University of Padova

Department of of Physics and Astronomy “Galileo Galilei”

Bachelor Thesis in Astronomy

Inventory of the inner and irregular satellites in the Jovian system

Supervisor
Prof. Monica Lazzarin
University of Padova

Co-supervisor
Prof. Giuseppe Mitri
Università degli Studi G. D’annunzio

Master Candidate
Bianca Ranieri

Student ID
1173992

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A zio Sandro,
che puntando il dito verso la notte mostrava le stelle.
Spero che da lassù starai sorridendo, perchè ce l’ho fatta, anche per te.

A Giovannino e i suoi miagolii,
aspettami, ora sono felice.

Al passato.
Perché ora non c’è più,
per fortuna.

Abstract

This study presents a comprehensive inventory of the inner and irregular satellites in the Jovian system. The satellites are categorised according to the orbital parameters such as samimajor axis, orbital inclination and eccentricity, and physical characteristics such as density, visual geometric albedo and the discrete compositional characteristics and details about the presence or absence of various chemical elements, also through new methdos applied to astrophysics. Theories of formation of the Jovian satellites are discussed.
Further investigations are suggested to better understand the relationships among these groups.

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Introduction

It was the 7th of January 1610, Galileo was pointing his telescope for the first time at Jupiter, the gas giant, when he discovered four bright mysterious objects apparently orbiting it.

This discovery brought a revolution in the way humankind would see the universe. In the 19th century observations became significant thanks to scientists to the likes of Laplace, that determined a theory of motion for the satellites and used the resonant properties of their orbits to estimate their masses, and Barnard, that using the new refractors at Yerkes and Lick established an estimate for their masses.

This was just the beginning. In the early 20th century new photographic techniques led to the discovery of the prograde group and retrograde group of small outer satellites, and beginning in the 1970s' the first space missions began to explore in depth this miniaturised "solar system" that can help scientist understand how our own Solar System was born and what was made of and how it evolved, even leading to improved theories of extrasolar systems formation.

To grasp what the primitive solar system was composed of we have to look for clues in the most primitive objects in the solar system that have remained virtually the same since around 4.6 billion years ago. These objects are asteroids and comets, that can be found in the Main Belt, between the orbit of Mars and Jupiter, in the Lagrangian points L4 and L5 sharing Jupiter's orbit, in the Kuiper belt and in the Oort cloud.

In this thesis the focus will be on the outer region of the Jupiter satellite system, where

these probable ancient objects are within our grasp.
In this region the satellites have extremely eccentric, high angles, prograde or retrograde orbits, with respect to the inner two other groups of satellites.
This information, coupled with Jupiter's capacity to capture anything that comes to close to its massive gravitational pull, led scientists to consider them captured asteroids.

The scope of this thesis is to try to compile a comprehensive inventory all the objects that are part of Jupiter's huge and complex system through researching the existent literature about this compelling subject. A more in depth discussion of the current knowledge of Jupiter's satellite system and how we can divide and subdivide the different categories of its objects will be discussed in the first chapter. Following theories of formation and the taxonomy will be analysed to further understand the origin and the grouping of the various objects in orbit around the gas giant.
Lastly, a brief discussion on the further developments that this study could lead to.

1.1 An Introduction to the Jovian System

Jupiter is the biggest gasseous planet in the Solar System. Its satellites can be grouped into two broad categories: the *Regular Satellites* and *Irregular Satellites*. This categorization is based upon orbital parameters.

Figure 1.1: A family portrait. Composite image of Jupiter and the four Galileian moons, in order of distance: Io, Europa, Ganymede and Callisto. Distances and sizes are not to scale.

The Regular Satellites are in turn categorized into the *Inner Satellites* or *Amalthea group*, that keep in check the faint main ring, and the *Galileian Moons*. These objects have prograde, near circular orbits and low inclinations.
The Irregular Satellites are more distant objects with more eccentric orbits and higher inclinations. These can be further divided into the *Prograde* and *Retrograde* groups. Moreover these smaller objects can be grouped into families with similar orbital parameters such as semi-major axis, inclination and eccentricity. [1]

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[1] S.S.Sheppard, *Jupiter's Known Satellites*, Departament of Terrestrial Magnetism at Carnegie Institution for Science, 2018. available at https://sites.google.com/carnegiescience.edu/sheppard/moons/jupitermoons

2

The Jovian System

Jupiter is the fifth planet from the sun and it is the biggest gasseous planet and biggest planet overall in the Solar System. Its mean radius is 69911 km long and its mass is 1.8982×1027 kg, that is 10.973 and 317.8 times respectively of that of the Earth's.
Its massive size created a miniaturised solar system composed of satellites that can be grouped into two broad categories: the *Regular Satellites* and *Irregular Satellites* in turn divided into four groups. This categorization is based upon orbital parameters. Moreover a faint ring system completes the complex structure of the Jupiter's family.
All the data regarding this chapter has been sourced from **Jupiter Fact Sheet**[1], **The Jovian Satellite Fact Sheet**[2] and **Moons of Jupiter**[3] by Scott S. Sheppard from the Carnegie Institution for Science, unless explicitly stated otherwise.

2.1 The Regular satellites

The orbits of the Regular satellites are almost circular and coplanar to that of Jupiter's equatorial plane. These orbits are all prograde.

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[1] https://nssdc.gsfc.nasa.gov/planetary/factsheet/jupiterfact.html

[2] https://nssdc.gsfc.nasa.gov/planetary/factsheet/joviansatfact.html

[3] https://sites.google.com/carnegiescience.edu/sheppard/moons/jupitermoons

2.1.1 The inner most satellites or The Amalthea Group

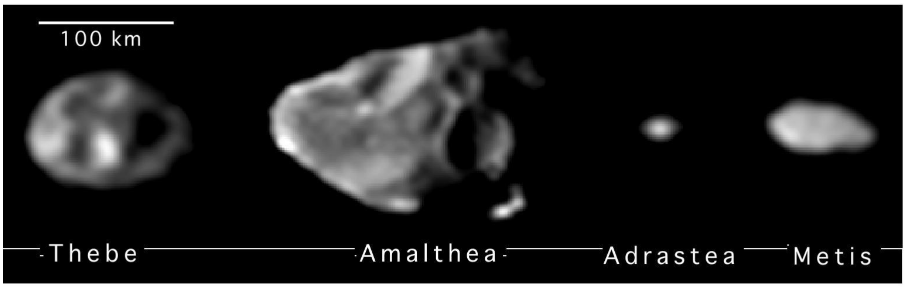

Figure 2.1: Composite image of the four Inner moons, in order of distance from the farthest: away to the closest Thebe, Amalthea, Adrastea, Metis. The picture was taken by the camera on NASA's Galileo spacecraft. Photojournal: PIA01642; Source: NASA/JPL/Cornell University; Published: September 15, 1998

This group is composed of four relatively small satellites; in order of increasing orbital mean radius, they are *Metis*, *Adrastea*, *Amalthea* and *Thebe*, the biggest of them being Amalthea with dimensions of 250 × 146 × 128 km(Thomas Burns et al. 1998). Their orbits extend ranging from $1.79R_J$ to $3.11R_J$

Following are summarized all the known orbital and physical parameters for these objects.

