A Use of Graph Theory Properties of Constellations in Stellar Colonization

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Abstract. Space colonization has been a big dream of astronomers for many years. Even though no space colony established yet, stellar colonization is feasible with advances in AI, robotics, manufacturing, and propulsion technology. Hence, assuming that every star is a hospitable location, a model of settlement network is proposed based on understanding connectivity within and between complex systems. It outlines a new growth area for settlement research. Also, it brings the concept of scale-free hierarchical networks with preferential tendencies, best described by the power curve. Considering the main purposes of stellar colonization as manufacturing of goods using resources of stars and stellar navigation, edges of the settlement network were defined as interstellar economic connections and transportation connections. Here, it is assumed that the economic connections and transportation connections are similar to the patterns of constellations. A scale-free network is proposed and made conclusions about which stars to be colonized firstly and identified the influential stars within the network. This method can be used as a guide to make a real colonization network by analysing real potential connections between stars.

Keywords: Authority, Centrality measures, Clustering Coefficient, Hub, Scale free

Introduction

This paper discusses about the applicability of graph theory for stellar colonization and also proposes a stellar settlement network that can be used as a model. Here, the nodes are the stars and edges are the economic and transportation connections between stars. Since the lack of information about how these links would be, for this model, it is assumed that the connections between stars occur according to constellation patterns. A scale free network is proposed, and conclusions are made about which stars to be colonized firstly. And it also identifies the influential stars within the network. This method can be used as a guide to make a real colonization network by analysing the real potential connections between stars.

A previous study was done by Jones (2014) and he states that stellar travel is beyond the technical abilities; what with the inability to wield space-time, finite life-spans, and technical inabilities and all. Also, a navigation network is built based on an arbitrarily imposed maximum travel distance. Seeman and Marinova (2009) states that new settlements methods are predictive methods and evaluative/diagnostic approaches based on scale-free hierarchical networks with preferential tendencies.

Stellar colonization is the concept of human habitation of locations on stars. It is a major theme in science fictions, as well as a long-term goal of various space programs (Beckstead, 2014). Survival of human civilization, vast resources in space, alleviating overpopulation and resource demand, spread life and beauty throughout the universe, ensure the survival of our species, make money through new forms of space commercialization such as solar-power satellites, asteroid mining, and space manufacturing and save the environment of Earth by moving people and industry into space can be identified as the main reasons for space colonization.

When it comes to settlement projects, according to Seeman and Marinova (2009), researches on human settlements have traditionally focused on one or a few descriptive or functional aspects, such as geographical characteristics of the locality, the economy, housing, transport, infrastructure, education or health, or created models with varying degrees of complexity that attempt to bring these elements together. However, the modern concepts are based on connectivity within and between complex systems. It discusses concept of scale-free hierarchical networks with preferential tendencies, which can be best described by the power curve.

Background

A scale free network is a network whose degree distribution, or the number of connections from each node, follows a power law. The most important feature of a scale free network is the connectivity between its nodes. With many links, the network can exhibit fault-tolerant behaviour or robustness, which is a property which allows it to operate in a reliable way even if there is a degree of failure. If a node is affected and becomes non-functional, the connectedness within the network can be restored through an alternative path, using a different combination of nodes and links. The Figure 1 shows the difference between exponential networks and scale free networks.

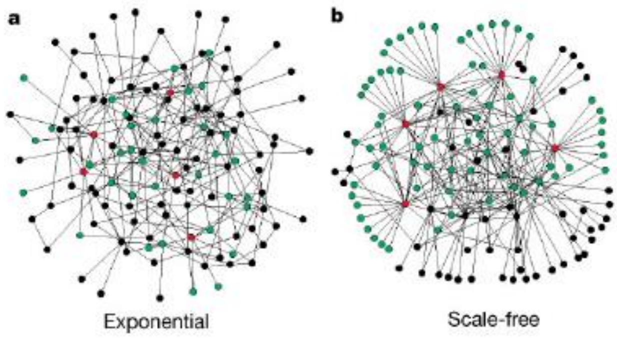

Figure 1. Difference between exponential and scale free network

Characteristics of scale free networks:

- Degree distribution follows a power law, at least asymptotically.
- Relative commonness of vertices with a degree that greatly exceeds the average.
- The highest-degree nodes are often called "hubs".
- The scale free property strongly correlates with the network's robustness to failure.
- Scale free networks allow for a fault tolerant behavior.
- Hubs are both strength and a weakness of scale free networks.
- The clustering coefficient distribution decreases as the node degree increases.
- This distribution also follows a power law.
- This implies that the low degree nodes belong to very dense sub-graphs and those sub-graphs are connected to each other through hubs.
- The average distance between two vertices in a network is very small (ultra small world phenomenon)
- The diameter of a growing scale free network might be considered almost constant in practice.
- Scale free graphs remain scale free under transformations.
- Generative mechanism used to create them.

Methods

The main purpose of this application part is to generate a scale free network. The following procedure is followed in order to make the network scale free.

Nodes: Stars

Edges: Lines connect nearest neighbor pairs of stars

1. Identify all the hubs within each constellation.

As the first step of making a scale free network, all the hubs within every constellation are identified. The identified hubs are the stars which are having the highest hub values.

2. Connect the hubs within the constellation.

Some constellations have more than one hub. As the second step of making the network, these intra-hubs are connected to each other. Connecting of these hubs, should be done because it strengthens the entire network.

3. Choose and link the nodes which are generating triangles with the hubs.

One of the important characteristics of scale-free networks is the clustering coefficient distribution, which decreases as the node degree increases. Since the clustering coefficient mainly depends on the triangles in a network, generating of triangles makes the clustering coefficient distribution as stated above. Here, the nodes which are capable of making a triangle are connected with hubs.

4. Choose the nodes with degree ≥3 and link with the hubs.

This linking is useful to make the graph strong and to increase the node degree as degree distribution follows the power law.

5. Choose and link the nodes which are having shortest path length ≥5 between the hubs and node.

The average distance between two vertices in a scale free network should be very low. To satisfy this property, the nodes having shortest path length ≥5 with the hub are chosen and they are connected to the hub(s) of the graph. Then any node can have connection with the hub at least in three steps.

6. Connect neighboring constellations (only hubs are connected).

As the final step of the process of generating scale free network, hub(s) are connected with the hubs of bordering constellations assuming that there is a zero probability for distant constellations to be connected. Therefore, the connections are only with neighboring constellations. The 88 disconnected constellations are connected in order to have one connected network.

Assumptions

- All the stars are hospitable locations.
- Stars sit statically relative to each other.
- Zero probability for distant constellations to be connected.

Network Properties

Degree: Number of connections with the neighboring stars.

Degree Centrality: The number of links incident upon a node. Node with the highest degree centrality denotes the most popular star or most developed star.

Hubs: A node with a number of links that greatly exceeds the average. Hubs are the stars to colonize firstly.

Betweenness Centrality: Number of times the node lies on the shortest path (considering only the connection not the distance). The star which influences the flow around the system (e.g.: Interstellar navigation). High betweenness centrality indicates the star which holds the authority of the network.

Closeness Centrality: The average length of the shortest path between the node and all other nodes in the graph. The stars which are best placed to influence the entire network. High closeness indicates the star which is closer to all stars.

Eigenvector Centrality: It is the measure of the influence of a node in a network. It measures the importance of the star based on its connection with other stars. The most central star indicates that it is connected to important neighbors.

Eccentricity Centrality: The distance from a given starting node to the farthest node from it in the network. Higher centrality indicates the easily accessible star from other stars.

Modularity: It measures the strength of division of a network into modules (also called groups, clusters or communities). Stars are more densely connected than other stars.

Density: It measures how close the network is to complete. How close all the stars in the settlement network connect to all other stars.

Diameter: How far apart are the two most distant stars?

Radius: The radius of a network is the smallest path of all the calculated shortest paths in a network. How far apart is a star from the center of the network?

Average Path Length: This shows us, on average, the number of steps it takes to get from one star of the network to another.

