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(Research Article)

Complex Network of sunspots

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Summary

The Sun is an external object that significantly impacts the earth's atmosphere and space weather conditions. Flares and coronal mass ejections are large-scale solar atmospheric features that mainly emerge at active regions above the sunspots and have influenced the earth. The sunspots, considered signatures of solar activity, are fascinating features related to the internal dynamics and activity of the Sun. The appearance of the sunspots in the photosphere shows the complexity of the magnetic field on the Sun. The frequency and size of sunspots change over time which show periods (e.g., eleven years periodicity) that may be a sign of the complex Sun. The time series of the sunspot numbers have been recorded for several centuries, and this time series is significantly changed over time. The complex network approach is a way to investigate the inherent property of complex time series, such as the sunspots time series.

In this study, the growing complex network with the visibility condition is constructed using the time series of the sunspots (time and numbers) for 1922 to 2016 collected by SILSO. We compute the complex network parameters such degree of nodes, shortest path length, and clustering coefficients. We examine the sunspot complex network's scale-free, small-world, and assortative properties.

We show that the degree distribution of the complex network for the time series of the sunspots obeys a power-law distribution function. We applied a method via maximum likelihood estimation in the Bayesian framework to obtain the power indicated. Therefore, the degree exponent is obtained larger than three, so the complex network for the time series of the sunspots is small-world and scale-free. The power-low behavior is an essential characteristic of self-organized or self-organized criticality systems. Limited productivity is a crucial property for these complex systems. The small word behavior indicates that the large sunspot numbers in the time series are clustered with several small values neighbors and linked with distinct large values in the time series.

The small-world network represents a small characteristic path length with a high clustering coefficient. The scale-free and small-word behavior for the network of the sunspots time series may imply that the sunspots and sunspot groups forming via complex non-linear dynamics. Changing the magnetic polarity of the sunspots during the solar cycle can be a characteristic of such complex systems. The limited predictability in sunspots' time series, e.g., the intensity of activity within a solar cycle, may also be another sign of the complex Sun.

The behavior of the degree of node distribution, clustering coefficient, and shortest path length indicates that the time series of sunspots is a non-random system. We showed that the degree of correlation is a function of the network size and can be considered as an assortative, dis-assortative, or neutral network.

Keywords: Sunspots, Small-world network, Scale-free network.

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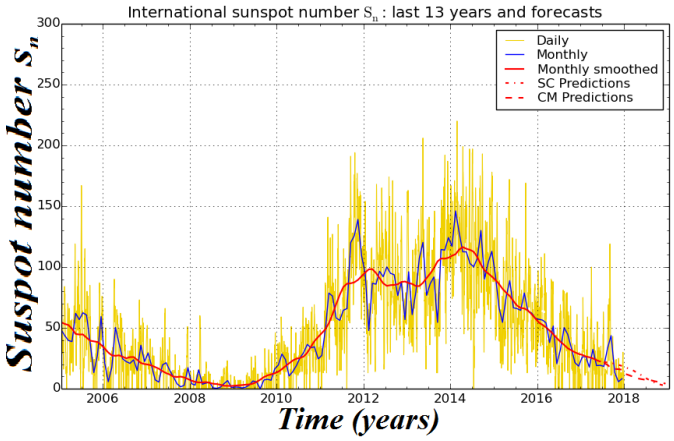