The Amalthea Group - orbital parameters				
Denomination	Semi-major axis (Jovian Radii)	Orbital Period (days)	Inclination (degrees)	Eccentricity
Metis (JXVI, S/1979J3)	1.79	0.294779	0.06	0.0002
Adrastea (JXV, S/1979J1)	1.80	0.298260	0.03	0.0015
Amalthea (JV)	2.54	0.498179	0.40	0.003
Thebe (JXIV, S/1979J2)	3.11	0.6745	0.8	0.018

Table 2.1: Orbital parameters for the innermost satellites, the Amalthea Group.

The Amalthea Group - physical parameters				
Denomination	Mass (10^{20} kg)	Radius (km)	Mean density (kg/m^3)	Visual geometric albedo
Metis (JXVI, S/1979J3)	0.001	30x20x17		0.06
Adrastea (JXV, S/1979J1)	0.0002	10x8x7		0.10
Amalthea (JV)	0.075	125x73x64	3100	0.09
Thebe (JXIV, S/1979J2)	0.008	58x49x42		0.05

Table 2.2: Physical parameters for the innermost satellites, the Amalthea Group.

2.1.2 The main Group or The Galilean satellites

Figure 2.2: Composite image of the four Galileian moons, in order of distance: Io, Europa, Ganymede and Callisto. Distances and sizes are not to scale. The Solid State Imaging (CCD) system aboard NASA's Galileo spacecraft acquired the Io and Ganymede images in June 1996, the Europa images in September 1996, and the Callisto images in November 1997.

This group is the longest known collection of objects in the Jovian system. They were discovered by Galileo Galilei on the 7th of January 1610 during a terse night in Padua. Their discovery was one of the most important in the history of humankind.
They are some of the largest objects in the Solar System, of course not considering the sun and the 7 biggest planets. Some of these satellites are even bigger than Mercury.
Their orbits lie coplanar to that of Jupiter's and moreover the first three Galilean moons

are tidally locked to one another in a 1:2:4 resonance[4]: They are, in order of increasing orbital mean radius, *Io*, *Europa*, *Ganymede* and *Callisto*, Ganymede being the largest between them and the largest satellite in the solar system at 2631.2 km radius.

The Galileian Satellites - orbital parameters				
Denomination	Semi-major axis (Jovian Radii)	Orbital Period (days)	Inclination (degrees)	Eccentricity
Io (JI)	5.91	1.769138	0.04	0.004
Europa (JII)	9.40	3.551181	0.47	0.009
Ganymede (JIII)	14.97	7.154553	0.18	0.001
Callisto (JIV)	26.33	16.689017	0.19	0.007

Table 2.3: Orbital parameters for the main group, the Galileian Satellites.

The Galileian Satellites - physical parameters				
Denomination	Mass (10^{20} kg)	Radius (km)	Mean density (kg/m^3)	Visual geometric albedo
Io (JI)	893.2	1821.5	3530	0.62
Europa (JII)	480.0	1560.8	3010	0.68
Ganymede (JIII)	1481.9	2631.2	1940	0.44
Callisto (JIV)	1075.9	2410.3	1830	0.19

Table 2.4: Physical parameters for the main group, the Galileian Satellites.

They are interesting worlds on their own: Io is the most geologically active object in the solar system [5], Europa, Ganymede and Callisto are frozen worlds with potential water oceans underneath their thick icy shells[6].

The discussion of these incredibly complex systems are way beyond the scope and analysis of this thesis, so there will be only brief descriptions and discussions from now onward.

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[4] (A. T. Sinclair, *The Orbital Resonance Amongst the Galilean Satellites of Jupiter*, Monthly Notices of the Royal Astronomical Society, 171 (1), 1975 p.59–72

[5] R. MC. Lopes, *Io: The Volcanic Moon*, In Lucy-Ann McFadden, Paul R. Weissman, Torrence V. Johnson (eds.), Encyclopedia of the Solar System, Academic Press, 2006 pp.419–431.

[6] (W. Clavin, *Ganymede May Harbor 'Club Sandwich' of Oceans and Ic*, NASA, Jet Propulsion Laboratory, 2014

2.2 The irregular satellites

These objects are considerably smaller than the other Jovian satellites and their orbits are highly eccentric and inclined.

They can be distinguished by the direction of their orbital motion, Prograde or Retrograde. They can be furthermore grouped into smaller families of objects with similar orbital and spectral characteristics.

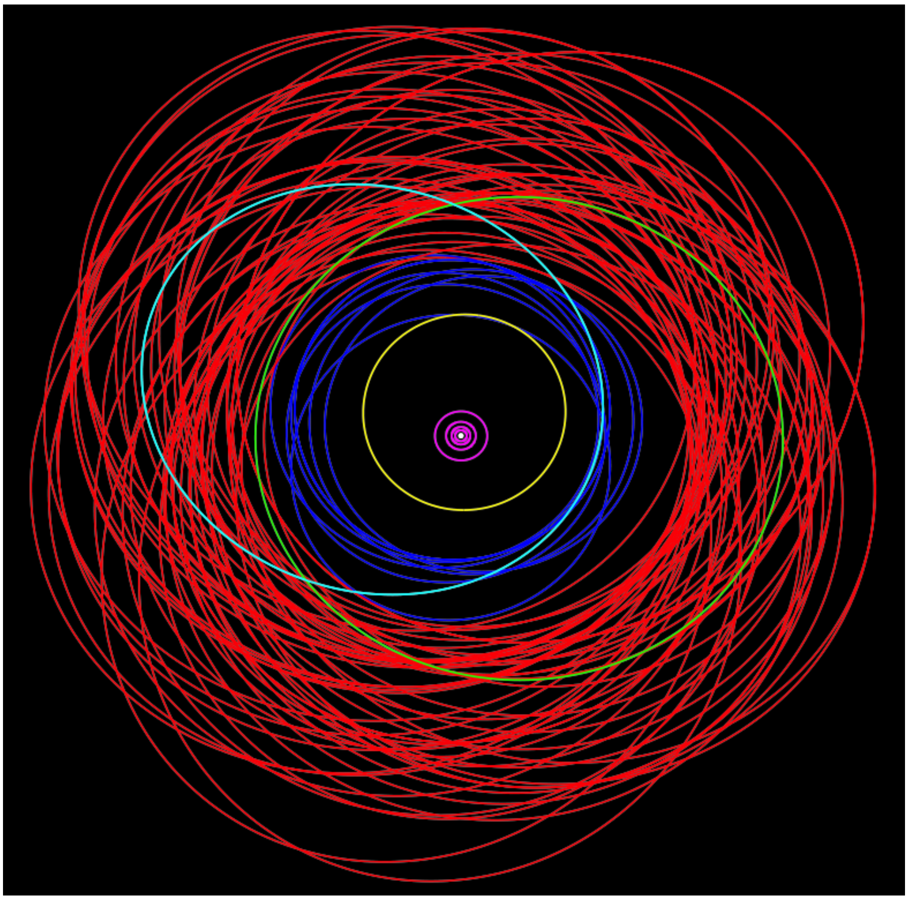

Figure 2.3: A face-on schema of Jupiter's satellite system showing the various groups and families in different colors: Galileian moons in purple (the inner moons are not visible because of their small orbits), the lonely Themisto in yellow, carpo in sky blue and valetudo in green, the Himalia Prograde Group in blue, Ananke Group, Carme Group, Pasiphae Group all in retrograde orbits in red. Picture from Moons of Jupiter by Scott S. Sheppard from the Carnegie Institution

