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DISCOVERY AND CLASSIFICATION AS PROBLEMS IN THE PHILOSOPHY OF ASTRONOMY

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Abstract: In this paper we examine the mutual interactions of discovery and classification in astronomy, discuss the importance of a comprehensive classification system for all astronomical objects, and consider discovery and classification as problems in the new discipline of philosophy of astronomy. Five propositions encapsulate our conclusions, including the extended nature of discovery, the nature of pre-discovery and post-discovery classification, the best methods for determining taxon level, and the primacy of the physical nature of the astronomical object when classifying. The history of astronomy provides essential data for the evolving discipline of philosophy of astronomy, an endeavor that in turn enriches the history of astronomy, providing an overarching interpretative framework for its many diverse subjects.

Keywords: David DeVorkin; discovery in astronomy; classification in astronomy; planet classification star classification; galaxy classification; philosophy of astronomy; pre-discovery; post-discovery; Three Kingdom classification system; Thomas Kuhn; Edwin Hubble; W.W. Morgan; Henry Norris Russell; William Herschel.

1 INTRODUCTION: DAVID DEVORKIN AND THE HISTORY OF ASTRONOMY

David DeVorkin and I both began our careers in Washington, DC at about the same time—I at the U.S. Naval Observatory (USNO) in mid-1979, and he only a short distance away at the National Air and Space Museum (NASM) in early 1981. Since that time our paths have crossed many times and we have collaborated on numerous history of astronomy projects, notably at meetings of the American Astronomical Society (AAS), the International Astronomical Union (IAU), the National Aeronautics and Space Administration (NASA), the National Air and Space Museum, and the biennial Notre Dame History of Astronomy workshops. At the AAS, for which David compiled the definitive centennial history (DeVorkin, 1999), we both gave numerous papers and organized many sessions, including one on "Astronomy and the State: U.S. and Soviet/CIS Perspectives" in 1994, and a particularly memorable one in 2014 "From Barnard's Star to the Kepler Mission" with pioneers of the search for exoplanets (American Astronomical Society, 2014 and Figure 1). We served on many AAS Historical Astron-



Figure 1: Presenters at the American Astronomical Society Historical Astronomy Division (HAD) session "From Barnard's Star to the Kepler Mission: Searching for Low-Mass Companions to Stars", held in January 2014 in Washington, D.C. Left to right: David DeVorkin (NASM), Geoff Marcy (University of California, Berkeley), David Latham (Harvard-Smithsonian Center for Astrophysics), Timothy Brown (Las Cumbres Observatory Global Telescope Network), Bill Borucki (NASA Ames), Gordon Walker (University of Victoria), Edward Dunham (Lowell Observatory), and Steven Dick (USNO & NASA) (photograph: Steven Dick).



Figure 2: AAS/HAD International Relations Committee meeting at the USNO, in the office of Steven Dick (seated) in March 1995. Standing left to right: David DeVorkin, Robert McCutcheon, Ron Doel, and LeRoy Doggett. LeRoy died from cancer the following year (photograph: Steven Dick.

omy Division (HAD) committees together, including the HAD's International Relations Committee (Figure 2), which sought to support astronomers in the former Soviet Union, resulting in part in the 1994 meeting just mentioned (Bracher, 1999: 281). David was also the winner of the biennial AAS LeRoy E. Doggett Prize for lifetime achievement in history of astronomy, awarded in 2008 after my award in 2006 and before Michael Crowe's award in 2010 (Figure 3). At the IAU we both served as officers of the History of Astronomy Commission 41. At NASA David participated at many conferences (sometimes co-sponsored with NASM) during my time as NASA Chief Historian from 2003 to 2009 (Figure 4). I in turn participated in NASM's conference on the Legacy of the Hubble Space Telescope (Launius and DeVorkin, 2014) and serv-



Figure 3: Three consecutive winners of the LeRoy E. Doggett Prize: Steven Dick (2006), David DeVorkin (2008) and Michael Crowe (2010). This image is taken at the 2010 AAS Meeting when Crowe was awarded the Prize (photograph: Steven Dick.



Figure 4: David DeVorkin at NASA Headquarters in Washington, D.C., on the occasion of Steven Dick's retirement from NASA in July 2009. The background image shows Dick at Shuttle launch STS-125 on 11 May 2009, the fifth and final Shuttle mission to service the Hubble Space Telescope (courtesy: NASA).

ed there as the Charles A. Lindbergh Chair in Aerospace History under David's sponsorship in 2012.

Not least, as a resource for present and future historians David perhaps holds the world record for oral histories in astronomy (American Institute of Physics, 2024), a few of which we conducted jointly when it came to important astronomers in the history of the USNO (Dick, 2003). These audio histories were expanded as part of the Sloan Videohistory Project from 1988 to 1992. His work at the Museum, especially his "Explore the Universe" gallery that opened in 2001 and continued over several decades, was admired not only by the general public who viewed it by the thousands, but also by scholars in the history of science and technology. In short, David has contributed broadly and deeply to our discipline in its science, technology, and public outreach aspects, not to mention his historiographical contributions such as his essay "History is too Important to be Left to the Historians", commenting on Don Osterbrock's 2002 Doggett Prize Lecture by the same title and laying out what it takes to create useful and accessible history of astronomy (DeVorkin, 2013b; Osterbrock, 2002).