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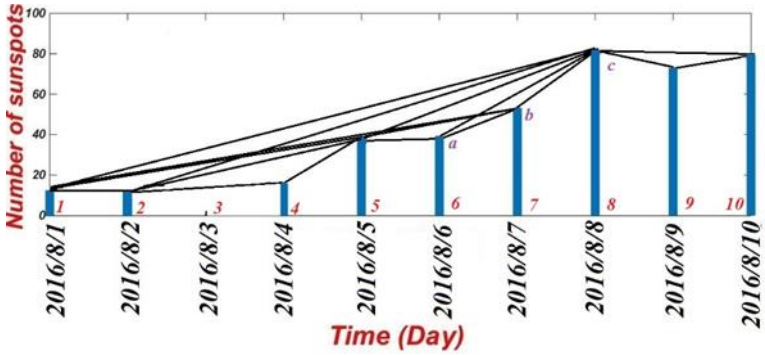
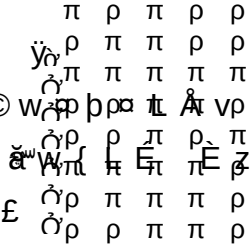
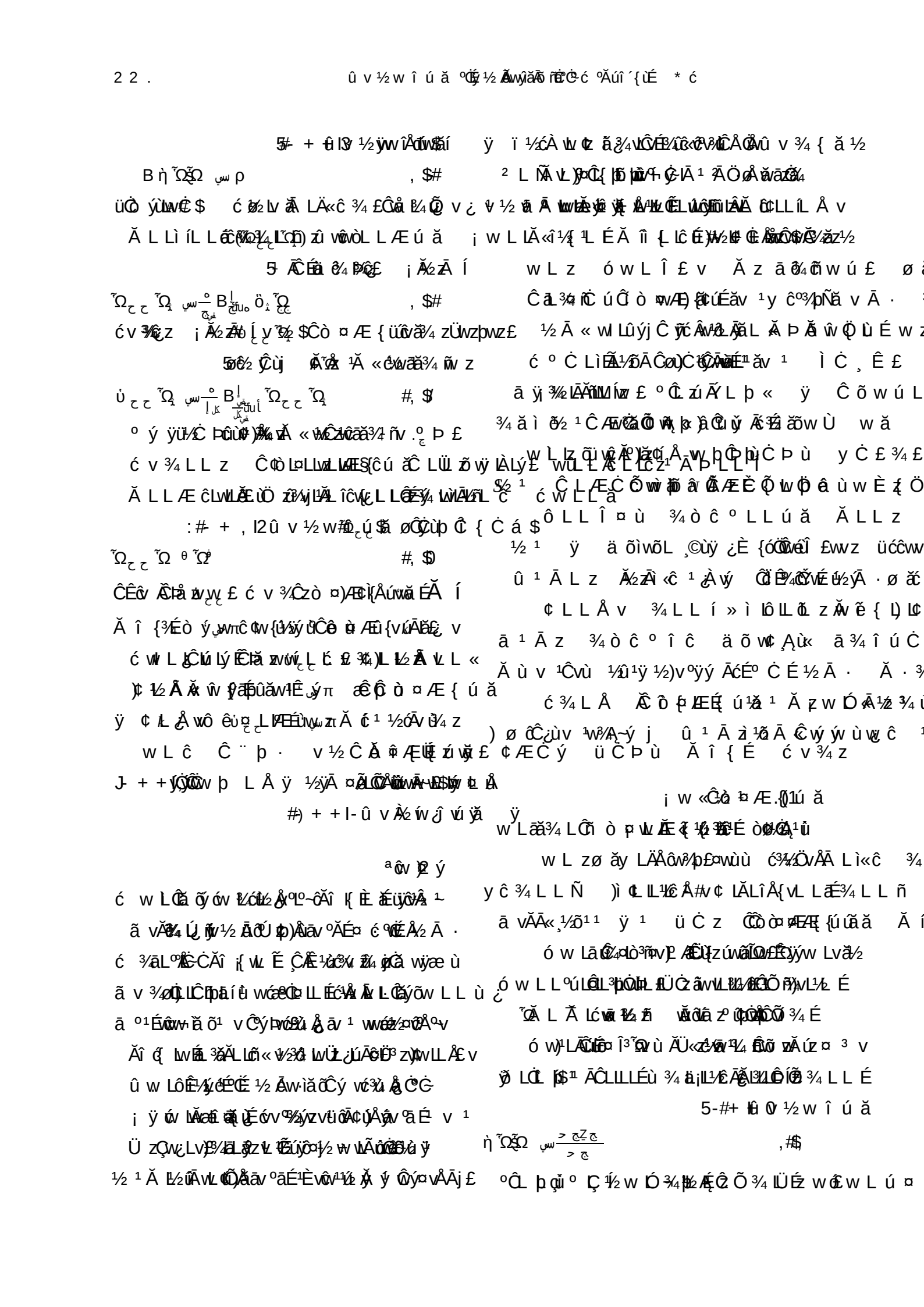

Number of sunspots
Time (Day)
2016/8/1
2016/8/2
2016/8/3
2016/8/4
2016/8/5
2016/8/6
2016/8/7
2016/8/8
2016/8/9
2016/8/10
a
b
c