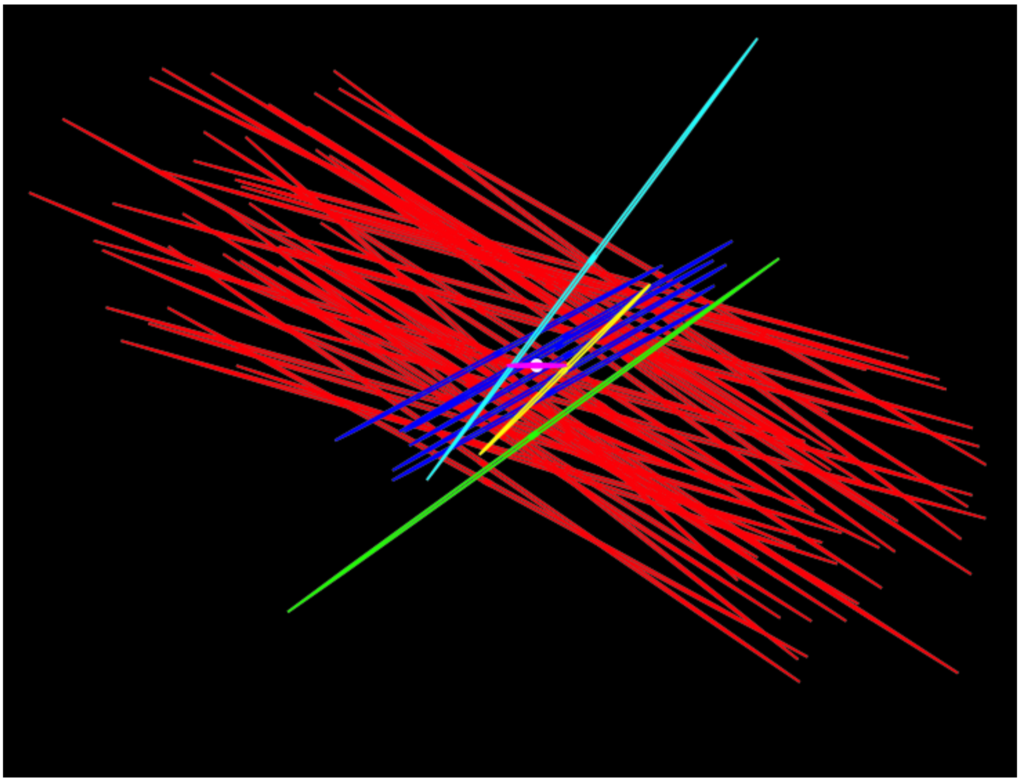

Figure 2.4: An edge-on schema of Jupiter's satellite system showing the various groups and families in different colors: Galileian moons in purple (the inner moons are not visible because of their small orbits), the lonely Themisto in yellow, carpo in sky blue and valetudo in green, the Himalia Prograde Group in blue, Ananke Group, Carme Group, Pasiphae Group all in retrograde orbits in red. Inclinations can be appreciated here. Picture from Moons of Jupiter by Scott S. Sheppard from the Carnegie Institution

2.2.1 the Prograde Satellites

These are the innermost objects among the outer satellites. There are 9 known satellites in this group them being *Themisto*, the inner most one and the ones belonging to the *Himalia Group*, and other two solitary satellites *Carpo* and *Valetudo* (also known as S/2016 J2). Their semi-major axis range from 105.00 R_J (Themisto) to 264.4 R_J (Dia also nown as S/2000 J11, from the Himalia Group).

Among the Prograde Irregular satellites there is only one known group, the Himalia Group. The objects that fall in this category share the same orbital characteristics and possibly the same spectroscopical features as well.

Themisto - orbital parameters				
Denomination	Semi-major axis (Jovian Radii)	Orbital Period (days)	Inclination (degrees)	Eccentricity
Themisto (S/1975J1)	105	130.02	45.67	0.242

Table 2.5: Orbital parameters for the first outer satellite Themisto.

Themisto - physical parameters		
Denomination	Radius (km)	Visual geometric albedo
Themisto (S/1975J1)	4	0.04

Table 2.6: Physical parameters for the first outer satellite Themisto.

Carpo - orbital parameters and physical parameters					
Denomination	Semi-major axis (Jovian Radii)	Orbital Period (days)	Inclination (degrees)	Eccentricity	Radius (km)
Carpo(S/2003J20)	237.6	456.1	51.4	0.430	3

Table 2.7: Orbital and physical parameters for the solitary satellite Carpo.

Valetudo - orbital parameters and physical parameters					
Denomination	Semi-major axis (Jovian Radii)	Orbital Period (days)	Inclination (degrees)	Eccentricity	Radius (km)
Valetudo (S/2016J2)	264.4	533.3	34.0	0.222	1

Table 2.8: Orbital and physical parameters for the solitary satellite Carpo.

The Himalia Group - orbital parameters				
Denomination	Semi-major axis (Jovian Radii)	Orbital Period (days)	Inclination (degrees)	Eccentricity
Leda(JXIII)	156.2	240.92	27.47	0.164
Ersa(S/2018J1)	160.6	252	30.61	0.094
Himalia(JVI)	160.3	250.5662	27.63	0.162
Pandia(S/2017J4)	161.2	252.1	28.15	0.18
Lysithea(JX)	163.9	259.22	27.35	0.112
Elara(JVII)	164.2	259.6528	24.77	0.217
Dia(S/2000J11)	175.7	287	28.2	0.248

Table 2.9: Orbital parameters for the only group in the prograde family of outer satellites, the Himalia Group.

The Himalia Group - physical parameters			
Denomination	Mass (10^{20} kg)	Radius (km)	Visual geometric albedo
Leda(JXIII)	0.00006	5	0.07
Ersa(S/2018J1)		3	
Himalia(JVI)	0.095	85	0.03
Pandia(S/2017J4)		3	
Lysithea(JX)	0.0008	12	0.06
Elara(JVII)	0.008	40	0.03
Dia(S/2000J11)		2	0.04

Table 2.10: Physical parameters for the only group in the prograde family of outer satellites, the Himalia Group.

2.2.2 Retrograde Satellites

These objects are the farthest out in the satellite system. They are clustered into three groups: *The Ananke Group*, the *Carme Group*, and the *Pasiphae Group*.
These groups have very different orbital characteristics from one another, except for being in a retrograde orbit:

- **The Ananke Group** ranges from 271.2 R_J (euporie) to 300.6 R_J (S/2017 J9) in semi-major axis, from 147.0° to 152.7° in inclination and from 0.156 to 0.229 in eccentricity.

