Highlights of Spanish Astrophysics XII, Proceedings of the XVI Scientific Meeting of the Spanish Astronomical Society held on July 15 - 19, 2024, in Granada, Spain. M. Manteiga, F. González Galindo, A. Labiano Ortega, M. Martínez González, N. Rea, M. Romero Gómez, A. Ulla Miguel, G. Yepes, C. Rodríguez López, A. Gómez García and C. Dafonte (eds.), 2025

The Iberian explorations: the roots of the Scientific Revolution

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Abstract

Cosmography, a science that combined geography and astronomy to inform us about our place in the universe, underwent an extraordinary change between the 15th and 16th centuries, an evolution that was linked to exploration, politics, culture and technology. It also had a great impact on the Scientific Revolution of the 17th and 18th centuries. These developments were based on the great intellectual activity that emerged from the Iberian and Italian peninsulas. Therefore, the beginning of modern astronomy has part of its roots, sometimes overlooked, in Portugal and Spain. In addition, the resolution of the "Longitude problem", achieved in the 1770s, had very important contributions from these two nations. A comprehensive overview of these processes is provided here.

1 The heritage

In the middle of the 5th century, with the end of the Western Roman Empire, a political and cultural cycle came to a close. At that point, various syntheses produced by Greek and Roman scholars, which included Mesopotamian and Egyptian influences, had been distilled into several compendia that provided a rational interpretation of the world (Fig. 1). As for cosmography, the discipline that combined geography and astronomy, the texts of Claudius Ptolemy (*ca.* 100–*ca.* 170 CE) would determine the vision of several civilizations for more than a millennium, although he was not the only author that endured.

Thus, Ptolemy's treatises *Mathēmatikē Sýntaxis* and *Geōgraphikē Hyphēgēsis* (later known by the titles *Hē Megálē Sýntaxis* or *Almagest*, and *Geographia*, respectively) were instrumental in describing Earth and its inhabited continents (the "ecumene"), and its position in the kosmos. Other books by Ptolemy achieved great diffusion, such as *Handy Tables* or *Planetary hypotheses* Unfortunately, his astrological treatise *Tetrabiblos* (*Quadripartium*) also had a significant impact (Jones, 1991).

In addition, the size of the Earth had been estimated by various authors: Aristotle gave