Here we consider a stellar colonization network where the nodes are the stars linked by spatial flows that move information, materials or people. Assume that these links will be arisen according to the constellation patterns. The edge of the constellation pattern is the line which is connecting nearest neighbor pair of stars. A node is therefore a non-empty location will be occupied by at least one resident while K_{ij} is a generic link between node *i* and *j*. The link between the nodes can be manifested as the exchange of goods, relocation of people, interstellar navigation etc.

Assume that pair of nodes can be joined by at most one link and that all existing links have equal weight. Also, assume that zero probability for distant constellations to be connected. Take each constellation I is the home to a set of nodal locations defined by the index *i = 1, 2, 3... N*. Then the constellation *I*'s are the number of links to another constellation J.K_{IJ} measures the strength of the interactions between the two constellations.

$$K_{IJ} = \sum_{i \in I, j \in J} K_{ij}, \tag{1}$$

where K_{ij} is a binary indicator.

It is equal to 1 if a link exists between node $i \in I$ and node $j \in J$ and 0 otherwise. For completeness we set $K_{ii} = 0$. I.e. a node is not connected to itself. Note that when $I = J$ then the number of links K_{II} measures the degree of local (Intra-Constellation) connectivity i.e. the extent to which the same constellation residents interact with each other. The average volume of links possessed by a constellation *I*'s nodal location is;

$$< K >_I^{in} = K_I^{in}/2N_I \quad , \tag{2}$$

$$< K >_I^{out} = K_I^{out}/2N_I, \tag{3}$$

$< K >_I^{in}$ - Average number of intra-constellation links

$< K >_I^{out}$- Average number of inter-constellation links

On average a constellation I has $< K >_I^{in}$ local connections and$< K >_I^{out}$out of constellation connections. Here the homogeneity is assumed within the same constellation. This means that each constellation *I*has$< K >_I^{in}$ same constellation connection and at the same time is linked to K_{IJ} / N_I stars of constellation *J*. The statistical properties of the geometric network are thus fully described once $< K >_I^{in}$ and $< K >_I^{out}$ have been determined for every settlement.

The present studies assume that distance between nodes matters as far as interactions among them are concerned. The proposed connections between intra constellations have a power relationship.

$$K_{II} = C_0 N_I^{\alpha}, \tag{4}$$

where, C_0- Constant,α- Power.

The Inter-Constellation interactions relative to the total given by,

$$S_I = \frac{<K>_I^{out}}{<K>_I^{in} + <K>_I^{out}}. \tag{5}$$

Results and Discussion

Inter and Intra Constellation Interactions

The Table 1 contains the obtained values for inter and intra constellation interactions and it concludes that the *Microscopium* is the constellation with the highest inter-constellations interactions and *Orion* has the lowest inter-constellations interactions. Also, *Microscopium* can be identified as the constellation which is having the highest average number of links for a node with other constellations while *Capricornus* is having the highest number of average links for a node.