In my own work on a variety of subjects I often found that David had already been there, whether on the supernova of 1006 (DeVorkin, 1985; Dick, 2019: 275; van der Hucht, 2007), stellar classification (DeVorkin, 1981; Dick, 2013; 2019), or subjects in space science such as the Hubble Space Telescope (DeVorkin and Smith, 2008; Dick, 2014a; 2014b). His masterpiece biography of Henry Norris Russell (DeVorkin, 2000), which I drew upon for my history of astronomical classification, will remain a classic in the field, stemming from his work on stellar classification beginning with his PhD dissertation (DeVorkin, 1978; 1981). Two more biographies, of Fred Whipple (DeVorkin, 2018) and George Carruthers (still in progress), the former also an institutional history of the Smithsonian Astrophysical Observatory, have rounded out his stellar career.

Altogether, ours has been a productive collaboration over the decades, illustrating and reinforcing our mutual interests on a variety of subjects. In this special issue in honor of David's work, I will focus on classification as a problem in the philosophy of astronomy, a nascent field to which David and other historians of astronomy have perhaps unwittingly contributed, since the discipline is only now coming into its own as a recognized enterprise using historical work to illuminate meta-historical issues (Dick, 2020).

2 DISCOVERY AS AN EXTENDED PROCESS

The problem of classification in astronomy is closely related to the nature of discovery. What exactly is a 'class' of objects? How do astronomers know when they have discovered a new class? Who decides if an object like Pluto, or a quasar or pulsar is a new class? How has this happened historically, and what light does this shed on classification efforts in astronomy? The takeaway from my personal experience with the Pluto debate at the 2006 IAU General Assembly in Prague, where I was one of those voting members (as was DeVorkin), was that discovery and classification are concepts that need to be studied, dissected, analyzed and put back together again. This is what I did in my books *Discovery and Classification in Astronomy* (Dick, 2013) and *Classifying the Cosmos* (2019). And since that time David Wooten has problematized the concept of discovery itself, demonstrating how it has evolved over time (Wooten, 2015).

Elaborating on one of the many ideas included by Thomas Kuhn (1922–1996) in his *Structure of Scientific Revolutions* (Kuhn, 1962), my conclusion was that discovery is an extended process consisting of detection, interpretation, and understanding, with pre-discovery and post-discovery phases, and technological, conceptual, and social roles at each stage, while classification itself is a deep philosophical problem (Figure 5). The idea of an extended structure of discovery also entails an embrace of the idea of collective discovery, which historians of science have investigated in some detail (Caneva, 2005; Dick, 2013: 177, 198).

Many concrete examples from the history of astronomy illuminate this anatomy of discovery. As Albert van Helden has shown, when Galileo (1564–1642) turned his telescope to Saturn the object he first saw surrounding it was not at all obviously a ring (Figure 6). This is what he wrote on 30 July 1610:

> I discovered another very strange wonder ... the star of Saturn is not a single star, but is a composite of three, which almost touch each other, never change or move relative to each other, and are arranged in a row along the zodiac, the middle one being three times larger than the lateral ones, and they are situated in this form: oOo … (van Helden, 1974a: 105; cf. van Helden, 1974b).

The nature of this strange wonder awaited the interpretation of Christiaan Huygens (1629–1695) more than 40 years later using better telescopes (van Helden, 1974a; 1974b). And only

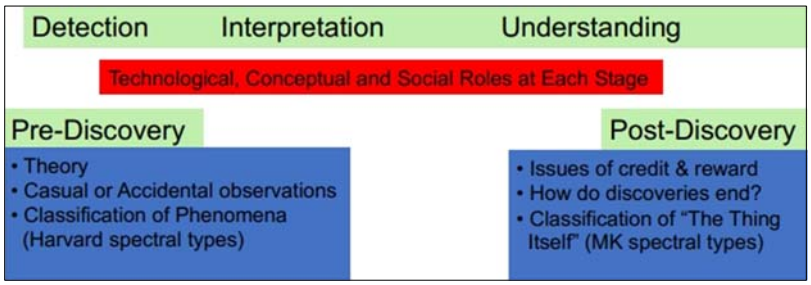


Figure 5: The extended structure of discovery, showing its three stages of detection, interpretation, and basic understanding, as well as pre-discovery and post-discovery phases. Classification can occur both as a pre-discovery and post-discovery activity. Discovery also has a microstructure consisting of conceptual, technical and social roles (after Dick (2013: 178).

in the mid-nineteenth century did James Clerk Maxwell (1831–1879) show that the rings could not be a solid body, but must consist of small individual objects. The rings of Saturn are thus an excellent case of extended discovery.

Nor is this an unusual case in astronomy or in science. Jumping forward two centuries, in his 1811 paper "Astronomical Observations Relating to the Construction of the Heavens", William Herschel (1738–1822) illustrated 42 different morphologies of nebulae he had observed with his state-of-the-art telescopes (Figure 7; Herschel, 1912: 480). He first divided these into eight classes based on appearance, and later defined 12 classes based on what he believed to be their physical nature (Sticker, 1964). Today we recognize them as six modern classes, including reflection nebulae, globular clusters, planetary nebulae, H II regions, spiral galaxies, and binary galaxies. Moving forward another century and a half, even in the late twentieth century it was not immediately evident that pulsars were neutron stars, or that quasars were active galactic nuclei, both qualifying in the end for new class status (Kellermann, 2023). Numerous other examples are given in Dick (2013).

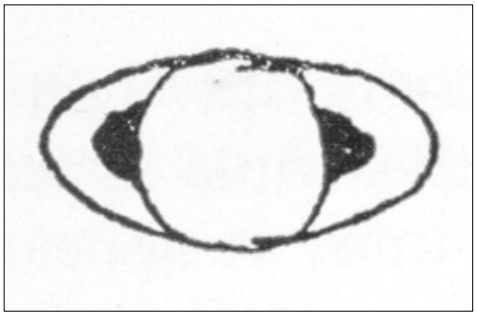


Figure 6: Galileo's drawing in 1616 of what was later explained as Saturn's rings. Galileo himself had no idea what they were, and their identification as rings was left to Christiaan Huygens 40 years later (after Favaro, 1902: 276).