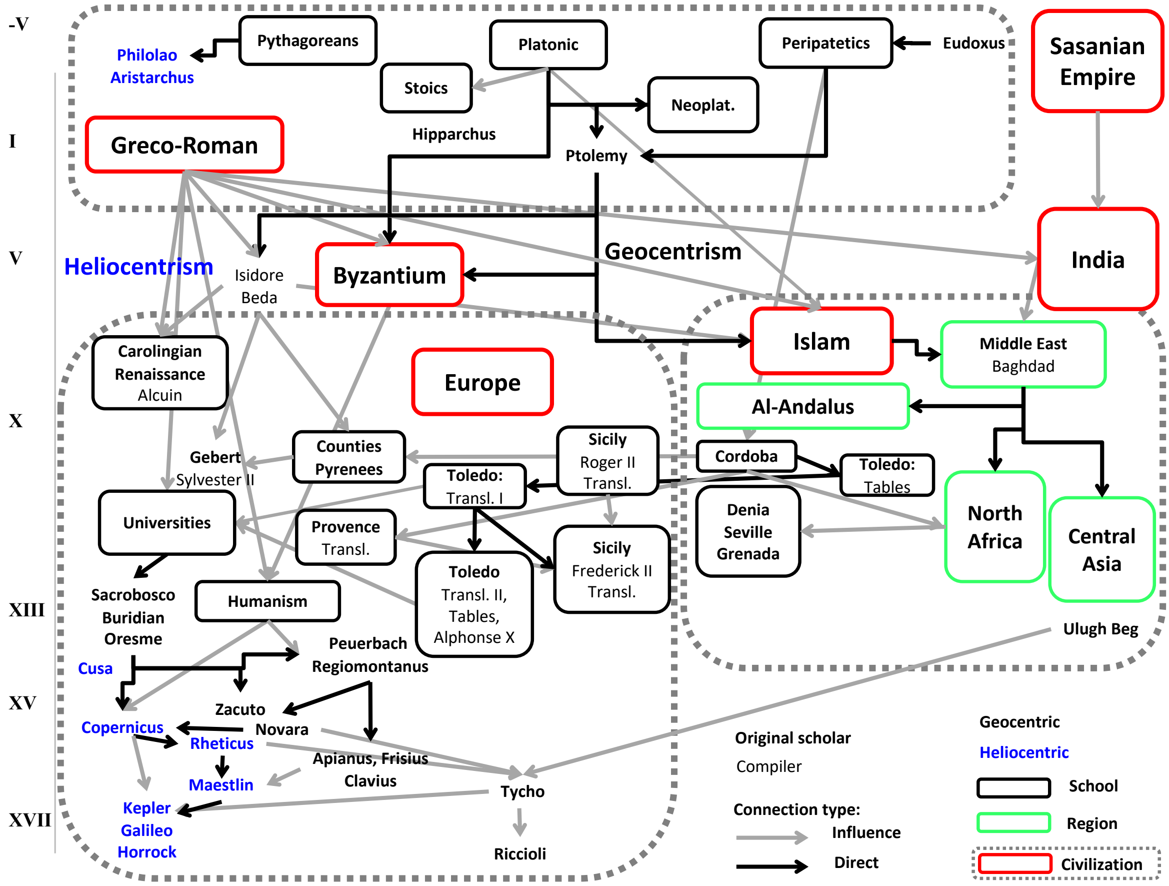

Figure 1: The intellectual heritage: different traditions in relation to the evolution of astronomy. The connections between prominent astronomers within their cultural spheres are shown, from antiquity to the beginning of the Scientific Revolution.

a first value of 400,000 stadia in the 4th century BCE, without leaving any record of either the author or the method. Subsequently, both Eratosthenes of Cyrene (276–196 BCE) and Posidonius of Apamea (*ca.* 135–51 BCE) obtained values between 252,000 and 180,000 stadia. In the case of Eratosthenes, depending on the different possible equivalences of the stadia, his estimate could have been extraordinarily close to the true value.

This conception of the kosmos was maintained during the High Middle Ages in Western Europe, but also in the Byzantine Empire, heir in the East of the Roman Empire, in India (due to the influence of the Hellenistic kingdoms of Central Asia) and, later, in Islam (Fig. 1). Europe, after the 12th century, when the first universities were founded, inherited all this intellectual heritage, mainly through translations made in al-Andalus and the school of translators of Toledo from the Arabic versions, but also from Greek originals coming from Constantinople (Barrado Navascués, 2021, 2023).

Thus, during the European Late Middle Ages, cosmology was perfectly established within a geocentric and geostationary conception: a universe with an immobile and spherical Earth at the center, in which there were three continents that covered a large part of its surface, and planets and a sphere of fixed stars orbiting around it. These movements were described by a complex mathematical apparatus. However, the extremes of the ecumene presented great unknowns. Moreover, the widely used cosmological model of Ptolemy had shown its limitations, specially concerning the determination of the positions of Mercury and Venus.

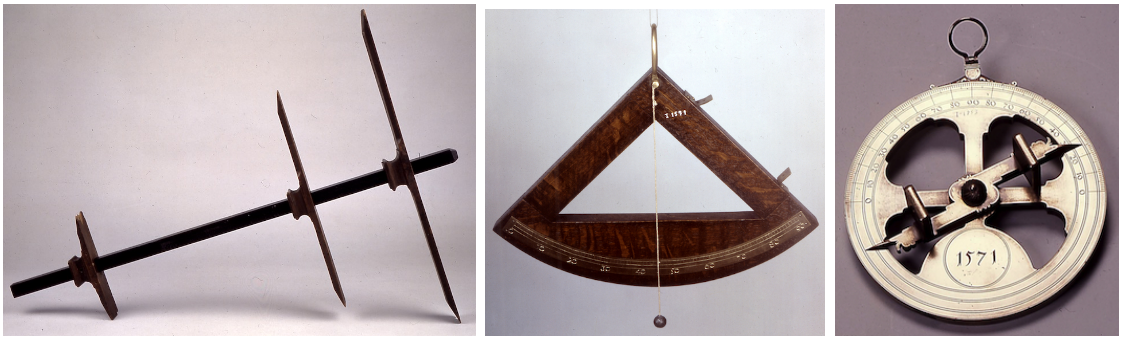

Figure 2: Nautical and astronomical instrumentation: **left** ballestilla (crossbow or Jacob's staff); **center** quadrant, end 15th century; **right** astrolabe. (Museo Naval, Madrid).

2 *Geographia* and the new geographical horizons

In the 13th century, European exploratory missions were sent to Asia, beyond the dominions of the Muslim states, for political, religious or commercial reasons. John of Plano Carpini, Marco Polo, Odorico de Pordenone, Giovanni de' Marignolli or Jordanus Catalani (or de Sévérac) visited both the Mongol Empire and India and left testimony of those lands. In 1291, Vadino and Ugolino Vivaldi attempted an unsuccessful circumnavigation of Africa (Rogers, 1955), emulating legendary voyages that might have taken place in ancient times (the Carthaginian Hannon, the Persian Satespes or the expedition sent by pharaoh Necho II). That same year saw the conquest by the Mamluk sultan of Egypt of St. John of Acre, the last Crusader stronghold in the Levant and gateway to goods from the Far East. The Treaty of Monteleón defined the areas of influence of Aragón and Castile in North Africa. It would be the first of a succession of treaties between different Iberian states, such as Ayllón (1411), Alcáçovas-Toledo (1479), Tordesillas (1494) and Saragossa (1529), which would divide the globe between Portugal and Castille, and later Spain.