The Ananke Group - orbital parameters				
Denomination	Semi-major axis (Jovian Radii)	Orbital Period (days)	Inclination (degrees)	Eccentricity
Euporie(S/2001 J10)	271.2	553.1	147	0.156
(S/2003J1)	289.5	606.3	146.5	0.119
Eupheme(S/2003J3)	256.5	504	143.7	0.241
(S/2010J2)	284	588.1	150.4	0.307
(S/2016J1)	287.7	602.7	139.8	0.141
Mneme(S/2003 J21)	294.7	620	148.6	0.227
Euanthe(S/2001 J7)	290.9	620.6	148.9	0.232
(S/2003J16)	293.7	595.4	148.6	0.27
Harpalyke(S/2000 J5)	295.3	623.3	148.7	0.227
Orthosie(S/2001 J9)	289.8	622.6	145.9	0.281
Helike(S/2003 J6)	297.4	634.8	154.8	0.156
Praxidike(S/2000 J7)	295.8	625.3	148.7	0.22
(S/2017J3)	289.5	606.3	147.9	0.148
(S/2003J12)	265.8	533.3	145.8	0.376
(S/2017J7)	288.5	602.6	143.4	0.215
Thelxinoe(S/2003 J22)	296	628.1	151.4	0.221
Thyone(S/2001 J2)	292.9	627.3	148.5	0.229
(S/2003J2)	399.6	982.5	151.8	0.38
Ananke(JXII)	297.7	629.8	148.9	0.244
Iocaste(S/2000 J3)	297.5	631.5	159.7	0.218
Hermippe(S/2001 J3)	295.6	633.9	150.7	0.21
(S/2017J9)	300.6	639.2	152.7	0.229

Table 2.11: Orbital parameters for one the retrograde group of the outer satellites, the Ananke Group.

The Ananke Group - physical parameters			
Denomination	Mass (10^{20} kg)	Radius (km)	Visual geometric albedo
Euporie(S/2001 J10)		1	
(S/2003J1)		2	
Eupheme(S/2003J3)		2	
(S/2010J2)		2	
(S/2016J1)		1	
Mneme(S/2003 J21)		2	
Euanthe(S/2001 J7)		1.5	
(S/2003J16)		2	
Harpalyke(S/2000 J5)		2	0.04
Orthosie(S/2001 J9)		1	
Helike(S/2003 J6)		4	
Praxidike(S/2000 J7)		3.4	0.04
(S/2017J3)		2	
(S/2003J12)		1	
(S/2017J7)		2	
Thelxinoe(S/2003 J22)		2	
Thyone(S/2001 J2)		2	
(S/2003J2)		2	
Ananke(JXII)	0.0004	10	0.06
Iocaste(S/2000 J3)		2.6	0.04
Hermippe(S/2001 J3)		2	
(S/2017J9)		3	

Table 2.12: Physical parameters for the retrograde group of the outer satellites, the Ananke Group.

- **the Carme Group** ranges over 1.210^6km in semi-major axis, 1.6° in inclination $165.70.8^\circ$, and eccentricities between 0.23° and 0.27°.

the Carme Group - orbital parameters				
Denomination	Semi-major axis (Jovian Radii)	Orbital Period (days)	Inclination (degrees)	Eccentricity
Pasithee(S/2001J6)	323.1	716.3	165.4	0.288
(S/2017J8)	325	719.6	164.7	0.312
Chaldene (S/2000J10)	324.2	723.8	165.4	0.238
(S/2017J2)	326	723.1	166.4	0.236
Isonoe(S/2000J6)	324.8	725.5	165	0.261
Kallichore (S/2003J11)	336.3	764.7	165.5	0.264
Erinome (S/2000J4)	325.6	728.3	164.9	0.27
Kale(S/2001J8)	324.8	729.5	165	0.26
Eirene(S/2003J5)	336.8	759.7	165	0.21
Aitne(S/2001J11)	324.9	730.2	165.1	0.264
Eukelade (S/2003J1)	330.9	746.4	165.5	0.272
Arche(S/2002J1)	320.7	723.9	165	0.259
Taygete(S/2000J9)	326.7	732.2	165.2	0.251
(S/2011J1)	281.9	580.7	162.8	0.296
Carme (JXI)	327.3	734.2	164.9	0.253
Herse(S/2003J17)	323.1	715.4	164.2	0.2
(S/2003J19)	318.9	701.3	162.9	0.334
(S/2010J1)	326.1	723.2	163.2	0.32
(S/2003J9)	313.9	683.0	164.5	0.269
(S/2017J5)	325	719.5	164.3	0.284
Kalyke(S/2000J2)	329.8	743.0	165.2	0.243
(S/2003J10)	339.2	767.0	164.1	0.214

Table 2.13: Orbital parameters for the retrograde group of the outer satellites, the Carme Group.

The Carme Group - physical parameters			
Denomination	Mass (10^{20} kg)	Radius (km)	Visual geometric albedo
Pasithee(S/2001J6)		1	
(S/2017J8)		1.9	
Chaldene (S/2000J10)		2	
(S/2017J2)		2	
Isonoe(S/2000J6)		1.9	0.04
Kallichore (S/2003J11)		2	
Erinome (S/2000J4)		1.6	0.04
Kale(S/2001J8)		1	
Eirene(S/2003J5)		4	
Aitne(S/2001J11)		1.5	
Eukelade (S/2003J1)		4	
Arche(S/2002J1)		1.5	
Taygete(S/2000J9)		2.5	0.04
(S/2011J1)		2	
Carme (JXI)	0.001	15	0.06
Herse(S/2003J17)		2	
(S/2003J19)		2	
(S/2010J1)		2	
(S/2003J9)		1	
(S/2017J5)		2	
Kalyke(S/2000J2)		2.6	0.04
(S/2003J10)		2	

Table 2.14: Physical parameters for the retrograde group of the outer satellites, the Carme Group.

- **The Pasiphae Group** ranges from 307.7 R_J (Philophrosyne also known as S/2003 J15) to 343.3 R_J(Kore) in semi-major axis, from 141.5° to 141.5° in inclination and from 0.229 to 0.436 in eccentricity.

The Pasiphae Group - orbital parameters				
Denomination	Semi-major axis (Jovian Radii)	Orbital Period (retrograde - days)	Inclination (degrees)	Eccentricity
Philophrosyne (S/2003J15)	307.7	668.4	140.8	0.11
Eurydome (S/2001J4)	319.9	717.3	150.3	0.276
(S/2011J2)	326.3	726.8	151.9	0.387
(S/2003J4)	325.4	723.2	144.9	0.204
(S/2017J6)	314.1	683	155.2	0.557
Hegemone (S/2003J8)	335	739.6	155.2	0.328
Pasiphae (JVIII)	330.4	743.6	151.4	0.409
Sponde(S/2001J5)	328.6	748.3	151	0.312
Megaclite (S/2000J8)	333	752.8	152.8	0.421
Cyllene (S/2003J13)	340.6	737.8	149.3	0.319
Sinope (JIX)	334.9	758.9	158.1	0.25
(S/2017J1)	329.9	734.2	149.2	0.397
Aoede(S/2003J7)	335.4	761.5	158.3	0.432
Autonoe (S/2001J1)	322.3	762.7	152.9	0.334
Callirrhoe (S/1999J1)	337.1	758.8	147.1	0.283
(S/2003J23)	336.5	759.7	149.2	0.309
Kore(S/2003J14)	343.3	779.2	152.4	0.325

Table 2.15: Orbital parameters for the retrograde group of the outer satellites, the Pasiphae Group.

The Pasiphae Group - physical parameters			
Denomination	Mass (10^{20} kg)	Radius (km)	Visual geometric albedo
Philophrosyne (S/2003J15)		2	
Eurydome (S/2001J4)		1.5	
(S/2011J2)		2	
(S/2003J4)		2	
(S/2017J6)		2	
Hegemone (S/2003J8)		3	
Pasiphae(JVIII)	0.003	18	0.1
Sponde(S/2001J5)		1	
Megaclite (S/2000J8)		2.7	0.04
Cyllene (S/2003J13)		2	
Sinope(JIX)	0.0008	14	0.05
(S/2017J1)		2	
Aoede(S/2003J7)		4	
Autonoe (S/2001J1)		2	
Callirrhoe (S/1999J1)		4	0.04
(S/2003J23)		2	
Kore(S/2003J14)		2	

Table 2.16: Parameters for the retrograde group of the outer satellites, the Pasiphae Group.