In short, if discovery begins with detection, continues with data-gathering and its interpretation, and ends with a basic understanding of the object discovered, then the role of the discoverer in each of these phases must be made clear. Such a view constitutes a more sophisticated picture of what discovery actually entails as an extended process, and it mitigates what are usually counterproductive arguments about the true discoverer. These considerations lead us to our first Proposition about discovery and classification:

Proposition 1: Discovery is an extended process consisting of detection, interpretation, and understanding, with pre-discovery and post-discovery phases, and technological, conceptual, and social roles at each stage.

As the case of Herschel hints, and as Figure 5 indicates, because of this extended nature of discovery, classification historically takes place both before and after the nature of the objects is known, as we shall now demonstrate.

3 CLASSIFICATION: CLASSIFYING PHENOMENA VS. THE THING ITSELF

Just as with discovery, formal classification was not always a concern in the history of astronomy. Galileo knew only that his observations of Saturn were anomalous compared to what was previously known, and did not consciously attempt to 'classify' it. The situation had changed by the early nineteenth century. In correspondence from Herschel to Giuseppe Piazzi (1746–1826) in 1802 in the wake of the latter's discovery of Ceres, Herschel argued the object should be designated a new class that he termed 'asteroids'. Herschel's letter is well worth quoting for its explicit recognition of classification issues more than two centuries ago, and for its sociocultural recommendation for class status:

> ... if we were to call [Ceres] a planet, it would not fill the intermediate space

> between Mars and Jupiter with proper dignity required for that station. Whereas, in the rank of Asteroids it stands first, and on account of the novelty of the discovery reflects double honour on the present age as well as on Mr. Piazzi who discovered it. I hope you will see the above classification in its proper light, as so far from undervaluing your eminent discovery it places it, in my opinion, in a more exalted station. To be the first who made us acquainted with a new species of primary heavenly bodies is certainly more meritorious than merely to add what, if it were called planet, must stand in a very inferior situation of smallness (Herschel, 1802: 251).

Piazzi and most astronomers at the time did not take Herschel's advice, and considered Ceres a planet (Cunningham, 2016). But the passage shows that classification was now a formal concern, even if Herschel's sociocultural argument is surely not the best methodology. He would employ better methodologies when it came to classifying the numerous 'nebulae' seen in Figure 7.

3.1 Planets

The history of classification in astronomy illustrates how classification has taken place both before and after the nature of the objects has been known. The planets in our Solar System were at first distinguished (one would not even use the word 'classified') only in the most general way, first based on their motions as 'wanderers' in the sky compared to the fixed stars, then based on size. Although the outer planets were recognized as 'giant' in size since the micrometric observations of them in the seventeenth century (van Helden, 1985), *gas* giant planets were not widely recognized as a separate class until the twentieth century once their physical composition was determined. Only by the 1940s did observations of the masses, radii and rotation periods of the giant planets, together with new knowledge of the high-pressure behavior of matter, constrain the composition of Jupiter and Saturn to be predominantly hydrogen. Ice giants were not identified as a new class until the 1990s after Voyager 2 provided data that constrained models of the interiors of Uranus and Neptune (Marly, 1999: 352; Hammel, 2006: 251–265). Pulsar planets, discovered by Wolszczan and Frail in 1992, have also been distinguished by being inferred as physically very different due to the extreme nature of their environments and their probable different origin around neutron stars (Wolszczan and Frail, 1992).

It is thus notable that historically (prior to the modern era of thousands of exoplanets) all classes of planets have been distinguished based on their physical nature. The exception is Pluto's designation as a dwarf planet, which the International Astronomical Union declared was not a planet based on the dynamical criterion of not having "… cleared its neighborhood …" rather than for physical reasons (International Astronomical Union, 2006 and Figure 8). Discovered by Clyde Tombaugh (1906–1997) in 1930, its small size and mass remained unknown until the discovery of Pluto's largest moon Charon at the U.S. Naval Observatory in 1978 (Dick, 2003: 423–429). With the simple application of Kepler's Laws to two bodies in orbit, the resulting mass was only 1/400th of the Earth and a diameter of less than 1500 miles, considerably smaller than our Moon. By allowing an accurate mass for Pluto to be calculated, Charon began Pluto's decline from planetary status. In the end it was the discovery of a new class of Trans-Neptunian objects beginning in 1992 that precipitated the change in Pluto's class status, especially when one of these, dubbed 2003 UB 313 (now known as Eris), was preliminarily determined to be larger than Pluto (Michael Brown announced this discovery in 2005, based on images taken in 2003, another case of extended discovery). It turns out Eris is slightly smaller than Pluto by size, but slightly more massive. In any case there is a whole class of objects beyond Pluto in what is known as the Kuiper Belt (or sometimes the Edgeworth–Kuiper belt in Europe–another case of disputed discovery).

It was this situation that resulted in its 'demotion' in 2006 by vote of the International Astronomical Union. And, in a linguistic contradiction that has caused much confusion, Pluto was ruled to be a dwarf planet and a dwarf planet was ruled not to be a planet. Much more than science was involved in this decision; politics, personalities, and the predilections of different scientific communities were all in the mix, as described by DeVorkin and others in the following two decades (Bokulich, 2014; Brown, 2010; DeVorkin, 2013a; Dick, 2013; Gingerich, 2006; Messeri, 2010). Even in the scientific component, much more was involved than pointing a telescope and 'detecting' a new class of object; in this case it was many years before the new class was inferred and then declared.