At an undetermined moment in the early 14th century, the Genoese Lancelloto Malocello conquered the island of Lanzaronte, in the Canary Islands, thus initiating the discovery and conquest of the Atlantic archipelagos, mainly by Castilians and Portuguese throughout the 15th century (Martínez, 2001). During that same period the Lusitanians sailed along the African coast, until Bartolomeu Dias surpassed its southern tip between 1488 and 1489, and Vasco da Gama reached India, crossing the Indian Ocean in 1498, through the use of information provided by Muslim sailors. At the northern end of the Atlantic, João Vaz Corte Real and Alvaro Martins Homem in 1472–1474 might have sought a northwest passage to

Asia, Gaspar Corte Real reached Newfoundland in 1500–1501, and his brother Miguel Corte Real repeated the feat the following year. Christopher Columbus first voyage to America in 1492 was based on Posidonius' determination of the size of the Earth (the smallest of all those made in antiquity). The Caribbean islands and their American mainland coasts were explored subsequentently by him, Juan de la Cosa, Juan Caboto, Alonso de Ojeda, Vicente Yáñez Pinzón and Amerigo Vespucci, among others.

All these discoveries required a new way of navigating, much more technical and based on astronomical principles. Thus, new instrumentation was developed for marine use, as was the case of the ballestilla (crossbow or Jacob's staff), the quadrant and the nautical astrolabe (Fig. 2), together with the use of improved solar declination tables, which allowed the calculation of latitude (Samsó, 1994). The so-called School of Segres, sponsored by the Infante of Portugal Henrique "the navigator", the Universities of Salamanca and Coimbra played a very relevant role in these technical, theoretical and practical developments. On the other hand, the intake of the new geographical discoveries for the European cartography required an adequate conceptual framework. This was provided by Ptolemy's *Geographia*, rediscovered in the West at the beginning of the 15th century.

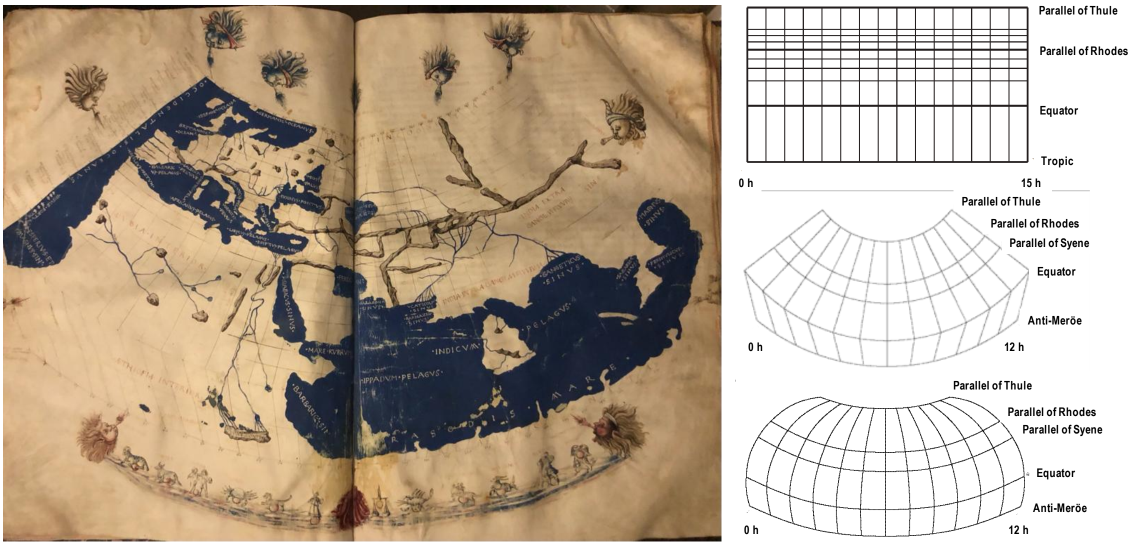

Figure 3: Ancient mapmaking. **Left** Mapamundi taken from *Cosmographia* (*Geographia*), by Ptolemy (2nd century CE). This manuscript, made in 1456, was a gift by Bishop Joan Margarit i Pau to Ferdinand II, King of Aragon and husband of Isabella I, Queen of Castille (Universidad de Salamanca, BG/Ms. 2586). **Right** Cartographic projections described in *Geographia*: proposal by Marino de Tiro, and the first and second projection by Ptolemy.