Table 1. Inter and intra constellation interactions

Constellation	K_I^{in}	K_I^{out}	N_I	$< K >_I^{in}$	$< K >_I^{out}$	S_I
Andromeda	17	11	15	0.5667	0.7334	0.5642
Antlia	4	13	9	0.2223	1.4445	0.8667
Apus	4	18	5	0.4	3.6	0.9
Aquarius	30	28	24	0.625	1.1667	0.6512
Aquila	14	29	10	0.7	2.9	0.8056
Ara	10	20	8	0.625	2.5	0.8
Aries	8	7	10	0.4	0.7	0.6364
Auriga	8	9	7	0.5715	1.2858	0.6923
Boötes	17	13	12	0.7084	1.0834	0.6047
Caelum	3	20	4	0.375	5	0.9303
Camelopardalis	8	9	8	0.5	1.125	0.6924
Cancer	5	10	6	0.4167	1.6667	0.8
Canes Venatici	3	10	4	0.375	2.5	0.8696
Canis Major	10	4	9	0.5556	0.4445	0.4445
Canis Minor	1	8	2	0.25	4	0.9412
Capricornus	55	100	11	2.5	9.091	0.7844
Carina	15	63	11	0.6819	5.7273	0.8937
Cassiopeia	4	5	5	0.4	1	0.7143
Centaurus	27	22	25	0.54	0.88	0.6198
Cepheus	14	6	10	0.7	0.6	0.4616
Cetus	19	14	14	0.6786	1	0.5958
Chamaeleon	15	66	6	1.25	11	0.898
Circinus	3	26	4	0.375	6.5	0.9455
Columba	5	8	6	0.4167	1.3334	0.7619
Coma Berenices	3	18	4	0.375	4.5	0.9231
Corona Austrina	7	18	6	0.5834	3	0.8372
Corona Borealis	8	11	7	0.5715	1.5715	0.7334
Corvus	7	12	5	0.7	2.4	0.7742
Crater	12	26	8	0.75	3.25	0.8125
Crux	6	8	4	0.75	2	0.7273
Cygnus	16	6	11	0.7273	0.5455	0.4286
Delphinus	9	33	5	0.9	6.6	0.88
Dorado	7	16	6	0.5834	2.6667	0.8205
Draco	18	8	15	0.6	0.5334	0.4707
Equuleus	3	15	3	0.5	5	0.9091
Eridanus	40	22	34	0.5883	0.6471	0.5238

Fornax	6	32	4	0.75	8	0.9143
Gemini	19	11	18	0.5278	0.6112	0.5367
Grus	14	23	11	0.6364	2.091	0.7667
Hercules	25	14	19	0.6579	0.7369	0.5284
Horologium	9	33	8	0.5625	4.125	0.88
Hydra	20	29	18	0.5556	1.6112	0.7436
Hydrus	7	46	6	0.5834	7.6667	0.9293
Indus	10	115	5	1	23	0.9584
Lacerta	10	5	9	0.5556	0.5556	0.5
Leo	22	18	15	0.7334	1.2	0.6207
Leo Minor	7	15	5	0.7	3	0.8109
Lepus	17	7	11	0.7728	0.6364	0.4517
Libra	6	7	6	0.5	1.1667	0.7001
Lupus	12	11	9	0.6667	1.2223	0.6471
Lynx	11	18	8	0.6875	2.25	0.766
Lyra	8	4	6	0.6667	0.6667	0.5
Mensa	3	26	4	0.375	6.5	0.9455
Microscopium	10	125	5	1	25	0.9616
Monoceros	6	8	8	0.375	1	0.7273
Musca	7	17	6	0.5834	2.8334	0.8293
Norma	10	45	5	1	9	0.9
Octans	6	71	5	0.6	14.2	0.9595
Ophiuchus	12	13	9	0.6667	1.4445	0.6843
Orion	28	5	21	0.6667	0.2381	0.2632
Pavo	15	16	11	0.6819	1.4546	0.6809
Pegasus	16	13	13	1	0.9566	0.8543
Perseus	22	9	16	0.6875	0.5625	0.45
Phoenix	17	19	13	0.6539	1.4616	0.691
Pictor	3	27	3	0.5	9	0.9474
Pisces	20	7	16	0.625	0.4375	0.4118
PiscisAustrinus	12	23	9	0.6667	2.5556	0.7931
Puppis	12	21	9	0.6667	2.3334	0.7778
Pyxis	3	33	3	0.5	11	0.9566
Reticulum	15	36	6	1.25	6	0.8276
Sagitta	6	24	4	0.75	6	0.8889
Sagittarius	27	39	19	0.7106	2.0527	0.7429
Scorpius	20	12	18	0.5556	0.6667	0.5455
Sculptor	10	45	5	1	9	0.9
Scutum	10	19	5	1	3.8	0.7917
Serpens	12	29	11	0.5455	2.6364	0.8286
Sextans	6	16	4	0.75	4	0.8422
Taurus	18	10	14	0.6429	0.7143	0.5264
Telescopium	15	90	6	1.25	15	0.9231
Triangulum	3	12	3	0.5	4	0.8889
Triangulum_Australe	6	36	8	0.375	4.5	0.9231
Tucana	15	78	6	1.25	13	0.9123
Ursa Major	29	14	20	0.725	0.7	0.4913
Ursa Minor	9	3	7	0.6429	0.4286	0.4