It is notable that had the definition of a dwarf planet been based purely on physical nature, it would still be considered a class of planet today. Alan Stern, the Principal Investigator of the New Horizons Mission to Pluto, indicated what Pluto's physical nature might be already in 1991 when he identified Pluto as a class of 'ice dwarf' planet and posited thousands

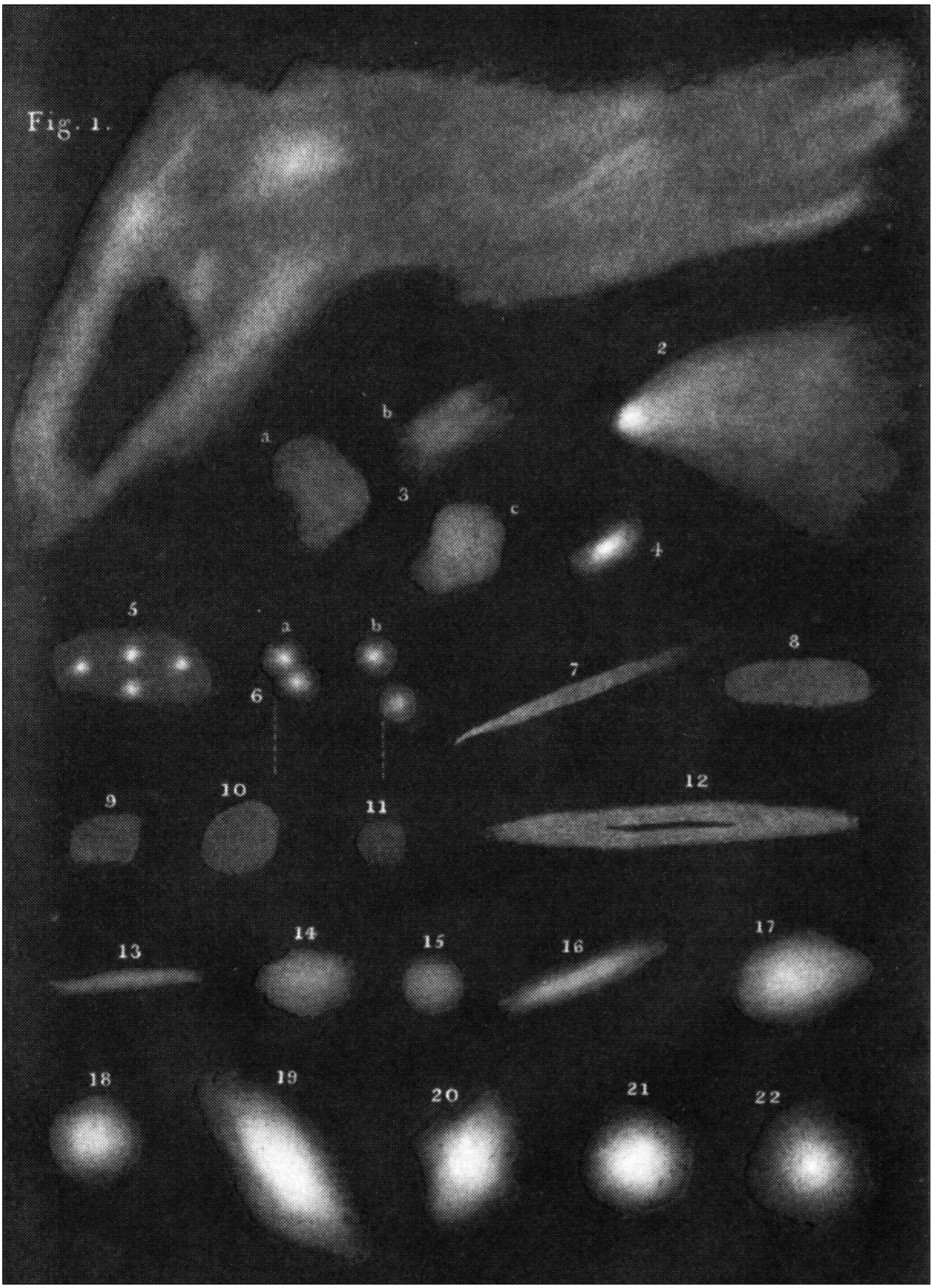


Figure 7: Nebulae morphologies as observed by William Herschel. Early on, Herschel divided nebulae into eight classes based on appearance, but later defined 12 classes based on what he saw as the physical nature of the objects rather their phenomenology. They bear little resemblance to modern classes, but those labeled 5 and 6 are what Herschel described as multiple nebulae and double nebulae (now multiple and double galaxies), while 18, 21 and 22 are globular clusters of stars (after Herschel, 1912: 480). This plate in Herschel (1912) is one of two depicting 42 morphologies; the other in on page 496.

of them in the outer Solar System (Cowen 1991; Lunine et al., 2021; Stern, 1991) as part of the system of trans-Neptunian objects known as the Kuiper Belt. 'Ice dwarf' is a designation Stern still maintains in the wake of the revelations of Pluto's physical nature after the New Horizons Mission, and he still argues Pluto should be classified as a planet, the IAU notwithstanding. In this case the Solar System would be considered to have four classes of planets: terrestrial, gas giant, ice giant, and ice dwarf. But that was not to be, at least as things now stand.