In 1397, the Byzantine scholar Manuel Chrysoloras traveled to the thriving city of Florence, where he taught Greek for three years. He brought a copy of *Geographia*, possibly copied by Maximo Planudes, a Byzantine theologian, grammarian and translator. Planudes, who lived from about 1260 to 1330, is responsible for the survival, due to his careful copying, of numerous texts of ancient scholars. The manuscript Chrysoloras brought was translated into

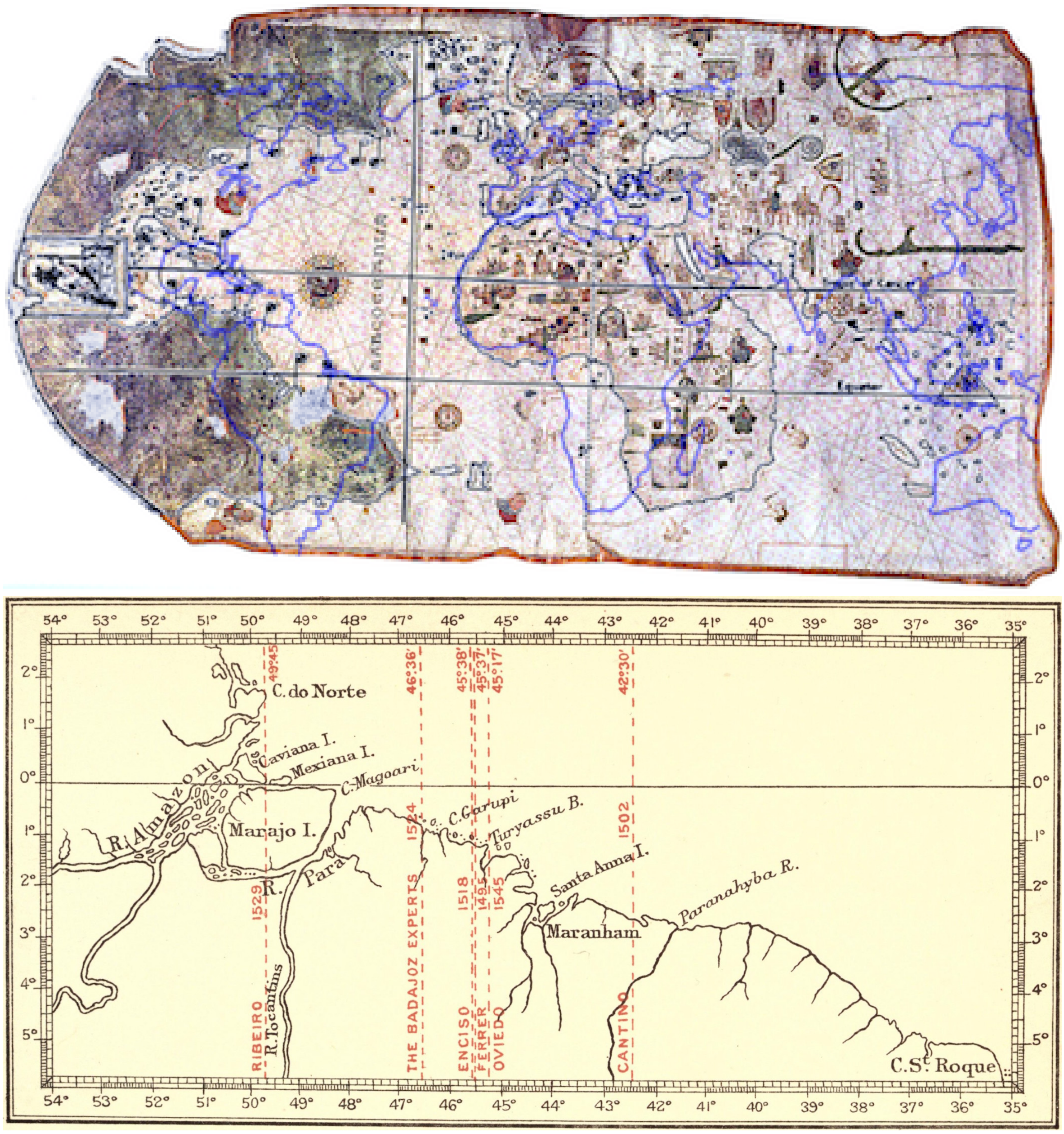

Figure 4: **Top** The first map of the new continent, by Juan de la Cosa in 1500 (Museo Naval, Madrid). The demarcation line between Portugal and Spain appears clearly. A modern map has been superimposed. **Bottom** Western limit of the Treaty of Tordesillas in the Caribbean. Different locations proposed by various authors of the 15th and 16th centuries, according to the interpretation of Harrisse (1897), have been included.

Latin by Jacopo d'Angelo in 1409/1410 and several copies were made (Fisher 1932). These manuscripts, profusely illustrated with a world map (Fig. 3, left) and with regional maps, were widely distributed and from 1477 onwards were printed numerous times (Lisi, 1994).

Ptolemy included in *Geographia* several proposals for transferring the spherical coordinates of any location to a plane (Fig. 3, right. See Dilke, 1987). His manual was essential to incorporate all the new cartographic knowledge, in spite of the great uncertainties regarding the positions of new lands, especially the longitude, estimated in an very approximate way (dead reckoning when navigating). The determination of the longitude corresponds, in fact, to the time difference due to Earth rotation translated into degrees.