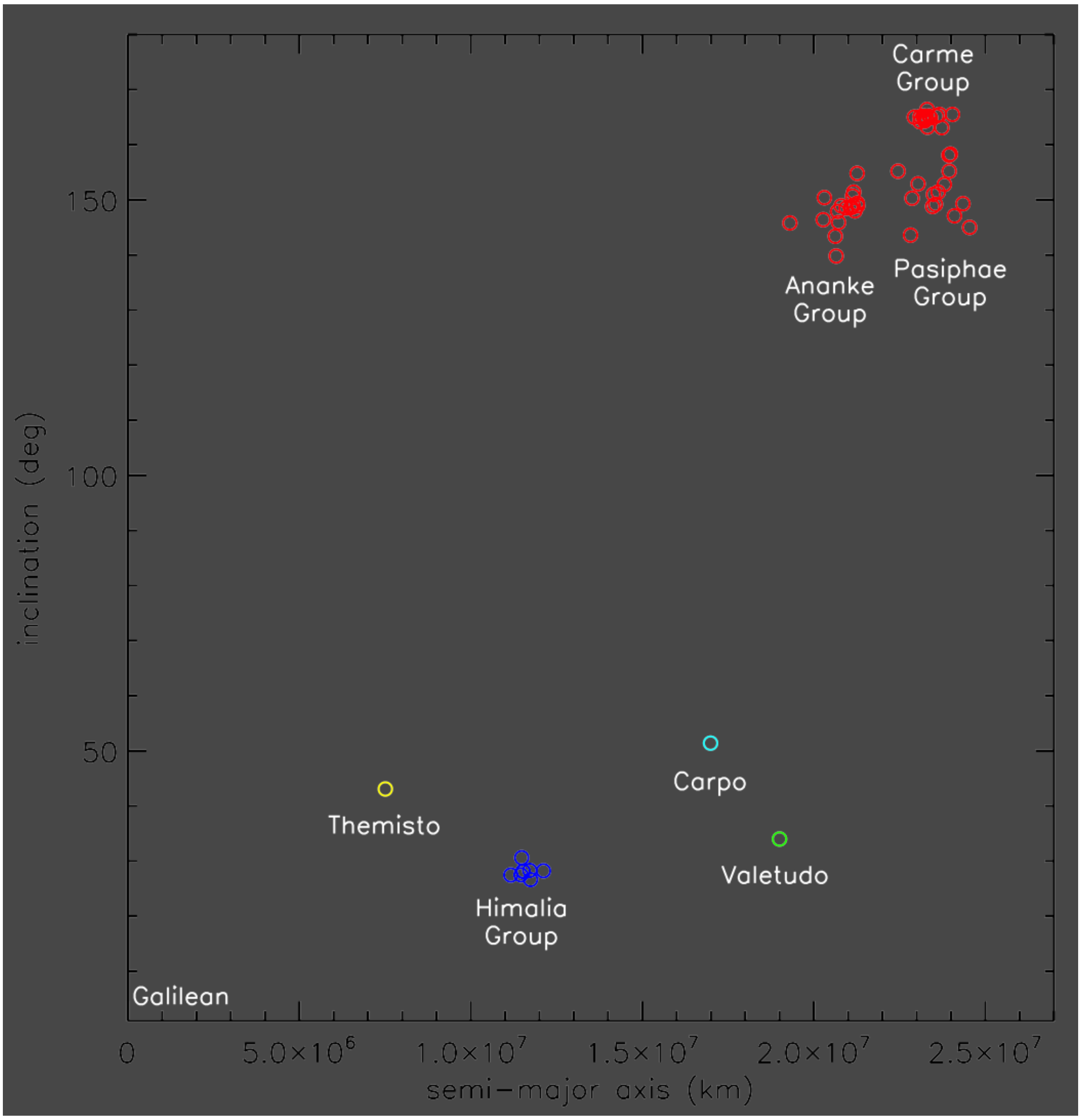

Figure 2.5: In this chart the similar characteristics within each group can be appreciated. Represented are on the x-axis the semi-major axis of the satellites in km, on the y-axis the inclinations in degrees.

2.3 The Ring System

The Jovian ring system has three components from the outside in [7]: the *halo* that extends vertically, the *main ring*, and two *"gossammer" rings*.

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[7] J. A. Burns et al., *Jupiter's ring-moon system*, 2015

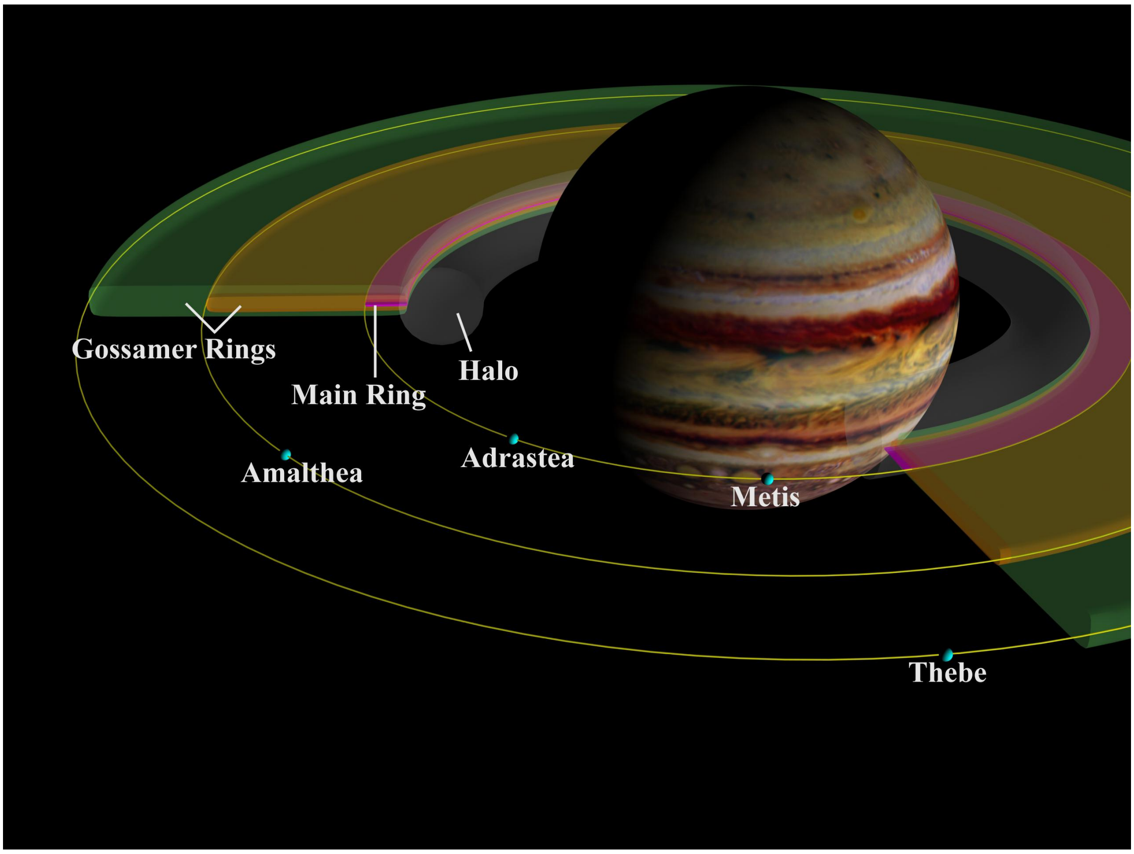

Figure 2.6: A schema of Jupiter's ring system showing the four main components. For simplicity, Metis and Adrastea are depicted as sharing their orbit. In reality, Metis is very slightly closer to Jupiter.