While the planets of our Solar System could be divided according to their physical nature (terrestrial, gas giant and ice giants), in the absence of compositional data the discovery of exoplanetary systems have been variously classified by orbital characteristics (highly elliptical or circular), proximity to their parent star (hot Jupiters), size and mass (super Earths and mini-Neptunes), habitability, and so on (NASA Exoplanet Exploration, 2024; Planet Characterization Workshop, 2024). According to the lessons of extended discovery, while these categories may be useful they are only preliminary phenomenal classifications. Final classifications will await knowledge of physical composition, and whether there are actually more classes of planets that differ enough from the terrestrial, gas giants, and ice giants of our Solar System to warrant new class status, such as putative styrofoam, carbon, and ocean worlds.

3.2 Stars

Stars, being much more numerous than planets, provided an excellent opportunity for classification, and astronomers did not disappoint. As DeVorkin (1981) has shown, by the late nineteenth century there were eight competing systems of stellar classification, including five from the Italian astronomer Angelo Secchi (1818–1878) and those of European astronomers Hermann Vogel (1841–1907) and Norman Lockyer (1836–1920) (DeVorkin, 1981). But by far the most robust stellar classification system was developed at Harvard under the supervision of E.C. Pickering (1846–1919), resulting in the familiar O, B, A, F, G, K, and M stars (DeVorkin, 2000; Sobel, 2016). Here Williamina Fleming (1857–1911) classified the spectra of 10,351 stars and produced the Draper Memorial Catalogue in 1890; Antonia Maury (1866–1952) undertook a more detailed study of the brighter stars, resulting in a catalogue of spectra for 681 stars published in 1897; and Annie Jump Cannon (1863–1941) produced a series of catalogues culminating with the Henry Draper Catalogue with 240,325 stars, published in nine volumes from 1918 and 1924. There followed the Henry Draper Extension between 1925 and 1936, yielding a total of more than 359,000 stars classified by Cannon between 1896 and 1941. This surely represents not only unparalleled individual efforts (with the help of an even larger corps of women assistants), but also an unparalleled natural history operation for any science over a similar period. Cannon, especially, deserves to be known as the Linnaeus of stellar astronomy; she classified so many stars that her system became the standard—no one wanted to repeat that massive effort. It took 50 years before a negotiated stellar classification consensus was reached at the meeting of the International Solar Union in 1910.

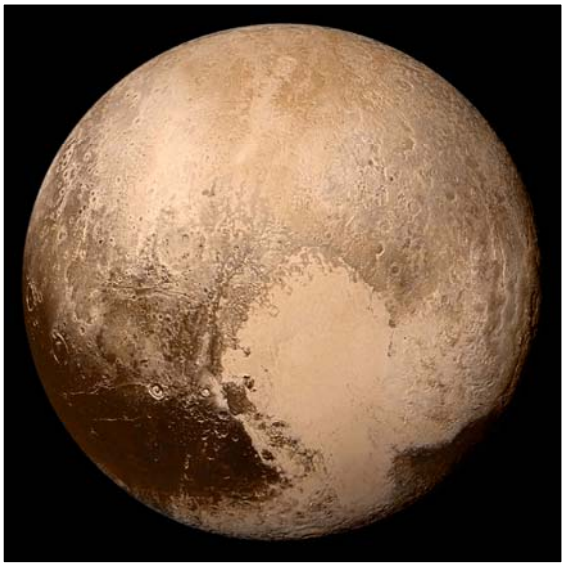


Figure 8: The dwarf planet Pluto, as seen by the New Horizons spacecraft on 14 July 2015. Four images were combined to create this global view. The images, taken from a distance of 280,000 miles (450,000 km), show features as small as 1.4 miles (2.2 km). The north polar region is at top, with bright Tombaugh Regio to the lower right of center and part of the dark Cthulhu Regio at lower left. Part of the dark Krun Regio is also visible at extreme lower right (courtesy: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute).

As DeVorkin has also written, by the early twentieth century American astrophysicists were becoming world leaders in astronomical natural history thanks to the unparalleled power of astrophysics to reveal the nature of celestial bodies:

> Akin to the naturalist, the typical American professional astronomer was collector and classifier. Instead of museum shelves and cases, astronomers stored their systematic observations in plate vaults and letterpress log books,