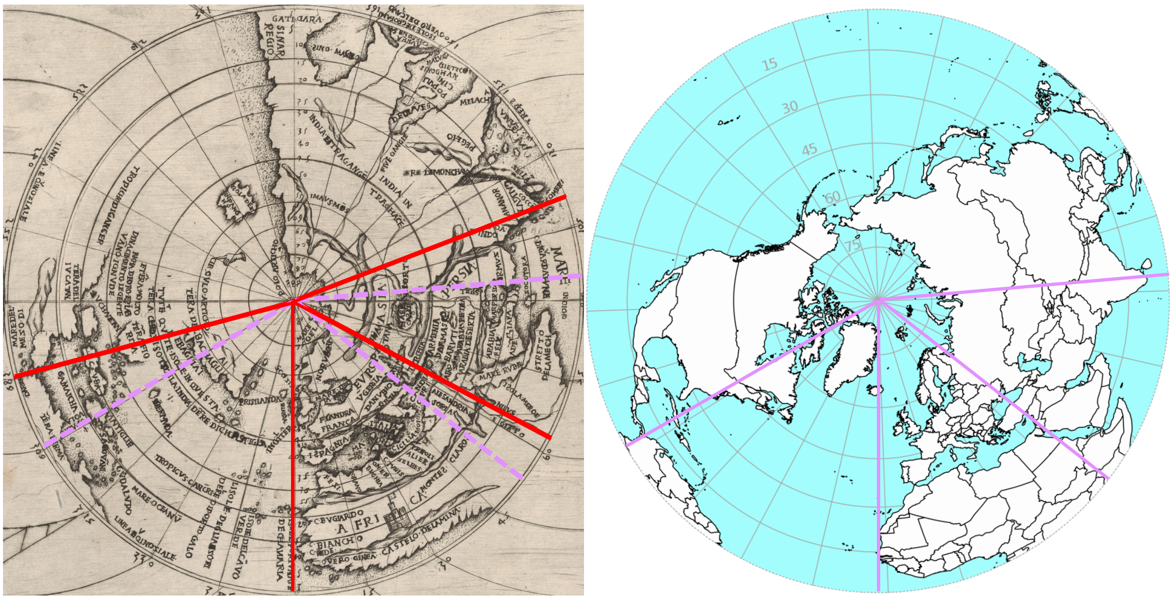

Figure 5: Detail of Juan Vespucio's map of 1524 (*Vespucci World Map*, Harvard university, HIST 1952) and comparison with a modern map. It was drawn in a polar stereographic projection. The errors in the longitude measurements, which caused the oversizing of the Eurasian landmass and the Mediterranean, and the consequent decrease in the size of the Pacific ocean, can be clearly seen.

The delimitation of areas of influence between Portugal and Castile established by the Treaty of Tordesillas in 1494 is a clear example of the "Longitude problem". The border was then defined as the meridian located 370 leagues west of the Cape Verde Islands, which implied that the lands located in what is now Brazil, whose coasts were explored in 1500 by Vicente Yáñez Pinzón and Pedro Alvares Cabral, fell in the Portuguese zone (Fig. 4, top). The uncertainty in the determination of the meridian, an essentially astronomical problem, had implications not only for the Caribbean coasts (Fig. 4, bottom), but also for the Far East and the dominion of the Spice Islands (the Moluccas). In 1508, the "Junta de Burgos" assembled a group of experts (Yáñez Pinzón, Amerigo Vespucci, Juan de la Cosa, Juan Díaz de Solís, Sancho Matienzo de la Casa and Juan Rodríguez de Fonseca. See Garnier Morga, 2018), in order to resolve this situation, aggravated by Vasco Nuñez de Balboa's discovery of the South Sea (the Pacific Ocean, as Ferdinand Magellan later named it) in 1513.

Magellan and Rui Faleiro proposed to Emperor Charles V (also king of Spain) a westward voyage to reach the Moluccas, supposedly in the hemisphere under Spanish influence. Magellan died in the Philippines, but the expedition (1519-1522), completed by Juan Sebastian Elcano, was first circumnavigation of the globe and the confirmation of the immensity of the new ocean. It also involved recalculating the dimensions of Ptolemy's ecumene, with the reduction of the size of the Mediterranean Sea from the original 62 degrees of the Alexandrian (Fig. 5). The limitations of the longitude estimates were manifest.

3 Longitude: The Institutionalization of Scientific Research

3.1 The beginings: the Portuguese developments

Throughout the 15th century, the Lusitanian explorations led to a remarkable improvement in shipbuilding and astronomical navigation techniques, as well as in instrumentation, such as the invention of the marine quadrant, whose first reference is due to Diogo Gomes in 1460 (Fig. 2. See Selles, 1994). The Casa da Índia e Mina, created in 1500, and the Armazés da Guiné e Índia were responsible for keeping updated information of the new discoveries and the production of nautical intrumentation (Barreto Xavier, 2018).

The anonymous text *Regimento do estrolabio e do quadrante: tractado da spera do mundo* may be the first scientific treatise on navigation. *Esmeraldo de Situ Orbis*, a comosgraphic and navigation treaty by Duarte Pacheco Pereira, was finished at about 1508, but it was not published until the 19th century. João de Lisboa wrote his *Tratado da agulha de marear* in 1514, which circulated widely in manuscript form and in which, along with the use of the compass, magnetic declination is discussed. Among other reputed cosmographers are João de Castro or Fernando Oliveira, all trained in critical thinking and a modern worldview (Albuquerque, 1983; Almeida, 2019).

