) shows a ratio  $B(t^*)/B_0 \simeq 1.35$  that leads to  $B_{0(0.1)} = 2.5$ , with  $B_{0(0.1)} = B_0/0.1$  mG. Such a relatively high  $B_0$  confirms that an amplification in W3 likely took place at the inward shock prior to year 2000, possibly via vorticity generation within the shocked layer due to the corrugation of the inward shock or an alternative mechanism [14].

The acceleration time-scale  $t_{acc}$  can be approximated by [15]

$$t_{acc} \simeq 1.83 \frac{3r^2}{r-1} \frac{D_0}{C_r^2} = (43.7 \text{yr}) \frac{3r^2}{r-1} k_0 \epsilon_{keV}^{1/2} B'_{0.1}{}^{-3/2} C_{r,3}^{-2} \quad (5)$$

where for an isotropic upstream turbulence  $D_0$  is the diffusion coefficient at the electron cut-off energy along the average direction of shock motion and  $k_0$ , assumed [15] to be equal upstream and downstream, is given by  $k_0 = D_0/D_B$ , where  $D_B$  is the Bohm diffusion coefficient at that energy. The departure from unity of  $k_0$ , both  $k_0 > 1$  ( $k_0 < 1$ ) for shocks close to quasi-parallel (or quasi-perpendicular) topology within the acceleration region, indicates that the turbulence is not dominant over the seed field [16]. Finally, the upstream field, constant in time as the amplification occurs downstream in the model presented here for the flux increase (plasma kinetic instabilities are neglected), is given by  $B'_{0.1} = B'/0.1$  mG and  $C_{r,3} = C_r/(1,000 \text{ km/s})$ . For the speed  $C_{r,3} = 6, 5$  at the latest *Chandra* observation, in region W3 we estimate  $k_0 = 4.7$  from Eq. 3 in [3]; for  $B'_{0.1} = 2.5$ , Eq. 5 provides  $t_{acc} \sim 42$  years, significantly greater than  $t_{cool} \sim 4$  years. A cooling faster than the acceleration is consistent with the observed flux decrease. More sophisticated models for the diffusion coefficient (e.g., [17], [18]) will not substantially change this qualitative argument. An extended discussion can be found in [5]. In the analysis by [19] of a sample of 11 young SNRs, including Cas A, the maximum energy attained by accelerated particles is inferred to be higher if the time evolution of the turbulent magnetic component is included. Certainly the vortical amplification needs to be accounted for in the modelling of the synchrotron emission downstream of the shock. The analysis presented herein offers a quantitative interpretation of *Chandra* observations in terms of magnetic field dynamics.

#### 4. Conclusion

We have outlined that the X-ray flux increase between years 2000 and 2009 in a number of small regions close to center and in the west limb of Cassiopeia A can trace [5] the growth of the magnetic field due to vortical amplification as determined in [8]. Values of the diffusion coefficient departing from the Bohm limit, that indicate relatively weak turbulence around the shock, are also consistent with the inferred modest field amplification. We have provided [5] a qualitative argument but not a firm theoretical model for the flux decrease between years 2009 and 2014. Further analysis is warranted and high-resolution follow-up monitoring of the region W3 is encouraged. This work demonstrates that the unfolding of a dynamo process formerly theoretically identified can be not only investigated in laboratory plasma astrophysics but also observed in astrophysical systems.

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