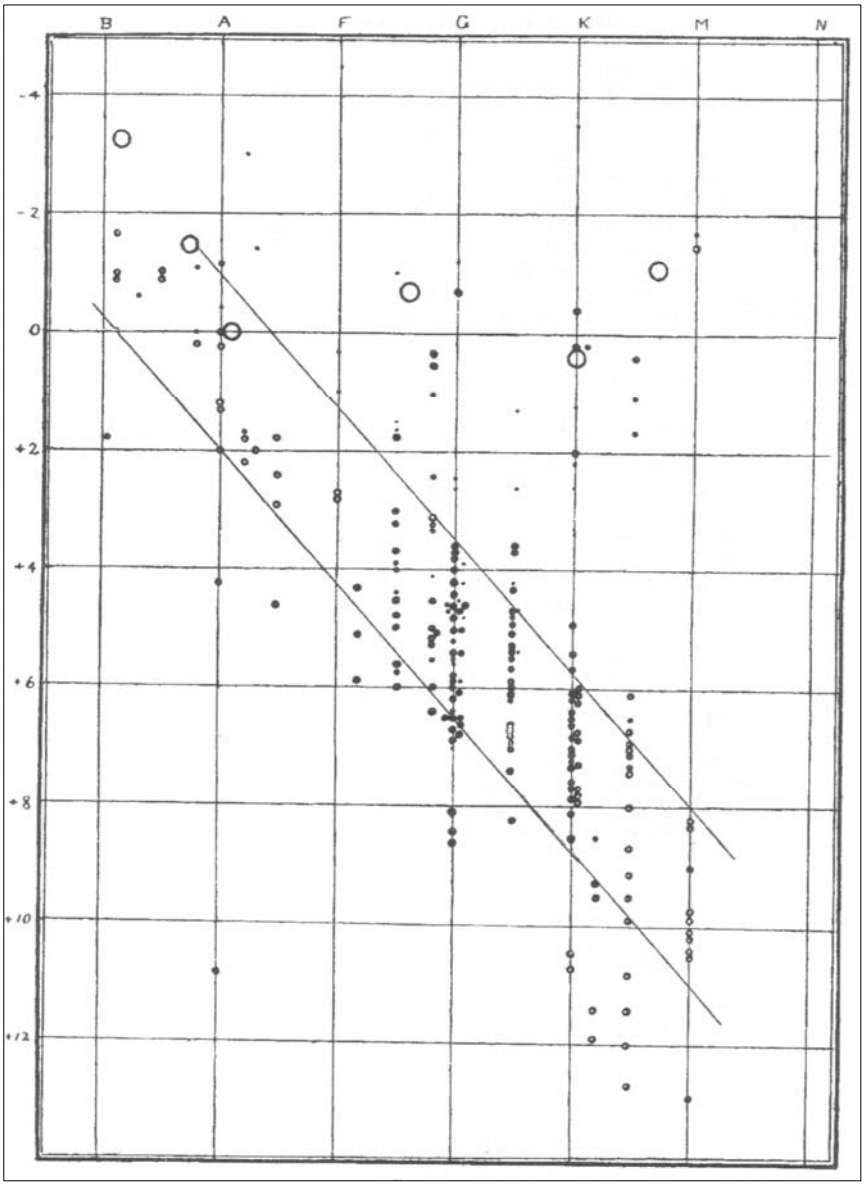


Figure 9: Henry Norris Russell's first diagram separating the classes of dwarf and giant stars. Harvard spectral types are shown at the top, and absolute magnitudes along the left side. Russell believed the absolute magnitudes represented luminosities 7,500 times that of the Sun at the top, and 1/5,000th of the Sun's luminosity at the bottom. Today we know the 'Main Sequence' between the two diagonal lines represents dwarf stars, while the much rarer stars at upper right represent giant stars. Note the single star at bottom left, still believed to be an anomaly at the time this was published, is now known to be the harbinger of a new class of stars—white dwarfs. The plot, today known as a 'Hertzsprung-Russell Diagram', was constructed in the Spring of 1913, and published simultaneously in *Nature* and *Popular Astronomy* in 1914.

and displayed them in catalogues sponsored by universities and observatories (DeVorkin, 1994: 103).

The question of what it all meant, however, only gradually dawned with the discovery of more physically meaningful stellar classes. As a group the Harvard classifiers may well be credited with the discovery of what was widely perceived (and is now known) to be a true temperature sequence, even though it ended up not being the evolutionary sequence they suspected. Most importantly, along with the distance and luminosity determinations gathered by others, their spectral types would prove crucial to Ejnar Hertzsprung (1873–1967) and Henry Norris Russell (1877–1957) and the construction of the Hertzsprung-Russell diagram, which clearly delineated the classes of giant and dwarf stars (DeVorkin,1984 and Figure 9). Even the discovery of those physical classes

was not the end of the story, with more stellar classes and the physical basis for their spectra based on ionization theory (yet another Rosetta Stone) still to be discovered. As DeVorkin concluded Russell (Figure 10) "… found astronomy an elaborate natural history, and left it firmly grounded in physics."

In particular, as more and more stellar spectra were gathered, they hinted at numerous variations in the nature of the stars. Once stellar physics was understood later in the twentieth century the reasons became clear: stellar structure depended on mass, temperature and luminosity, and the range of all of these physical variables was enormous. Moreover, stars existed in a variety of different ages, and (it turned out) in a variety of stages. Stars were born, lived and died; once the concept of stellar evolution was accepted the problem was figuring which stars were in which stages and how the physics worked under varying conditions, among the greatest puzzles in the history of science. Over the last half of the nineteenth century and the first half of the twentieth century this astrophysical collecting led to the discovery of new classes of stars. At first these were arranged according to various features in their spectral lines, but then in a more physically meaningful way according to their size and luminosity, resulting in the first stages of discovery of dwarfs and giants between 1905 and 1913, then supergiants (1917), subgiants (1930), and subdwarfs (1939).

Nor was this the end of the story. In the 1930s the young Yerkes astronomer W.W. Morgan (1906–1994; Figure 11) began work on a two-dimensional stellar classification system that incorporated the Harvard spectral types but went an important step further. Influenced by the philosopher Edmund Husserl (1859–1938), Morgan was interested in 'the thing itself', the physical nature of the stars he was classifying beyond just the Harvard temperature sequence. Based on the mass-luminosity relationship, color temperatures (T) and trigonometric parallaxes, by 1937 Morgan had estimated surface gravities (g) for a sample of bright stars, including supergiants, giants, dwarfs and one white dwarf. Morgan saw that this could function as the basis for a new 'two-dimensional' classification system, and the following year he formally introduced five luminosity classes ranging from supergiants (luminosity class I) to bright giants (II), normal giants (III), subgiants (IV) and main sequence stars (V) (Morgan, 1938). Under this system the criteria for luminosity classification were the ratios of line intensities, rather than the line intensities themselves that the Harvard astronomers had ridicul-



Figure 10: Henry Norris Russell, co-discoverer with Ejnar Hertzsprung of giant and dwarf stars. Their discovery, first known as the 'Russell diagram' and later as the 'Hertzsprung-Russell diagram', took place by inference rather than detection. This Russell photograph shows him measuring spectra at Mount Wilson, circa late 1920s. Photograph by Margaret Harwood, The University of Chicago Yerkes Observatory (courtesy: AIP Emilio Segrè Visual Archives, Tenn Collection).