In the second decade of the 16th century Rui Faleiro proposed a method for longitude measurement based on the determination of the angular distance between the Moon, the Sun, and the planets, as well as conjunctions and eclipses, which was successfully applied by Andrés de San Martín during Magellan-Elcano's voyage around the world (1519–1522). This method was independent of that proposed by Johanes Werner in 1514. Francisco Faleiro, while working in Spain, publised in 1535 his *Tratado del Esphera y del Arte del Marear*.

In 1537 Petrus Nonius (Pedro Nunes) published an anolagous book, namely *Tratado da Sphera*. He showed there that the courses that follow a fixed compass reading (constant angle with the meridians) describe asymptotic spiral curves (loxodromic curves) that end at the Pole. Therefore, they do not represent the shortest routes. Moreover, by means of the scale that bears his name, he made it possible, from 1522, to determine the position angles between stellar objects in a very precise way. Moreover, the astronomical ring, an instrument first described by Gemma Frisius in 1540, may have been Nunes'.

3.2 Scientific developments in Spain in the 16th century

The University of Salamanca played a very significant role in the development of cosmography in the 15th and 16th centuries (Gil Fernández, 2013). The influence of Abraham Zacuto, in the orbit of this institution, extended to Portugal (Cantera Burgos, 1935; Chabás and Goldstein, 2009). The studies carried out in Salamanca were also essential for the reform of the calendar, an astronomical problem but with multiple civil and religious implications, which was finally implemented in Portugal, Spain and the Italian states in 1582 (Carabias Torres, 2012).

Both Emperor Charles I and his son Philip II (monarch of Spain since 1556, and of Portugal since 1580 as Philip I) and grandson Philip III offered generous rewards to those who were able to solve the "Longitude problem". Essentially it requires the comparison of the local time at the point to be determined with the reference value, the zero meridian. As early as the 2nd century BCE Hipparchus of Nicaea proposed the use of lunar eclipses observed simultaneously in two locations. However, this is not a practical solution, due to the few events that occur annually. In any case it requires the use of clocks that reliably keep time for a few hours and accurate astronomical tables (Fernández Navarrete, 1852; de Grijs, 2017, 2020). The definitive solution would not be found until the third quarter of the 18th century, through the so-called method of lunar distances and also through the use of accurate naval chronometers. In the process, there were important technical innovations, above all, astronomical and mathematical ones, the core of what is known as the Scientific Revolution.

Despite the lack of success in solving the "Longitude problem", the sixteenth century saw the beginning of the institutionalization of science, the transition from courtly scholars to professionals at the service of society and not of the monarch. A decisive factor was the need for safe navigation and control of the Portuguese and Spanish Empires. The first step was taken with the foundation in 1503 of the "Casa de Contratación de Indias", in Seville, the reference center of the "piloto mayor", the professors of cosmography and other cosmographers and mapmakers (Pulido Rubio, 1950). In addition to the training of pilots and the verification of nautical instrumentation, the "piloto mayor" was responsible for the custody and updating of the "Padrón Real", the world map that contained the most accurate description of the known lands and oceans, an important state secret. Despite this reserve, more than 30 copies are preserved, in many cases signed or attributed to officials of the institution itself (Esteban Piñeiro, 2004). Seville thus became a cartographic center of the first magnitude. In 1552, the crown prince Philip, created there the "Cátedra de Cosmographia y Arte de Navegar" (Chair of Cosmography and the Art of Navigation), in order to train future pilots. The teachings, obligatory for one year, although the duration would be reduced on several occasions, were free of charge.

Alonso de Santa Cruz, appointed "Cosmógrafo de hacer cartas" of the "Casa de la Contratación" in 1537, acted de facto as tutor to the crown prince Philip, even lecturing him on *De revolutionibus*, the heliocentric text published in 1543 by Nicolaus Copernicus. Among the important works he wrote, which were not printed, are the *Islario general* (*ca.* 1542) and *Libro de las Longitudines* (*ca.* 1555), possibly the most exhaustive treatise for the resolution of the "Longitude problem". Long before, in 1530, he began the preparation of a map of the variations of the magnetic declination, one of the possible ways to determine the position, long before Edmond Halley (although the method would later be proven unfeasible).

