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October 22, 2017

Simulations of Cosmic Strings

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Started Mar 1, 2015; handed-in Jun 17, 2016

ABSTRACT

Aims. The main goal is to obtain simulation maps of pure Cosmic Strings based on the Kaiser-Stebbins (KS) effect.
Methods. For that, we have created a code implemented in Python from scratch which reproduces anisotropies produced by long cosmic strings according to the KS effect.
Results. We have obtained pure Cosmic Strings maps sub-standing a view of 12.8° with a resolution of 1.5 arcmin, together with it Power Spectrum.

Key words. Cosmic Strings, KS effect, Cosmology

1. Introduction

Cosmic Strings (CS) are considered to be one-dimensional topological defects that may have appeared during the breaking of symmetry in a phase transition in the early universe, and therefore they may form stable configurations of matter. Cosmic Strings can be associated with grand unified particle physics models, or they can form at the the Electroweak scale. They are though to be very thin and may stretch across the visible universe.

It is believed that Cosmic Strings leave imprints in the CMB through a signature denominated "Kaiser-Stebbins (KS) effect", that consists of line discontinuities in the temperature map formed from a combination of gravitational lensing and the Doppler effect. That is, photons from the last scattering surface that encounters a moving cosmic string will be observed to have a temperature which differs by a small amount proportional to the string tension G_μ.

1.1. Implementation of the code for pure Cosmic Strings

The code has been written from scratch, working in the “flat sky” approximation in which a segment of the sky may be approximated by a rectangle. We have simulated only into account pure Cosmic Strings that do not take account of its small structure and do not incur in loops.

The program is defined to evaluate the number of CS at different times t since the decoupling in terms of exponential steps. For that, it is necessary to evaluate the Hubble radius d_c at each of these steps following the iterative expression,

$$d_c = d_0 e^{t/3}, \tag{1}$$

where $d_0 = 1.8^{\rm o}$ is the Hubble radius at the time of decoupling $t = 0$. Once that the Hubble radius is obtained, we evaluate the number of Hubble volumes N_h at each time as,

$$N_h = \left(\frac{L}{d_c} + 2\right)^2 \tag{2}$$

where $L = 12.8^{\rm o}$ is the size of the square view. Finally, the number of CS that should be thrown at each time t is defined as,

$$N_s = N \times N_h \tag{3}$$

where $N = 10$ is a parameter that indicate the average number of strings per Hubble volume. Once that the number of CM is set, the program calculates randomly the position, orientation and projection of the strings that have to be thrown at each time. CS are thrown in a larger field view, that extends the original view L. The extended field is defined as $L_e = L + 2d_c$.

For every CS, each point of the grid represents a temperature fluctuation $\Delta T/T$ defined as,

$$\frac{\Delta T}{T} = 4\pi r v G_\mu \tag{4}$$

where v represents the root mean square (over all strings) value of the velocities (based on previous simulations a value of $v = 0.15$ has been selected), r a random number between 0 and 1 that adjusts the velocity to take into consideration the different velocities that the string might have as well as the projection of the velocity of the string onto the plane perpendicular to the line of sight. For every CS, the temperature fluctuation is randomly fixed to be positive or negative at each side of the string using a simple flag.

Therefore, the program runs in a loop of 15 steps the status and evolution of the CS and their effect in temperature fluctuation. The result is a final pure Cosmic String map that contains the superposed information of the central field of size L along the different evaluation times.

The repository where the software is found is available at HTTPS://GITHUB.COM/GCANASHERRERA/COSMIC-STRINGS.GIT. For installation, simply download the repository and execute the main script.

2. Results

2.1. Simulation maps

In this section some examples of pure CS maps are shown for different values of the string tension G_μ and time steps t.

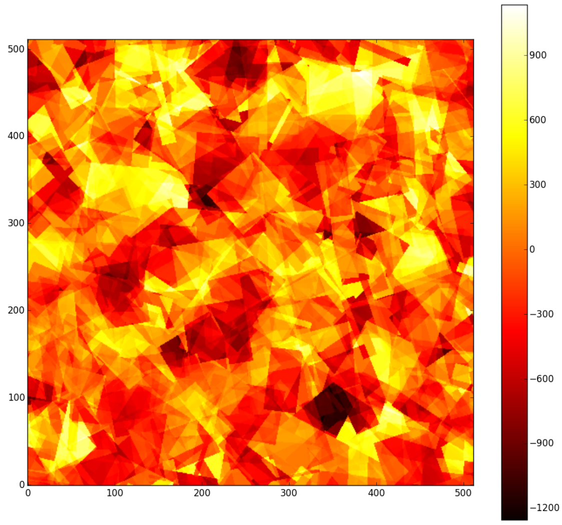

Fig. 1. Graphical representation of the Cosmic String map for the time step $t = 0$ for a string tension of $G_\mu = 1$ and $N = 10$.