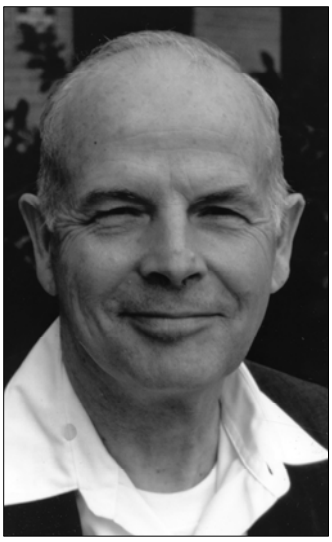


Figure 11: W.W. Morgan, the driving force behind the Morgan–Keenan–Kellman system for spectral classification. Unlike the phenomenological spectral line classification, Morgan sought to classify 'the thing itself' (photograph by David DeVorkin, courtesy AIP Emilio Segrè Visual Archives).

ed. This system, assembled with the help of Philip C. Keenan (1908–2000) and Edith Kellman (1911–2007) and therefore known as the MKK system, was published in 1943 as the *Atlas of Stellar Spectra, with an Outline of Spectral Classification* (Morgan, et al., 1943). It became one of the canonical publications in the history of astronomy.

Taken together the history of stellar classification illustrates pre-discovery and post-discovery classification: As shown in Figure 5, Harvard spectral types represent the classification of phenomena before understanding the physical nature of the stars; Morgan's MKK system represents post-discovery classification of the thing itself. Over many decades the further analysis of stellar spectra led to the interpretation and understanding of what turned out to be the evolutionary states of these classes of stars, as well as additional classes of evolutionary endpoints or penultimate endpoints: supernovae, white dwarfs, and neutron stars.

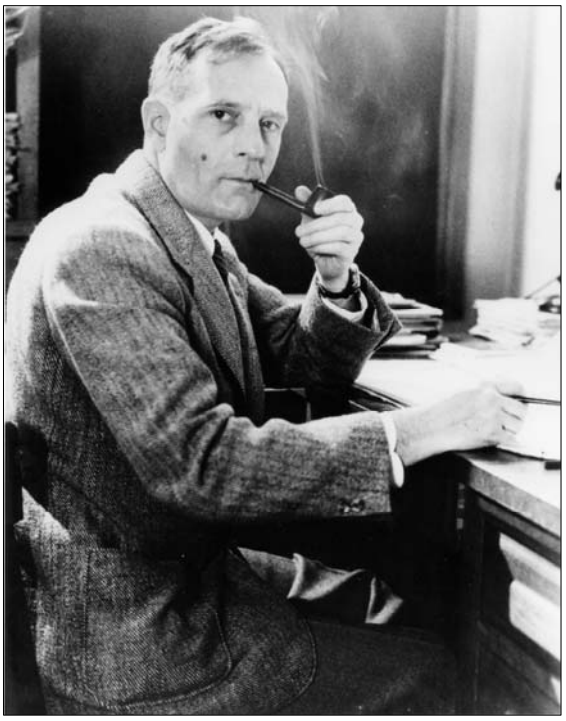


Figure 12: Hale Observatories photograph of Edwin Hubble, classifier of 'nebulae'. In 1924–1925 he demonstrated that most nebulae outside the plane of our Milky Way Galaxy are extragalactic systems of stars. In doing so, he added a new 'Kingdom' to astronomy (along with stars and planets), which he divided into three classes (courtesy: AIP Emilio Segrè Visual Archives).

3.3 Galaxies

For galaxies, as for stars, there were competing classification systems, including those of Max Wolf (1863–1932; Wolf, 1909), Edwin Hubble (1889–1953; Hubble, 1922; 1926), Knut Lundmark (1889–1958; Lundmark, 1926), and Harlow Shapley (1885–1972; see Curtis, 1933) based on morphology, concentration of matter, and other properties. It is a matter of history that the system of morphologies (elliptical, lenticular, spiral, barred spiral and irregular) laid out by Hubble in the 1920s, and elaborated by others, has triumphed, at least so far. There was no factor of distance involved when in 1922 Hubble (Figure 12) ventured a classification system based on nebular morphology, playing the biologist's role of natural historian (Hubble, 1922). The great bipartite division was between galactic nebulae (in the galactic plane) consisting of planetary and diffuse nebulae, and non-galactic nebulae (outside the galactic plane), divided into spiral, elongated (spindle and ovate), globular and irregular morphologies. The following year, in unpublished materials prepared for the International Astronomical Union, Hubble simplified his scheme and defined only three categories of non-galactic nebulae: ellipticals, spirals, and irregulars. This became the terminology employed in his classic paper of 1926, the foundation of the galaxy classification system still used today, the so-called Hubble sequence (Hubble, 1926 and Figure 13) and the basis for the famous Hubble 'tuning fork' diagram of the galaxy published ten years later in *The Realm of the Nebulae* (Hubble, 1936 and Figure 14).

Hubble's classification system for non-galactic nebulae therefore was in place well before the distances to these objects had been determined, in fact even before it was known whether they were galactic or extragalactic. But more than natural history was needed to solve the problem of non-galactic nebulae; for that, distance techniques were essential. As Hubble himself noted in *The Realm of the Nebulae*, three landmarks stand out in the road that eventually revealed the nature of the non-galactic nebulae as being really outside the galaxy: the first radial velocity measurements of a galaxy in 1912, the discovery of novae in 1917, and his own discovery of Cepheid variable stars in the Andromeda Nebula in 1925.