In 1561, Pedro de Esquivel, named the previous year "Matemático de Palacio" began the drawing of an updated map of Spain by means of geodesic triangulations, following the proposal of Gemma Frisius, formulated in 1533. The work that would occupy for more than

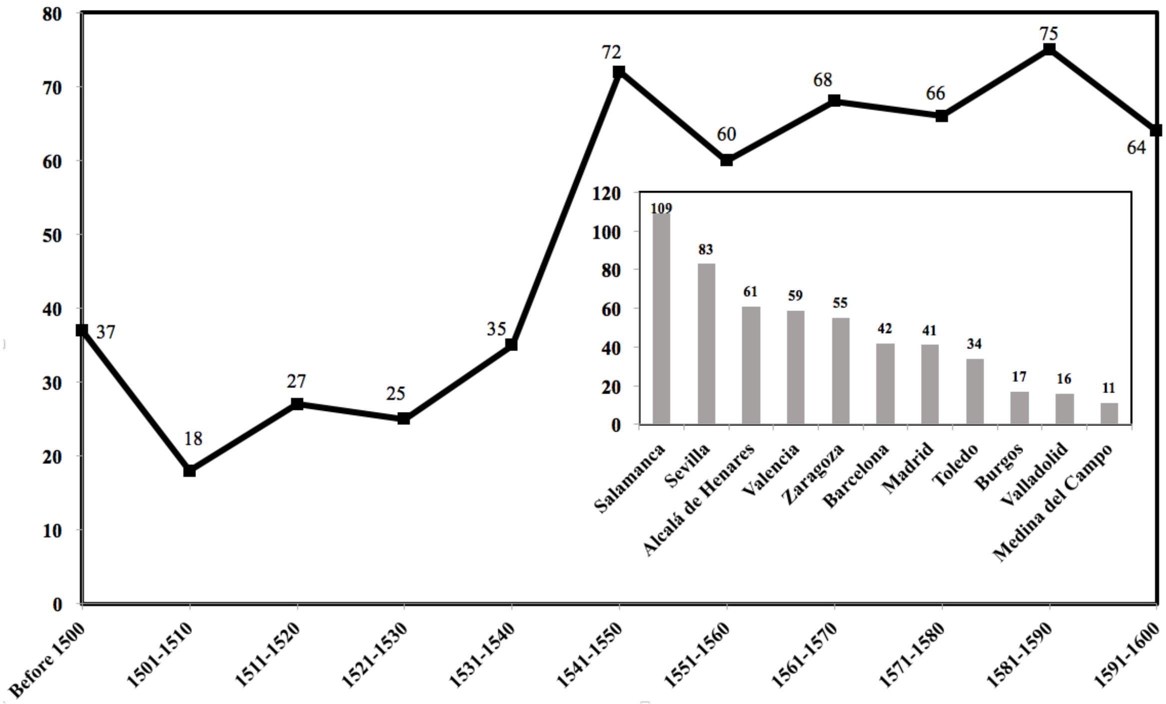

Figure 6: Number of printed works on physical-mathematical subjects in Spain in the 16th century. A total of 528 works related physics, astronomy, mathematics, engineering, architecture, the art of navigation or non-descriptive geography were printed. The diagram shows the number grouped by decades and the detail according to cities.

three decades several royal mathematicians after Esquivel's death. It thus anticipated by more than a century the task that Colbert, the minister of Louis IV of France, entrusted to Jean Picard and Giovanni Dominico Cassini. The "Consejo Real y Supremo de las Indias" (Royal and Supreme Council of the Indies) created, at the request of Juan de Ovando, from 1570 onwards several cosmographic new offices, among which the "Cosmógrafo-Cronista Mayor" (Major Cosmographer-chronicler) stood out. The main task was to improve the cartographic knowledge. The first one was Juan Lopez de Velasco. The "Academia Real Mathematica" (Royal Mathematical Academy) was founded in 1581 after a proposal by Juan de Herrera. The statutes of 1584 allowed the issuance of exclusive degrees for scientists and technicians, after an examination, for the first time in Europe. In any case, during the 16th century there were in Spain numerous official positions related to navigation and cosmography. As Esteban Piñeiro (2004) concludes, it is the beginning of the true institutionalization of science. However, a problem of Spanish science in that period was censorship and, above all, the seizure of books and maps, in some cases by direct order of the king. In spite of this, iberian manuals were the essential reference throughout Europe, such as those written by Martín Fernández de Enciso (1519), Pedro de Medina (1538 and c. 1545) or Martín Cortés de Albacar (1551). Some of them were translated to French, Flemish and English, among other languges, and printed numerous times. In fact, a considerable number of books dealing with mathematics or physics were published during this period (Fig. 6, based on data from Navarro Brotons et al., 1999). Moreover, when Sebastian Cabot moved from Spain to England in 1547, the Spanish navigation techniques started to have a profound influence there (Sandmand & Ash, 2004). The process was facilitated by the marriage (1554-1558) between the English queen Mary I and the Spanish crown prince, King Philip II since 1556.