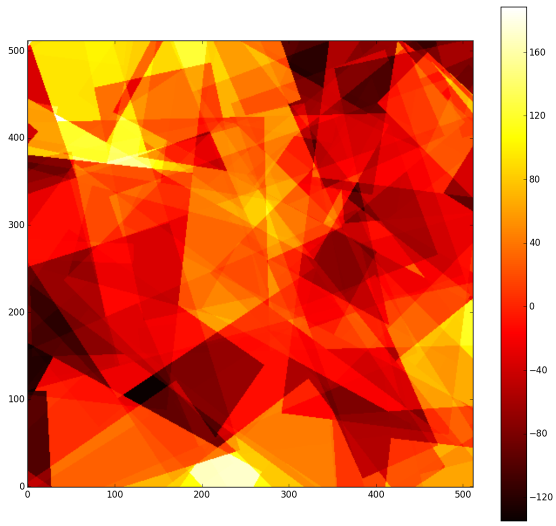

Fig. 2. Graphical representation of the Cosmic String map for the time step $t = 4$ for a string tension of $G_\mu = 1$ and $N = 10$.

It is possible to observe how if the time passes by (time steps increases), so does the Hubble radius, and therefore the number of strings get reduced. In Figure 1, it is observed that the number of strings is larger than in Figures 2 and 3, where in the last one only few strings are thrown. Moreover, the strings length l_s does also increase when the time step is incremented. This is due to the fact that the strings length is defined such as,

$$l_s = \gamma d_c \tag{5}$$

where in our simulations we have set $\gamma = 1$. When the simulation is run over the whole set of time steps (until $t = 15$). For further values of the most respresentative parameters of these simulations for different time steps, see Table 1.

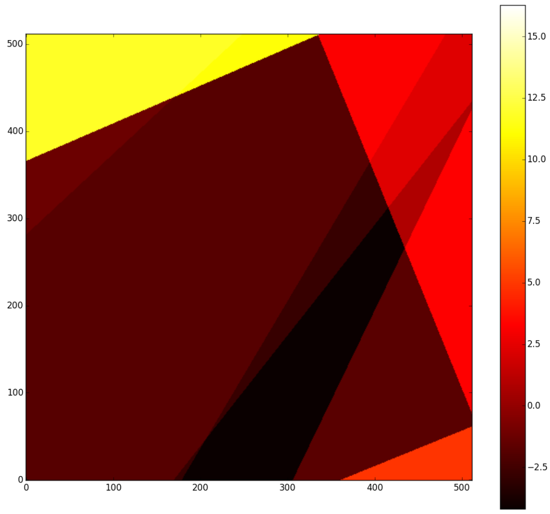

Fig. 3. Graphical representation of the Cosmic String map for the time step $t = 12$ for a string tension of $G_\mu = 1$ and $N = 10$.

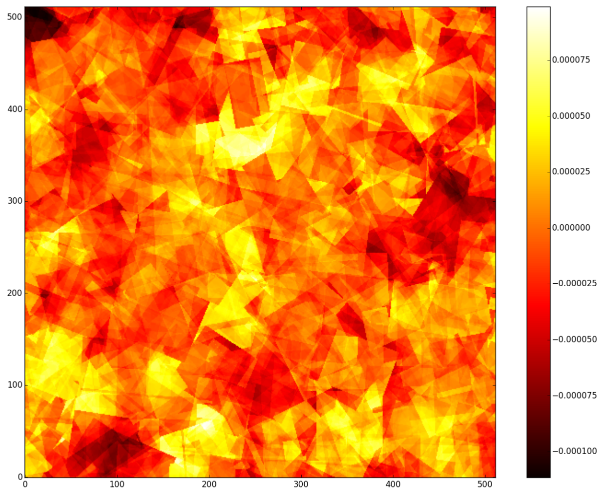

Fig. 4. Graphical representation of the final Cosmic String map integrated over 15 time steps for a string tension of $G_\mu = 6 \times 10^{-8}$ and $N = 10$.

In Figure 4, where the effects of all time steps are superimposed, we observe how the overlap of the straight line temperature discontinuities produced by individual strings are no longer visible, and therefore, the overlapping problem gets worse than in cases shown in Figures 1, 2, and 3. Furthermore, in Figure 5 we observe how pure Cosmic Strings map do not follow a normal distribution as expected.

t	d_c	N_h	N_s	L_e
0	72.0	83	830	656
1	100.5	50	503	713
2	140.2	32	319	792
3	195.7	21	213	903
4	273.1	15	150	1058
5	381.2	11	112	1274
6	532.0	9	88	1576
7	742.5	7	72	1997
8	1036.2	6	62	2584
9	1446.2	6	55	3404
10	2018.3	5	51	4549
11	2816.7	5	48	6145
12	3931.1	5	45	8374
13	5486.2	4	44	11484
14	7656.7	4	43	15825
15	10685.7	4	42	21883

Table 1. Values of the Hubble radius, number of Hubble volumes and cosmic strings, and the size of the extended view at different time steps.