Vela	28	72	8	1.75	9	0.8373
Virgo	18	13	14	0.6429	0.9286	0.591
Volans	8	15	6	0.6667	2.5	0.7895
Vulpecula	4	11	5	0.4	2.2	0.8462

Network Properties

Consider the Andromeda constellation graph. Figure 2 shows the constellation map and generated graph of Andromeda constellation. The Table 2 contains the obtained network properties for each node in the network of *Andromeda Constellation*. The columns are representing the star name, authority value (Aut.), hub value (Hub), node degree (D), eccentricity (E), closeness centrality (CC), harmonic centrality (HC), betweenness centrality (BC), modularity class (M), clustering coefficient (Clu.), number of triangles (T) and eigenvector centrality (EC) from left to right. The data given in the table have been analysed in order to identify the importance of a star within the constellation. The identification has led to make decisions on the network such as which star should be colonized firstly, which star should be developed as the flight maintenance and operation centre, which star should be developed as the main trade centre or communication centre and etc. According to Table 2, δAnd can be identified as the most important star within the constellation. It is connected to many stars than the other stars in the network.

Similarly, this is done for each and every constellation network described by International Astronomical Union.

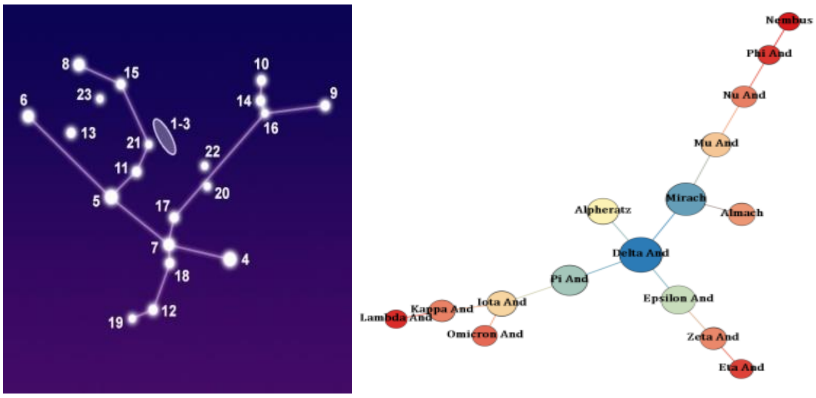

Figure 2. Andromeda Constellation Map

Table 2. Graph properties for nodes of settlement network - Andromeda

Star	Aut.	Hub	D	E	CC	HC	BC	M	Clu.	T	EC
Mirach	0.0001	0.0001	3	10	0.1805	0.2017	794	5	0.3334	1	0.0059
Almach	0.0001	0.0001	1	11	0.153	0.1649	0	5	0	0	0.0011
δ And	0.0015	0.0015	17	9	0.2198	0.2616	21184.6	5	0.125	17	0.043
Nembus	0	0	1	13	0.1173	0.1234	0	5	0	0	0.0007
ο And	0.0001	0.0001	1	11	0.153	0.1652	0	5	0	0	0.0012
λ And	0	0	1	12	0.1328	0.1409	0	5	0	0	0.0008
μ And	0.0001	0.0001	3	10	0.1806	0.202	2376	5	0.3334	1	0.006
ζ And	0.0001	0.0001	3	10	0.1804	0.2013	794	5	0.3334	1	0.0058
κ And	0.0001	0.0001	2	11	0.1531	0.166	794	5	0	0	0.0018
φ And	0	0	2	12	0.1329	0.1419	794	5	0	0	0.0013
ι And	0.0001	0.0001	4	10	0.1806	0.2024	2378	5	0.1667	1	0.0066

π And	0.0001	0.0001	2	10	0.1804	0.201	0	5	1	1	0.0054
ε And	0.0001	0.0001	2	10	0.1804	0.2007	0	5	1	1	0.0053
ν And	0.0001	0.0001	1	11	0.1529	0.1647	0	5	0	0	0.0011
η And	0.0001	0.0001	2	11	0.1531	0.1662	1586	5	0	0	0.0018