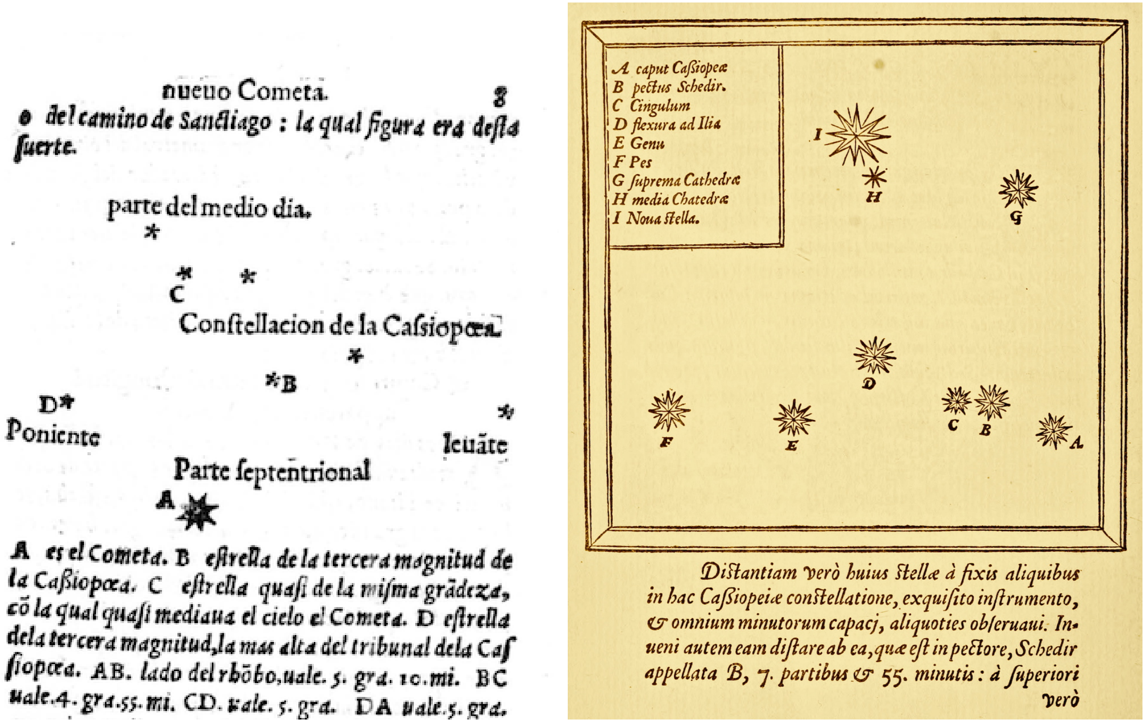

Figure 7: The supernova of 1572, in two representations by contemporary observers: **left** Jerónimo Muñoz; **right** Tycho Brahe. Note that the orientation is not the same.

3.3 The dimensions of the Empire: the first attempt at citizen science

López de Velasco initiated an ambitious geographic program to determine the true dimensions of the Spanish Empire. Already in 1569 the Royal Council of the Indies had requested cartographic information from overseas officials through questionnaires drafted by Santa Cruz that included the observation of lunar eclipses to determine longitude. This method had been proposed by Hipparchus, as described above, and had been applied on a few occasions with limited success, as was the case of Columbus in 1494. Questionnaires were sent out on several more occasions, including 1571, 1573 and 1577, with a small number of responses, unfortunately of reduced usefulness. Instructions for observing eclipses were also distributed: 1577 for that and the following year's eclipse, 1578, a reminder in 1580, and a new form in 1581 for observing that year's eclipse and another for that of 1582. Despite the simplicity of the instructions, written for use by laymen, there are no records of any responses for those eclipses, except for the event possibly observed in 1581 from Puerto Rico. However, there are records corresponding to the eclipse of 1584, observed, among others, by Jaime Juan in Mexico City (Edwards, 1969; Morato-Moreno, 2016). In any case, as Edwards argues, the questionnaires contributed qualitatively to the geographic knowledge. Thus, it is possible to conclude that these efforts represent an early attempt at citizen science.

4 Corollary: The New Astronomy and the "Longitude problem"

During the late Middle Ages the development of cosmography was quite slow above the Pyrenees, although Sacrobosco, Oresme, or Buridan stand out. In the 14th and 15th centuries Cusa, Peuerbach, Regiomontanus or Novara, Copernicus' teacher, had a very revelant role (Fig. 1).

Copernicus published in 1543 *De revolutionibus*, a text structured in an analogous way to Ptolemy's *Almagest*, but in which he proposed a heliocentric cosmology. Copernicus' proposal had little repercussion during the rest of the century, although Thomas Digges, Giordano Bruno, Christopher Rothmann, Diego de Zúñiga or Jerónimo Muñoz were, at times, firm defenders of this cosmology. Precisely, the latter was one of the first observers of the 1572 supernova, as was Tycho Brahe, an essential phenomenon to break with the traditional cosmological image of an immutable kosmos (Fig. 7). Among the founders of modern dynamics is, preceding Galileo, Domingo de Soto, in a text published in 1551.

In conclusion, Portuguese and Spanish astronomers, cartographers and navigators were essential to change Western cosmography and the idea of the kosmos, contributing in a decisive way to lay the foundations of the Scientific Revolution and the eventual resolution of the "Longitude problem", its main drive, a role that has not always been duly recognized.

Acknowledgments

The invaluable assistance by Dr. Marga Box is acknowledge with enormous gratitude.

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