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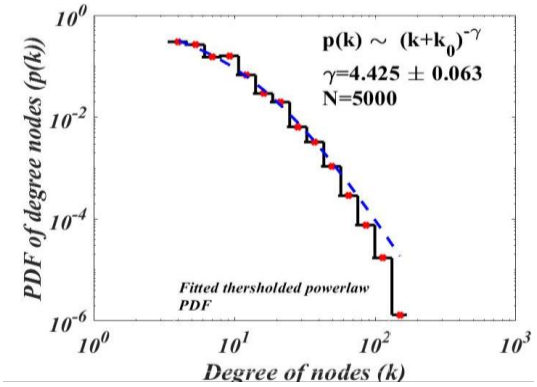

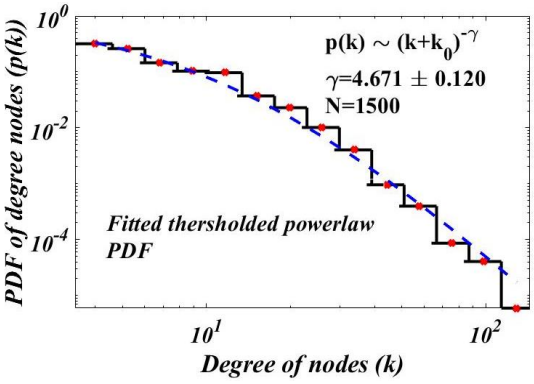

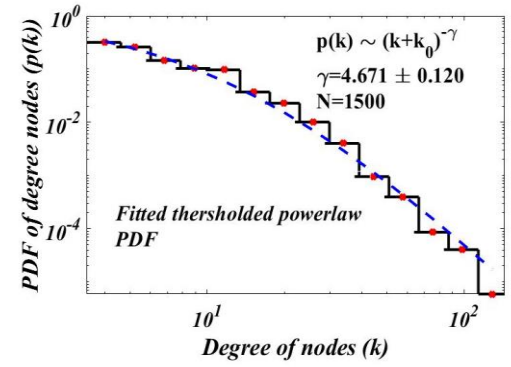

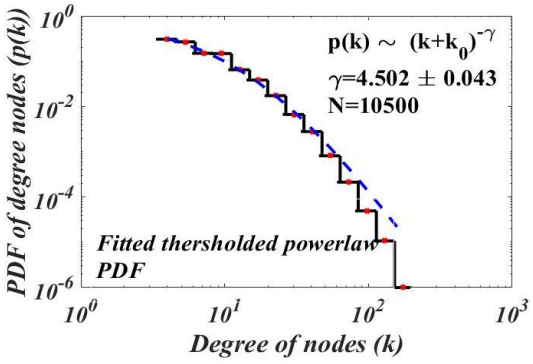

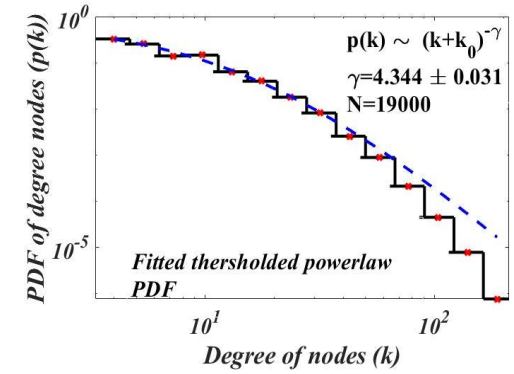

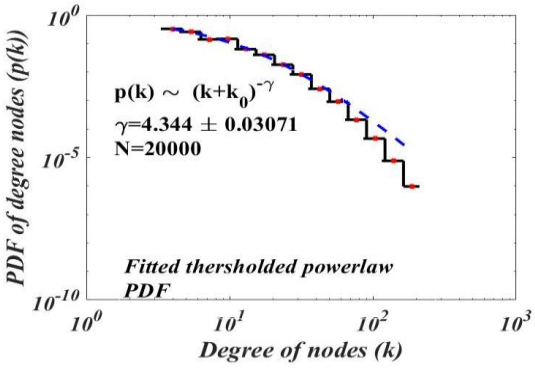

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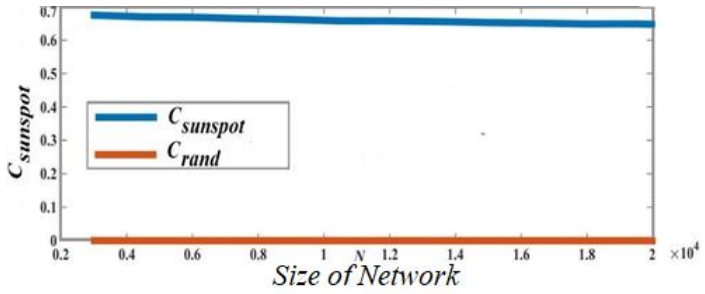