The innermost element, the halo, extends vertically between 20000 and 40000 km although is concentrated in the equatorial plane. It appears to be a torus that disappears at a radius of approximately $1.40R_J$, and fuses itself with the main ring at a radius of $1.72R_J$. The main ring is the brightest of these elements. It is a narrow band extending vertically for no more than 30km and has a width of approximately 6000 km. Its inner boundary fades gradually. On the contrary the outer boundary seems to fade more abruptly going closer to Adrastea's orbit, making the satellite its Shepard. The finer structures of the main ring is defined by the moon Metis.
The outer most components of the ring system are the two "gossamer" rings, *Amaltea's and Thebe 's rings*.
Amalthea's ring extends from $1.8R_J$ to $2.54R_J$, up to Amalthea's orbit. It has a rectangu-

lar cross section, similar to Thebe's ring that engulfs Amalthea's being more vertically extended. Thebe's ring stretches up to Thebe's orbit at $3.11R_J$.
Both rings appear to be thicker near their outer edges and slightly thinner at decreasing radii: the first ring is around 2300km thick and the second is 8400km thick.
These clues led scientists to theorise that the gossamer rings are fed by the two moons Amalthea and Thebe(Burns et al. 2015)

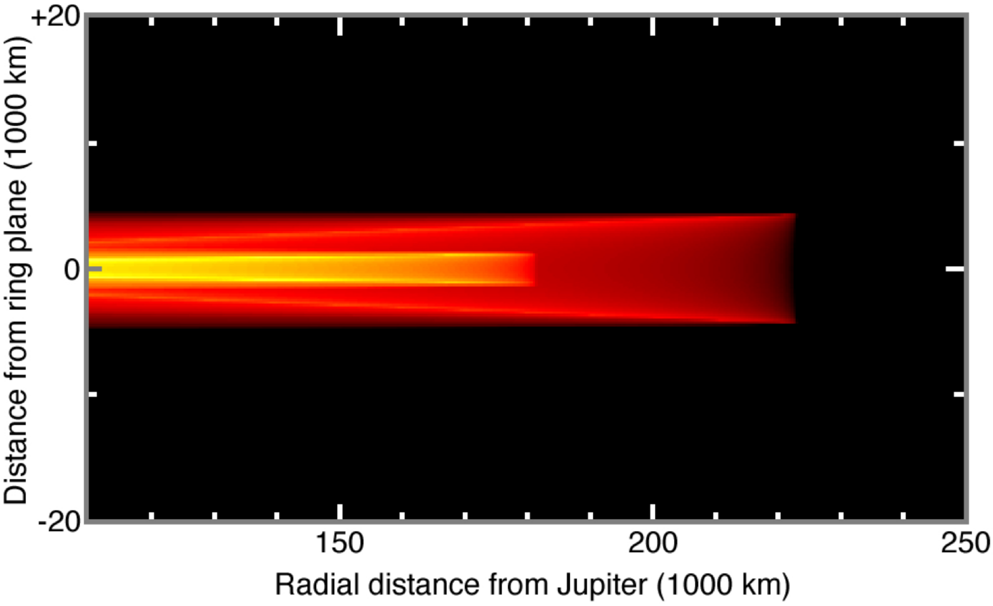

Figure 2.7: Model showing how the material of the two gossamer rings is distributed from the two satellites Amalthea and Thebe inward. Burns et al. 2015

These faint objects are composted of mostly dust sized particles. The rings are continuously replenished by dust and debris coming from impacts between bigger sized grains or small objects coming from outside the jovian system, and the small moons that inhabit the inner region around the gas giant (J. A. Burns et al. 2015).

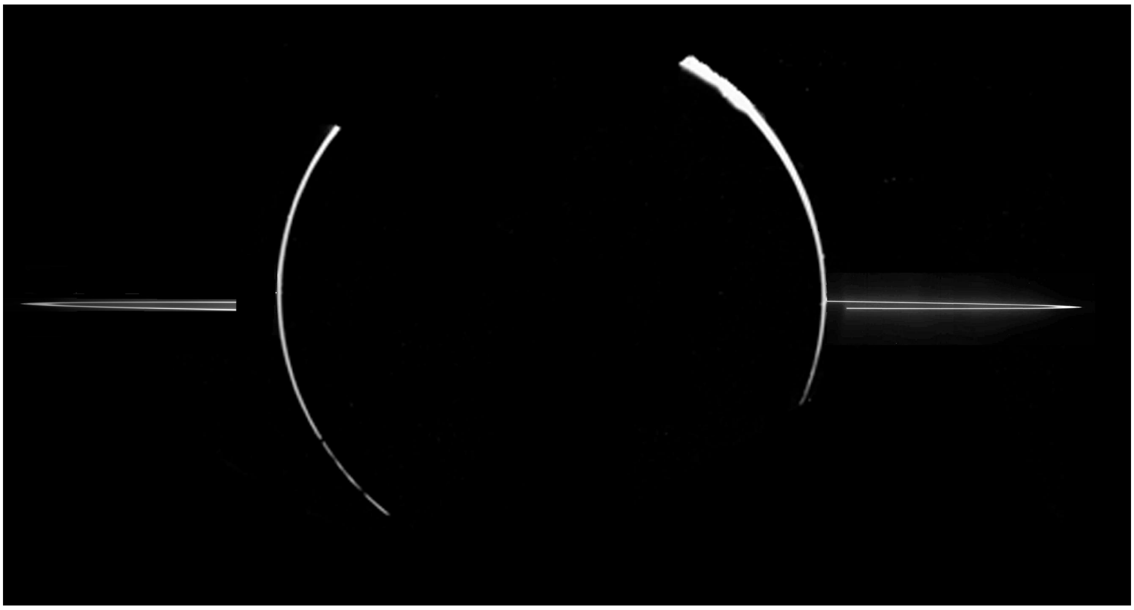

Figure 2.8: Mosaic of Jupiter's ring system acquired by NASA's Galileo spacecraft when the spacecraft was in Jupiter's shadow, peering back toward the Sun. At this angle the small particles are highlighted, so Jupiter's upper atmosphere and the rings appear glowing.

3

Theories of Formation

Following there will be a detailed description of the theories of formation of the previously mentioned categories of objects. Moreover this analysis will be useful to understand where the various objects where formed and what they can tell scientists about the early stages of planetary formation.