Analysis for Entire Network

The Figure 3 gives the scale free network generated considering all the 88 constellation patterns. For the whole network; the star with the highest hub value 0.230563 is *Kaus Media* (Sgr 19) in *Sagittarius*. It is the star also having the highest degree 48, highest number of triangles 288, highest authority value 0.230563 and highest eigenvector centrality 1. This implies that the Kaus Media is the star to be colonized firstly. Since it is the star having the highest degree it can be concluded as the most popular star or most developed star. Highest authority score implies that it is the star that stored most valuable information, i.e., many stars are likely to have connection with that star. The most central (eigenvector) star indicates that it is connected to important neighbors. So, the Kaus Media star is also connected to the important stars that can influence to the entire network. So many manufacturing plants should be implemented in this star. *Cebalrai* (Oph 12) is the star having highest closeness centrality 0.248671 which is contained in Ophiucus constellation. i.e. this is the star which is closer to all stars. (the best placed star to influence the entire network). *τ-5 Eri* (Eri 19) is the most betweenness central star in this settlement network having the value 62836.4523. It is in Eridanus constellation. τ-5 Eri is the star that lies in many shortest paths between the stars in the settlement network. High betweenness indicates the star which holds the authority of the network. For an example, this star can be developed as the main *flight operation and maintenance centre* which is helpful to interstellar navigation.

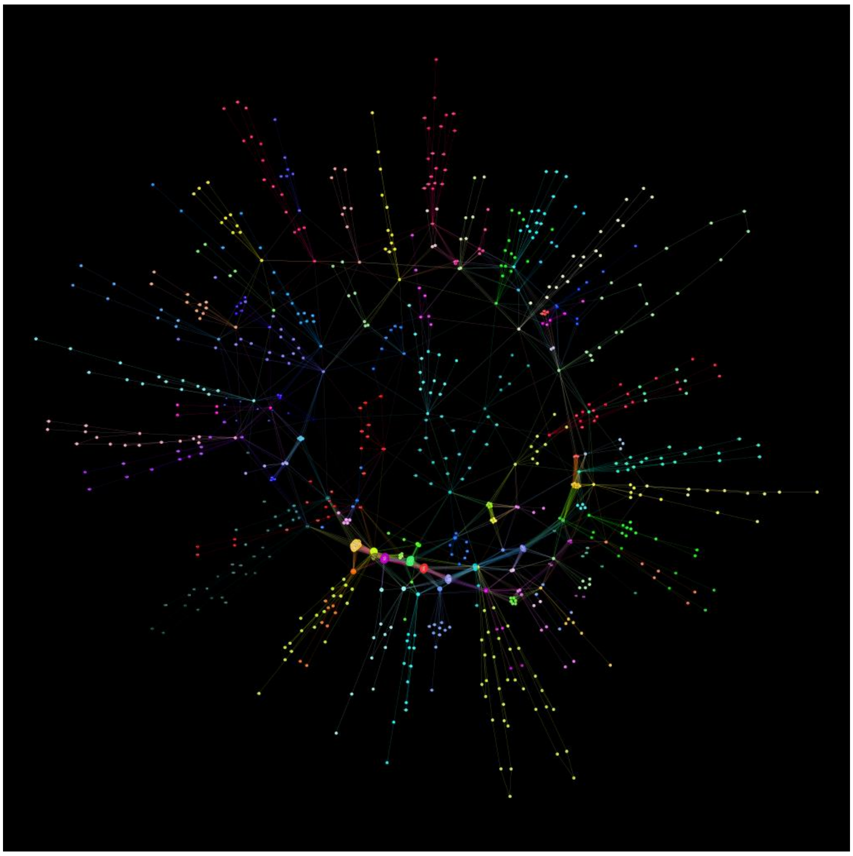

Figure 3. Generated Scale Free Constellation Network

Settlement Network

In this part, network properties are discussed considering their distribution graphs.
Number of Stars - 796
Number of Connections defined – 2175