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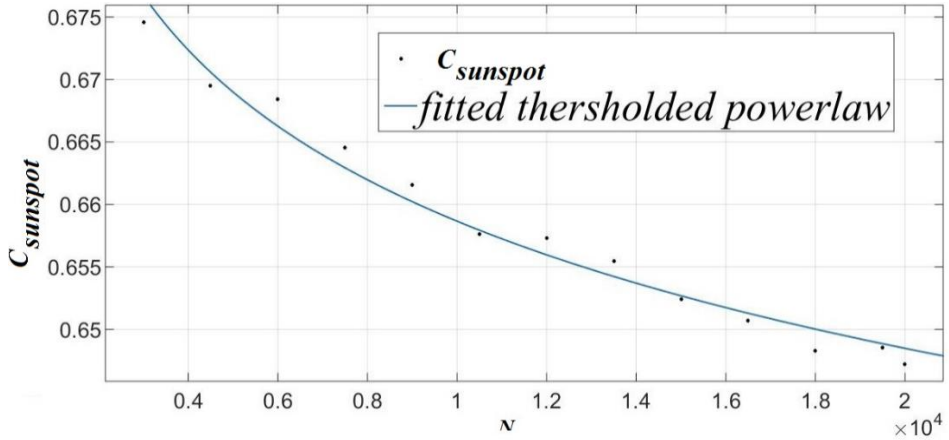

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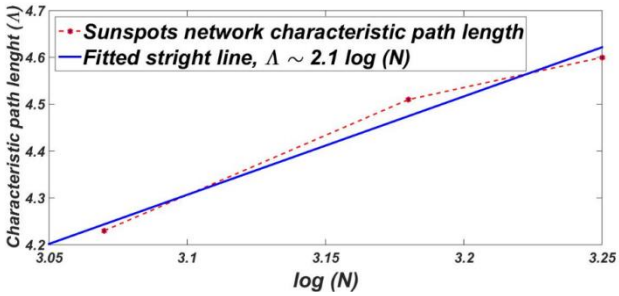

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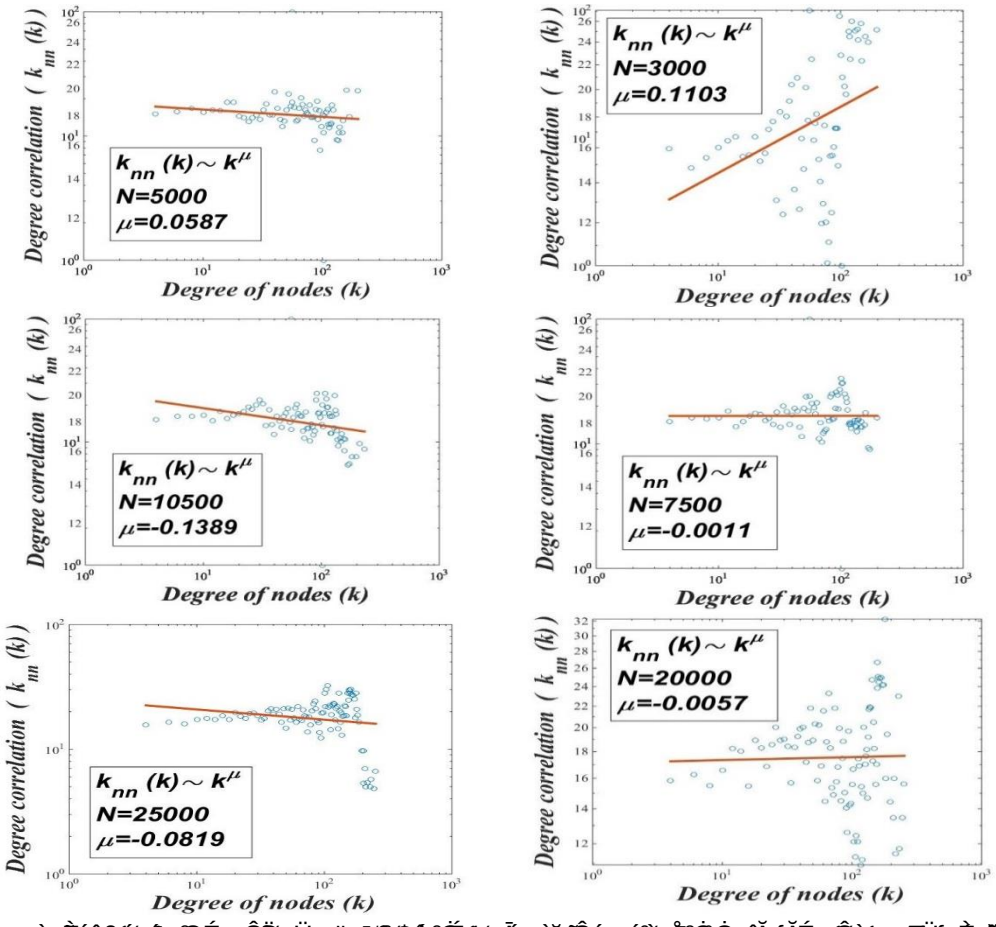
ÿ ā ¹ Ā L z ì õ ¾ È ą { Ö Ê Ą « ć ă ą Ć ¼ ì ¸ ú Ù ¾ ą ù W ą Ċ Ă î ú { ¹ ¼ Æ Ā z ¢ ¼ ų Ā ¥ « ~ º) É Ĉ ẅ ż p ·