The innermost group of satellites and the Galilean satellites are theorised to have formed from the early Jovian nebula through a mechanism of disk accretion (Canup and Ward 2002). This mechanism is analogous to that of planetary formation in a solar nebula(Lissauer 1987). Saltellites accrete from the planetary disk that would have lain coplanarly to proto-Jupiter. This explains the almost circular coplanar and prograde orbits of the regular satellites. The outer satellites both with prograde and retrograde orbits had to shape their orbital properties and physical characteristics through other means. There are two main theories about the mechanism that could explain the orbital properties of these small and irregular objects: via nebula drag (Pollack et al 1979; Ćuk Burns 2004; Kortenkamp 2005) or via dynamic capture (Nesvorný et al. 2003, 2007). The first theory premises the capture of two external bodies in the proto-Jovian nebula before the hydrodynamical collapse and the subsequent formation of Jupiter, that later formed the prograde and retrograde satellites. The capture would have been possible due to the gas drag, and because of it the two parent bodies were decelerated and fragmented. Because of the timing of the capture, in this theory, the orbital parameters of the two groups underwent limited evolution, and the fragments dispersed only at a later time probably due to the collision with another external vagrant body. Moreover this theory accounts for the orbital resonances of the three Galilean moons. It needs to be specified that according to this argument the irregular satellites we see today are the biggest remnants of a more numerous group of smaller bodies that fell spiralling into the centre of the gas nebula because of the continued gas drag. This big fraction of disappeared bodies could account for the heavy elements thought to compose Jupiter's core.

The second theory premises the impossibility of satellite capture within a three body system (in this case the Sun, Jupiter and the satellite). This theory argues that the irregular satellites were incorporated in the system during the later stages of the Jupiter formation during the migration epoch that is thoroughly explained by the Nice Model of the solar system (Tsiganis et al. 2005; Nesvorný et al. 2007, 2014) which includes the presence of four bodies that keep a satellite in a stable orbit inside Jupiter's Hill sphere, where this is the sphere of gravitational influence of a body. This theory also considers collisions between objects an important factor in the dynamical capture of the irregular satellites.

4

Taxonomy

An interesting approach to the problem of satellite taxonomy and categorisation is the cladistical method. Cladistics is an approach usually used in biology to classify organisms into cluster of objects, which then are called clades, based on characteristics shared among them. Thanks to this approach how closely organism are related to each other can be understood and consequently finding their most recent common ancestor is possible.

This method of analysis can be applied to astrophysics and astronomy to examine relationships among different objects, for examples stars (Fraix-Burnet & Davoust 2015; Jofré et al. 2017), globular clusters (Fraix-Burnet et al. 2009) and galaxies(Fraix-Burnet et al. 2006, 2010, 2012, 2015).

Thanks to these works, a new field of study and analysis has been coined with the name of “astrocladistics” (fraix-Burnet et al. 2015). In the words of Timothy R. Holt (2018): “there are good reasons to believe that cladistics can provide sensible groupings in a planetary science context. Objects that have similar formation mechanism should have comparable characteristics. Daughter objects that are formed by breaking pieces off a larger object should also have similar characteristics.”

The cladistical method works creating a 2D matrix array, where taxa, objects of interest, are positioned in the rows and each characteristic is positioned in the columns, and giving the characteristics a numerical state, 0 or 1, even though intermediate states can be used. 0 is used to indicate the original “base” state. To impose the “base” state 0, an *outgroup*, a taxa that is not within the area of interest, is used.

Phylogenetic trees are then crated from the taxa-character matrix, closely related taxa are grouped together in a tree. The trees are crated with in mind the *concept of maximum parsimony* (Maddison et al. 1984), that is that the tree with the shortest lengths, the smallest number of change, is most likely to show the true relationship (Timothy R. Holt et al. 2018).

The resulting branching of the taxonomic tree is therefore a good hypothesis for the relationship between taxa. There are other two metrics applied to the analysis of a tree to understand how reliable it is: the *consistency* and *retention inidices*.

In mathematical therms the consistency index (Kluge & Farris 1969) is

$$CI = M/S$$

where M is related to the minimum number of changes and S is the number of changes genuinelly observed in a tree. This index is not the best metric because it can show negative correlation with the number of taxa and characteristics (Archie 1989) so the retention index was introduced. The retention index (Farris 1989) is defined such as

$$RI = \frac{G-M}{G-S} \tag{4.1}$$

where G is the maximum number of changes and M and S are the same for the consistency index. These two metrics are a measure of *homoplasy*, or in other words the independent loss or gain of a characteristic. If a tree has high amounts of homoplasy, this is suggestive of random events instead of the searched relationship among taxa.

A tree with no homoplacy has a consistency index and a retention index of 1, so it is perfectly reliable, and shows the true relationships among taxa. In the paper *Cladistical Analysis of the Jovian and Saturnian Satellite Systems* by T. R. Holt et al. the taxon-character matrix consists of the Sun as the outgroup, 67 of the Jovian satellites of which 4 are the innermost satellites and 4 are the Galilean satellites.

For the characteristics considered in this study there are three broad categories, for a total of 38. The categories of parameters are orbital, physical and compositional. The orbital parameters that are considered are presence in orbit around Jupiter, prograde orbit or retrogade orbit, which are not continuous, and semi-major axis, orbital inclination and eccentricity that on the contrary are continuous values. For the physical parameters the characteristics considered are density and visual geometric albedo. The third group of

parameters comprehends the discrete compositional characteristics detailing the absence or presence of 31 chemical species. In this group in the matrix the ”base” state 0 is assigned in case of absence of an element, except for elemental hydrogen, hydrogen (H_2) and helium, being the Sun the outgroup. The results from this study are quite consistent with the traditional taxonomy classification, proposed by Nesvorný et al. (2003) and Sheppard & Jewitt (2003).
The consensus tree has a lenght score of 128, whith a consistency index of 0.46 and a retention index of 0.85. As said previously the retention index is the most accurate and its value suggests that the tree is reliable.

The following description is represented in the following pylogenetic tree.
Keeping the same nomenclature as the traditional Taxonomy, where each family is represented by its biggest member. First observation is that the prograde regular satellites belong to a separate cluster to the irregular satellites.
The Amalthea family is consistent with this new analysis, and is associated with the Galilean satellites. The hypotesized formation of these objects is compatible with the cladistical analysis and so it is a probable thesis.
For the irregular satellites the clustering is also compatible with the traditional classification. The Himalia family, having low inclitation with respect to the retrograde satellites, but having high eccentricity could be explained by distruption of a bigger object in the distant past.
This study clusters Themisto and Carpo with the Himalia family, instead the traditional classification leaves them ungrouped within the irregular satellites.
For the retrograde irregular satellites the broad traditional classification is mantained although the study suggests further research and analysis on the Ananke/Carme family because it could be further subdivided into subfamilies, since in this tree there is a continuum between them. Some of the objects that used to belong to the Ananke family are moved to other groups and no new objects are added to it.
Furthermore a new cluster is created: the Iocaste family. These objects have semi-major axis spans most all of the orbital space where the other irregular satellites are and are being discovered. The lower albedo and eccenticities separates objects in this group from the Pasiphae Group.