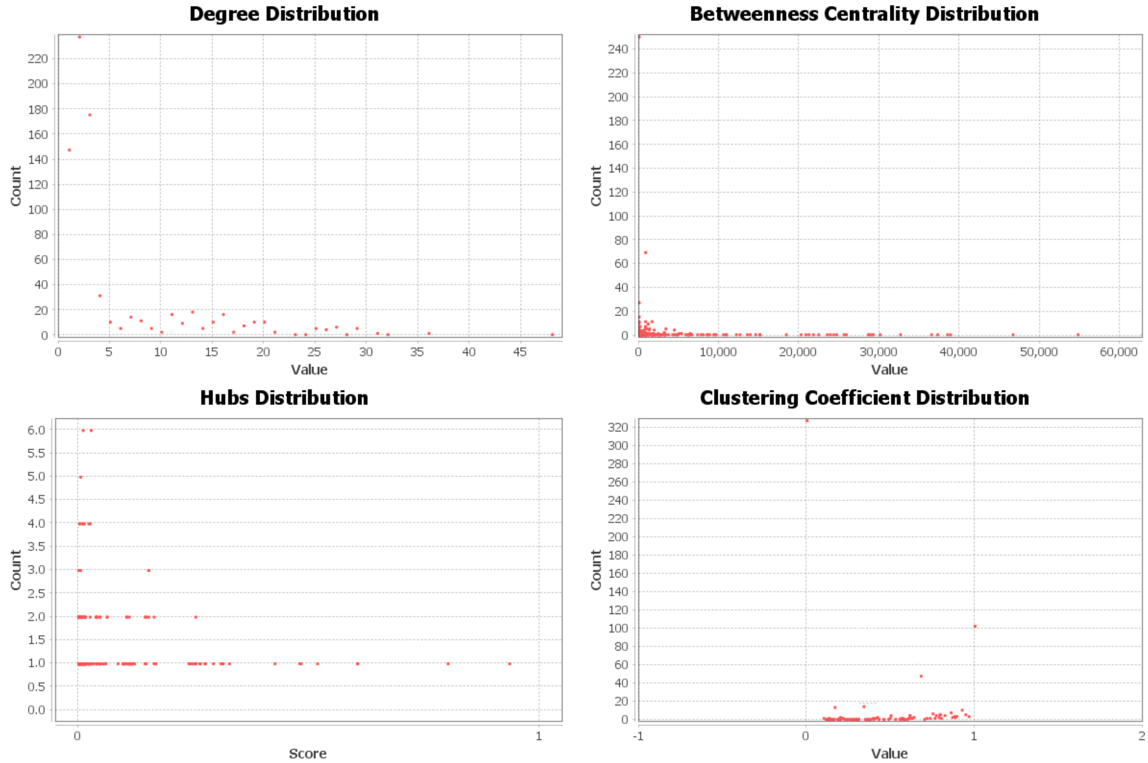

Figure 4. Properties distribution of the settlement network

Degree Distribution: According to Figure 4 (a) the suggested network is a scale free network since the degree distribution follows the *power law*. In this network, average degree is 5.456. According to the above graph, most of the stars have degree 2. The star *Kaus Media* in *Sagittarius* has the maximum degree *48*. That is Kaus Media has the highest number of connections in the network thus having the greatest potential to influence other stars within the network.

Network diameter: Diameter of this network is *13*. That is the number of connections in the longest path of all the calculated shortest paths in the network is 13.

Average Path length: The average path length of this network is *5.6425*. This indicates us, on average, the number of steps it takes to get from one star of the network to another.

Betweenness Centrality: In this graph, betweenness centrality distribution curve also has followed the power law (refer to Figure 4 (b)). Scale free networks have a power law in the distribution of the betweenness. Considering that the degree is highly correlated with the betweenness, the betweenness of scale free networks follows a power law distribution. But the power-law distribution of the betweenness is not restricted to the scale-free network but held true to other types of networks. In this network the highest betweenness centrality is 62817.55 and it is held by τ-5 Eri (Eri 19). The lowestis zero and there are 251 stars having this value. Then τ -5 Eri can be developed as a *flight operation and maintenance center* since it lies on most of the shortest paths in the network.