ì L ĉ ì õó Ā Ă L î Õ { É ½ ¹ û ¹ w Ă ą Ĉ ù ½ Ā «) ½ ¾ Ă ż î ą ¿ ù v Ê ą L ù ź É ¹ Ć Æ ź ¼ ą Æ ų w ï ă Ć Ê ý w ù ¿

) º É w z ć º Ċ É ½ Ă Ā î · ą ¿ L Ă É ¾ ¹ ¼ ź Ê Æ v ¾ Å Ò ź Ĺ ¾ Ć Ă Ġ ¾ ý ñ v



½ Ĉ ú ź w ÷ ò w Ê ú Ć ź ą Ç É ¿ v Ĉ ¾ ź Ü z ÿ w ă # $ ć º É ½ Ă w ï ă Ć ý w ć¾ å Ċ Ċ î Ă { Ă É « Ĉ ò ¹ ¤ Æ Ü{ z Þ w Ê £ ½ ý ô î É

) 0 + w ÷ £ + # N $ Ă ¿ ã v { É ý v

Ă L Õ¾Āvô¹³ŽĀÙÿĊ£áa ÿ ā L ¹Éćw ææ ¢ÿÿĂÅ v{ É

÷¼w¹L)ţñĈúÅĉ¼½ w½Ł vè½ĉÕĀ#ĺýÜÙwźĀwLŁĒ¾ z ½¢ĉ¹ ÿ º ćvL½ćºĊ¹ÙL LćĒw½ìĀLŁĀăý õv ù w L L L A