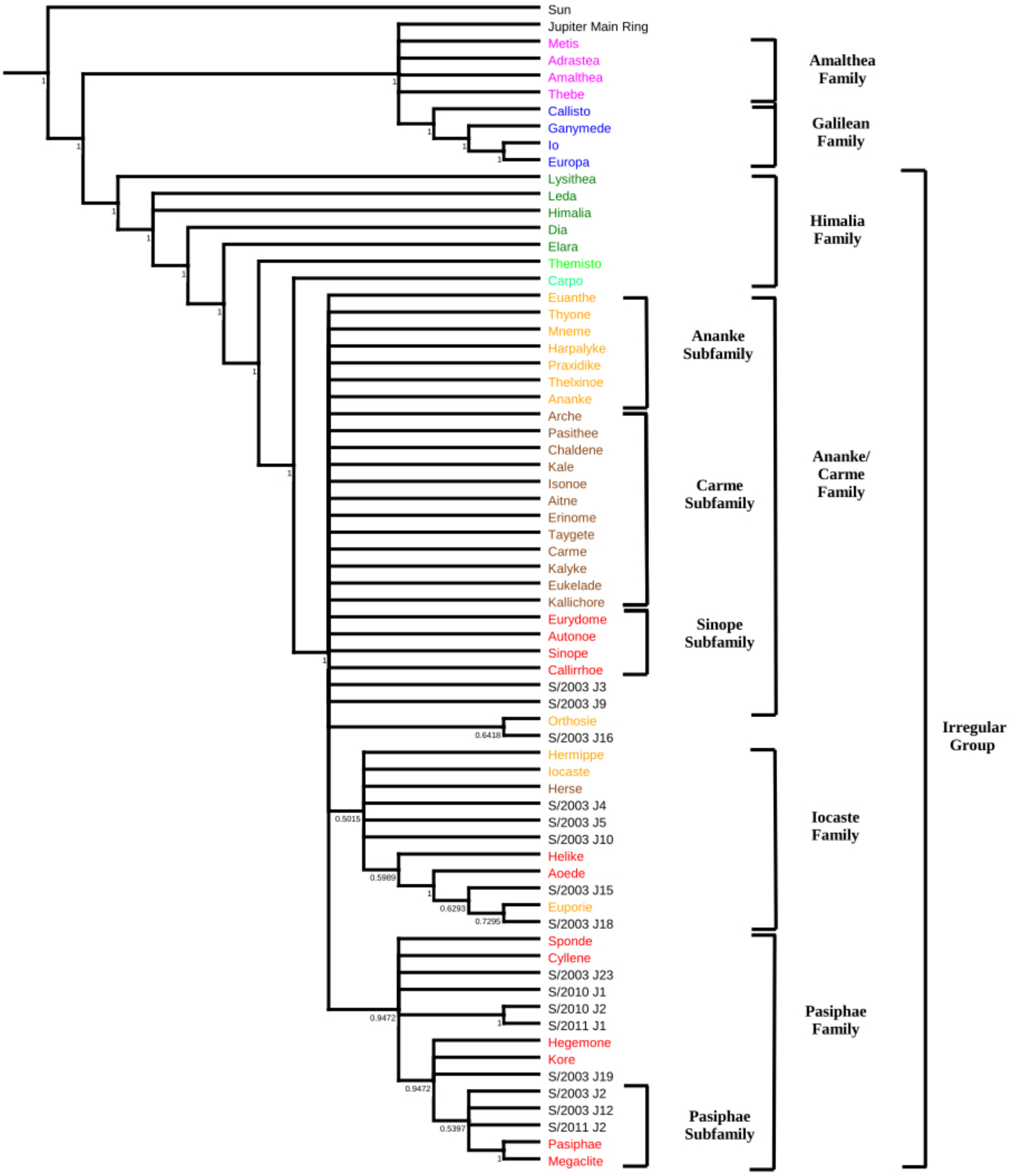

Figure 4.1: Majority consensus taxonomic tree for objects in the Jovian system. The numbers indicate the frequency of the node in the 10,000 most parsimonious tree block. The colors represent the traditional classification. The proposed groups and families are on the right. Picture from *Cladistical Analysis of the Jovian and Saturnian Satellite Systems* by T. R. Holt et al. 2018

5

Discussion

Some interesting results have emerged from the research on Jupiter's satellites through the study of literature on the subject.

First of all, the consensus is not unanimous about the dynamical grouping of the irregular satellites: they are traditionally divided into four groups as illustrated in *Chapter 2* but from analysis of the dynamical characteristcs of these objects from a different approach, such as the cladistical method described in *Chapter 4* the grouping is not as sure and defined as once traditionally thought.

The cladistical method could be a revolutionary tool with which more analysis on the irregular satellites could be carried out, since it is a powerful tool. More pylogenetic trees could be constructed considering other characteristic of the taxa together with the dynamical and physical, like spectroscopic characteristics, and consequently spectral type, as well.

Since Jupiter's irregular satellites are extremely small objects it is very difficult to capture clear photometric and spectroscopic data with a good signal-to-noise ratio. Nontheless, a few surveys such as the *Two-Micron All Sky Survey* (2MASS), and other more targeted observations by Nakamura & Sasaki (1997), T. Grav et al. (2003), Tolen & Zellner (1984), T. Rettig et al. (2001) and L. Luu (1991) among others, have permitted to gather photometric and spectral data of the biggest and brightest objects of each dynamical group of the irregular satellites. Thanks to this little information a preliminar cladistical analysys can be done but more data needs to be gathered to have clearer results.

As a matter of fact further spectroscopic data could be retrieved by forthcoming targeted surveys from the ground and space missions such as ESA's JUICE.

Thanks to the *remote sensing package* on the spacecraft JUICE, comprising the four instruments JANUS, MAJIS, UVS, SWI capable of imaging and spectral imaging from the ultraviolet to the sub-millimetre wavelengths, scientists could have plenty of new data to work with.

Hopefully even the smaller objects can be observed by the mission to better understand if the traditional dynamical grouping is congruous with the spectral classification of the smaller objects that will transpire from the new data.

Once scientists will have a unanimous understanding of the dynamical and spectral grouping, the formation hypotesis could be further investigated and the spectral families could be compared to other families of comets, asteroids and trojans that lurk in the solar system, understanding the region of formation of jupiter's irregular satellites, and consequently understand the capture mechanisms that can lead to the formation of such diverse and complex planetary systems.

Lastly JUICE's mission could lead to the acquisition of high definition images, in particular through the instrument JANUS, of the irregular satellites that could let scientists understand how cratered and what degree of aging the surface of these satellites are and consequently understanding more about the spectral types that these objects fall into.

The new developements in this field of study could lead to a deeper understanding of the Solar System, the processes that are involved in planetary formation and how the Solar System is similar or different to other extrasolar systems that can be comparable to our own.

6

Conclusion

The Jovian system is big and complex.

Its satellites can be traditionally divided into two families the Regular and the Irregular satellites, that can be further divided into 6 groups. The rings are a system to study on its own.

The Regular satellites have prograde, almost circular orbits and low inclinations. There are two groups in this family: the Amalthea group and the Galilean satellites.

The irregular satellites can be subdivided into prograde and retrograde families, both these two families have highly eccentric orbits and have high inclinations. The prograde family is the Himalia group, and the retrograde family has three different cluster of objects called the Ananke group, the Pasiphae group and the Carme group.

Further analysis with the cladistical method, suggests to review this classification for a few of the objects assigned traditionally to the Himalia group, the Pasiphae group, the Ananke group and the Carme group, suggesting even the further subdivision with the creation of a new dynamical group, the Iocaste group.

The grouping of these objects led scientists to formulate hypotesis to explain their genesis. The regular satellites were formed in the planetary nebula at the time of the formation of Jupiter, while the irregular satellites must have had a different origin. The most accredited hypotesis is that of satellite capture. The environment at the time of the capture is not certain. There are a few probable conjectures that involve gas drag, that led to the loss of energy of the satellites that kept them in stable orbits, and the fracture of the progenitor captured planetesimals throug gas drag or impacts, that led to the formation of the clusters of objects observed today.

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