Hubs Distribution: Hub is the star with several links that greatly exceeds the average. Also, hub is the major component in a scale free network. For this network, there are many stars that must be connected. So, these new stars in a scale free network tend to link to a star with a higher degree. Then most of the graph properties remain as it is after adding new stars to the network. It can be considered as an advantage of scale free networks. According to the above graph we can also see that the hub distribution has followed the power law. Considering that the degree is highly correlated with the hub, it is obvious that hubs of scale-free networks follow a power law distribution. As in Figure 4 (c), for the suggested settlement network, the highest hub value is *0.23737* and it is for *Kaus Media* (Sgr 19). So, this is the main star which dominates in the network. Then, Kaus Media can be selected as the star that has to be colonized firstly because many stars have impact from this star. Since hubs are both strength and a weakness of scale free networks, the identified hubs for both the entire network and each constellation should be colonized and developed in a secure way. As an example, if the main stars (hubs) get attacked by universal war, then the whole network will be broken down.

Clustering Coefficient Distribution: The well-connected hubs tend to have lower clustering coefficients than those of the less well-connected nodes. This situation arises because each node that connects to a hub creates as many potential connections as there are nodes that are already connected. The more neighbors, the more potential connections, tend to lower the clustering coefficient. By contrast, the nodes with fewer connections have fewer potential neighborly connections, so the ones that do exist contribute strongly to the clustering coefficient. Figure 4 (d) shows the clustering coefficient distribution. Here the stars with more connections tend to connect more stars than do those with fewer connections. Hence, those with bigger clusters of stars tend to grow bigger clusters of stars. Since the proposed network is scale free, clustering coefficient distribution decreases as the node degree increases. This distribution also follows a power law.

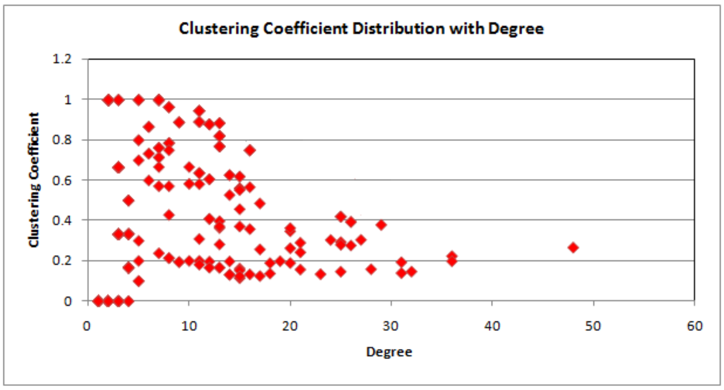

Figure 5. Clustering Coefficient Distribution with the Degree of nodes

From Figure 5, we can clearly see that the clustering coefficient distribution decreases as the node degree increases. The average clustering coefficient for this network is *0.451*.

Conclusions

The proposed network is a graph with 796 nodes and 2715 edges. The Kaus Media is the star to be colonized firstly. Since it is having the highest degree, can be concluded as the most popular star or most developed star. *Cebalrai* (Oph 12) is the star having highest closeness centrality, which is contained in Ophiucus constellation, i.e. the star which is closer to all stars.

(Eri 19) is the most betweenness central star in this settlement network and it is in Eridanus constellation. *τ-5 Eri* is the star that lies in many shortest paths between the stars in the settlement network. High betweenness indicates the star which holds the authority of the network. For an example, this star can be developed as the main *flight operation and maintenance center* which is helpful for interstellar navigation. The proposed network also having 5.6425 average path length, 5.456 average degree, 13 diameter, 8 radius, 0.007 density and 0.753 modularity.

Finally, this method can be used as a guide to make a real colonization network by analyzing real potential connections between stars. For the colonization network, the actual distances should be calculated and based on it, a minimal spanning tree should be defined. This will help to understand the actual navigation connections between all stars. Also, the existing resources of these stars should be identified and based on these information, economic connections between stars can be predicted. The process of future study will minimize the limitations of currently proposed stellar settlement network.

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