ć w ŁĂăõ ó vùăwŽĀÉ¹ Ă ûwźĀĒ¹ wwéæº¤ÞÅzv ÿćºĊL Éā¼ĀÙÿL½âú¹ üĀdŁŁăĉĈĒ¢ĊL ~

ćºŒÉ½ĀĊõ wţ¤ĊĀĈĒò ý ĀĂdÞ¯ĂźćºŒÉ½Ā · ā ¿ wĂŵ bźõñ ÂL ţĊ ĈýÅwă¾º´ýzw ù ¿ w Å ¹ Ā

¾ôv LwŁÙÅĴ wv LÿĺćºĊŁL½Éćźwź Ā½õÿĀ¹½ Ł Õ Ă ýìw ùŁûĉvŁĂĒ½ĵ Ý É½wĀŁĂĒõý ¹ v ¹

ºĊ L É ½Ā Ā¾«Œ dŴwdŁźăĉ¹ ā º ¹ŁwŒŁźăĉº ~ ¹āv 0 3 ¡ ú L ŵŒĒ õźĂv ¾ ĕ¼ēĀĊĈ-

)º É ă vĂĀ¤ ·· v ¹ ¾ ~, w, Ł-Ă½ŁĀĉå¿ ćºĊ L É ć½wĀ õ¿ăvĀ « Ā ù

ì L úŵ íLwzŁ ĕ¹õÿ ºûLw¤ŁŁĂù Ł¿ ÷ Ăĵ½ĵĂ å

Ĉ ý v ¹ ½ º é ÿº)LĂ¼ÉĒwŁLŁĕõŁĂĜĊĊĂ{ùĊ¹½ŁŁÉºãĉv ¾ L L ñ

sidc ā ¹ v ¹ ÀdŁĕ ú ź¾ā ù¹ Ł ź½ĕ¹ ¿āvº LûŁŵĀ¾ºŒÉ½Ł ĕŴ¤ĊĜĒìãÕÝŸv ¹¿ vÿĂº½Þ½£Āúć º z

ÿ º þ ú L ìüÉ¿ ½ þ)° º ú LĕŁ¾ý½Ł½vÚ¹ý ćź½ź wºĕ³ĉî ¾ź õ Ē½Ā ú vŸźŁLĒĂ ú å¾ ñ ¾ Ú ý

) ¹ĈĀùÉ Ĉ ý v ¹ ½ º é ¾Ñ w ³ Ă õ w ê ù ¹ Ā { Ą z ĵĉ¹ vć¾[zĒÝûº½ÿ v ¹

.¿ v¾ Ł ½ ÀûLv ŽĂŁŁ wŁĂ½ ŁĎĜ« ÆźĒ v Ă{£Õ

Ü « v ¾ ù ćºŒÉ½ ź w ìăõĈý wć¾ú Ąº ĉĜ- îĂ{ĂÉ¹ ûr w Ê ý

À½ćw ă ½ ¼½ Ł ĂwÞÅ)w#Ö$3ĵa. ćI ºwùåwÿ³ Ł¿ vĂ î ¾{Ł Ē½ćĵĜĵĂ Î ¸ćĒĀúÕ¹ ì Ā¯zĀ í

Ĉ ¤ Þ þ Íłć ¾ā÷wí ò¹)Ê ºĜŽ¼võŽźwĂźź½ õ (ûw¿ LvûĄwźŁ ŁĒ ý¿Ă ûr {Ł¾ĜÉćwõĈñ ĝ

)û v ã¼ĉ ¾ É I ćw ŁŁĜźõwć¾ŁāŁĄ¿ĜĊĂ{ ûŁ Ł Ē Ł Ł z Ā í

)û lõ þ ăÿ¾ûåI) v ½ J½)łĊĂ ¹ wŒĵĜĜ¾æ Í w ÿŁ ĉ½ĀĂø Ł¹Ívĉû ŭĊŁŁÊµý¹ü)½ćăŒÉ½Ā · û5w ¬ ŸŒÉ¿½ Āì·Ċ,ôv þĊźĂÕ w,)ÞŁ#$4ü2 c ºŒÉ½ ź w ìăõĈý wć¾ú Ąº ĉĜ- îĂ{ûÉ¹½ĀĂz « w ý

.û w ¬ ãÿwź ò Ê ý v ¹ ¡ v ½ ¼wŒÉ½ ý ¼ ¿ vô êćw ŁĂÆEyŒÉ¾Ā½ÿ·¹ ½Ĉò ¤ĂŒîz¿ãźĂºzý v

Ăû ŭwûĉ)ÿźĉ¾wĂõăĂĈĜĂ î {,)É#$4û+ æÔ õ)ĉ ÅĂv î {ãź º ý v

)û v ź¾ĉ ãwý ò ÊÉĈĂwþ É½w í Ĉ ý w ù ¿ ć¾Å .$4Ă)1î {ŁÉĂºý¹ŒÉ¹ĂźĂ· w Å -#+$, ũ)v#½ÿŭ½¿ ¹ìMúÉĂ{ûŁ{ŒĂźĉ ûŭ ÿ º z

Ł º ÉĈĂwþ É½Ăŭwźĉ ý é º Ċ éwźãõĂ · ć wúvýã¾ 9ĉùÅĂĵ½ĉ¹ wºêĵ¾ãĉ)Åāv ºãÉ¹ûw¹Ê ý

) û ûŭ¾ ê wý ò Ê ý v ¹¢ · wÙĂĂ ý z ÿ vôĜæ¢Ć)Å¡v ÿ wĂæõŭûĜĈûwź zý

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