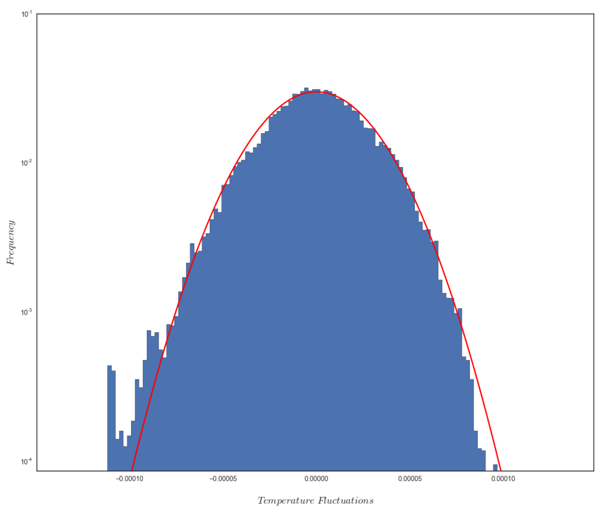

Fig. 5. Graphical representation in logarithmic scale of the histogram corresponding to the simulation map of Figure 5 (in blue), overlapping with a Gaussian distribution matching its standard deviation (in red). The mean of both distributions is equal to zero.

2.2. Power Spectrum

In order to analyze the obtained simulation maps, we have calculated the angular power spectrum of the map recorded in Figure 4. The power spectrum characterizes the size of the fluctuations as a function of angular scale. The results are placed in Figures 6 and 7. They show the the mean of the power spectrum for each l based on 100 runs. The error bars, no visible in the figures, are standard errors (of the order of 10^{-12}).

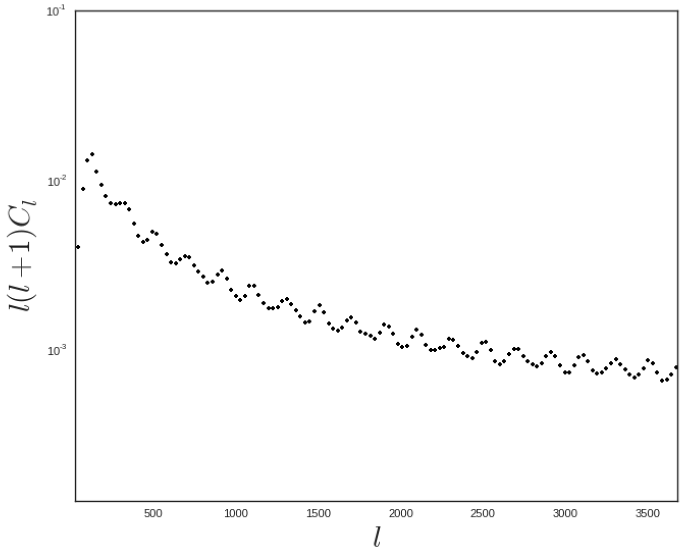

Fig. 6. Graphical representation of the angular power spectrum of the CMB anisotropy maps of pure CS for values N = 10 $G_\mu = 6 \times 10^{-8}$ and $N = 10$. The horizontal axis is l, the vertical axis is $C_l l(l+1)$.

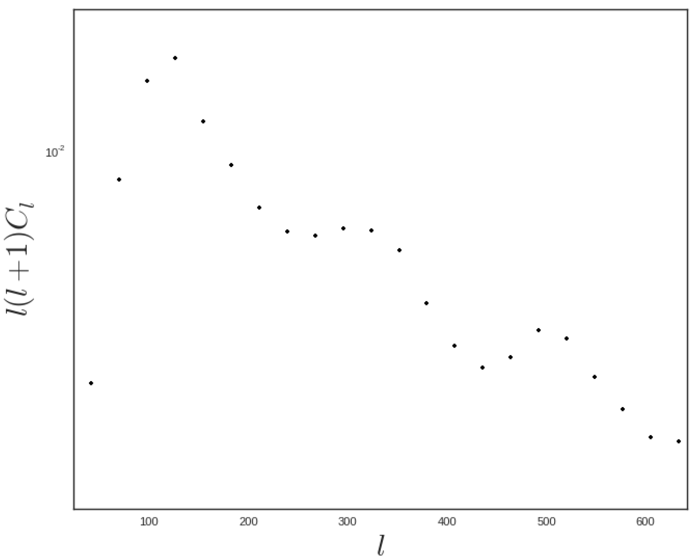

Fig. 7. Detail the angular power spectrum of the CMB anisotropy maps of pure CS for values N = 10 $G_\mu = 6 \times 10^{-8}$ and $N = 10$. The horizontal axis is l, the vertical axis is $C_l l(l+1)$.

3. Issues and conclusions

In spite of the fact that the maps obtained from the simulations look like the ones obtained by Rebecca J. Danos and Robert H. Brandenberger, we have concluded that there is a missing factor of around 10^9 to agree with their power spectrum of their CS simulation maps. Probably, this factor is included in their simulations.

References

[1] Rebecca J. Danos and Robert H. Brandenberger, *Canny Algorithm, Cosmic Strings and the Cosmic Microwave Background*, International Journal of Modern Physics D, Volume 19, Issue 02, pp. 183-217 (2010).

[2] Amsel, Stephen; Berger, Joshua; Brandenberger, Robert H., *Detecting cosmic strings in the CMB with the Canny algorithm*, Journal of Cosmology and Astroparticle Physics, Issue 04, id. 015, 14 pp. (2008).