All galactic classification systems prior to 1925 were thus necessarily constructed without knowledge of the distances of the "nebulae", and therefore consist of a mix of diffuse, planetary and what turned out to be extragalactic objects, the latter eventually recognized as galaxies. Classification of galaxies thus began as a pre-discovery activity and astronomers such as Alan Sandage (1926–2010), Hubble's successor at Mt. Wilson, carried it forward as a post-discovery activity with at least rudimentary knowledge of distances (Sandage, 1975; 2004;

CLASSIFICATION OF NEBULAE

	Symbol	Example
I. Galactic nebulae:		
A. Planetaries	P	N.G.C. 7662
B. Diffuse	D	.....
1. Predominantly luminous	DL	N.G.C. 6618
2. Predominantly obscure	DO	Barnard 92
3. Conspicuously mixed	DLO	N.G.C. 7023
II. Extra-galactic nebulae:		
A. Regular:		
1. Elliptical	E*n*	N.G.C. 3379 E0 221 E2 4621 E5 2117 E7
(n = 1, 2, ... , 7 indicates the ellipticity of the image without the decimal point)		
2. Spirals:	Symbol	Example
a) Normal spirals	S	.....
(1) Early	Sa	N.G.C. 4594
(2) Intermediate	Sb	2841
(3) Late	Sc	5457
b) Barred spirals	SB	.....
(1) Early	SBa	N.G.C. 2859
(2) Intermediate	SBb	3351
(3) Late	SBc	7479
B. Irregular	Irr	N.G.C. 4449

Extra-galactic nebulae too faint to be classified are designated by the symbol "Q."

Figure 13: Hubble's 1926 classification of nebulae divided them into galactic and extragalactic. The latter term at first signified outside the plane of our Milky Way Galaxy, and, after 1925, outside of the galaxy itself. Only after Hubble's death in 1953 did the term 'galaxy' come into widespread use (after Hubble, 1926: 321).

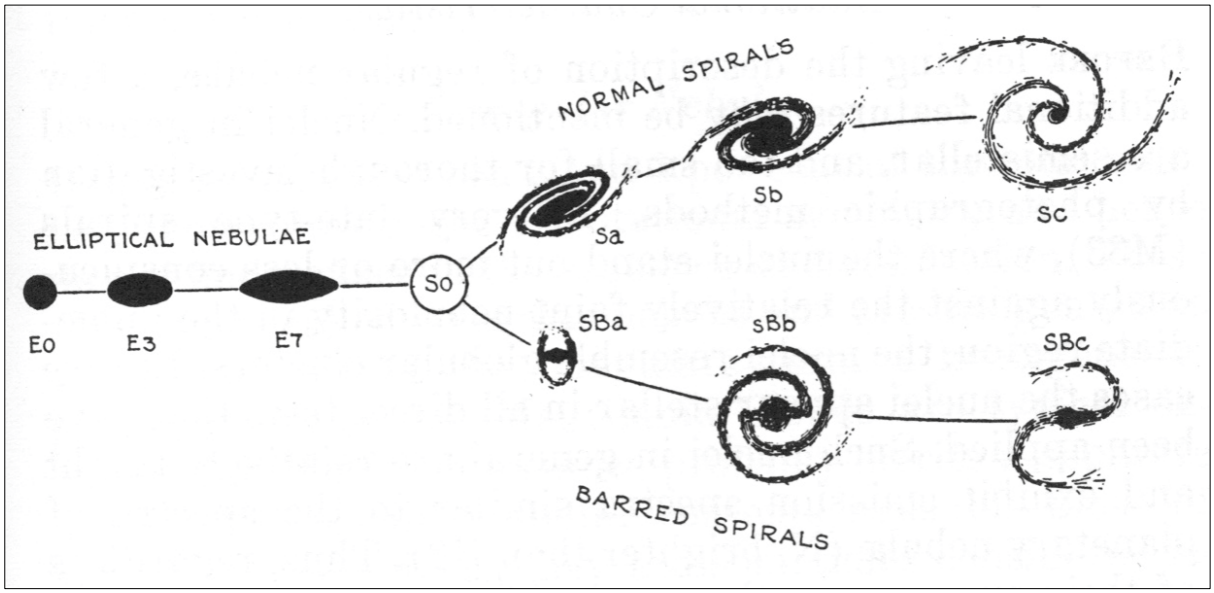


Figure 14: Hubble's 'tuning fork' diagram of galaxy classification, from his book *The Realm of the Nebulae*. Hubble referred to the diagram as "… the sequence of nebular types … a schematic representation of the sequences of classification." For Hubble the diagram represented an evolutionary sequence, moving from left to right. The diagram illustrates the difficulties of delineating classes; Hubble considered E7 lenticulars a "… transition stage … more or less hypothetical …", between ellipticals and spirals. The existence of a lenticular class of galaxies remains controversial to this day, when they are more often identified with Hubble's S0 galaxies (after Hubble, 1936: 45).

2005). Astronomers proposed modifications, extensions, and variants to the Hubble system, and even totally new systems. In 1959 the French-American astronomer Gerard de Vaucouleurs (1918–1995), for example, argued that Hubble's ordering of spiral galaxies, based only on how tightly the spirals were wound and whether they were barred or unbarred, was not enough. He developed another system that includes more refined criteria for bars and spiral arms, and added rings to the classification (de Vaucouleurs 1959; cf. Buta *et al.*, 2007). And in a parallel to what happened in stellar classification, the following year the Canadian astronomer Sidney van den Bergh introduced the concept of luminosity classes for galaxies (van den Bergh, 1998).

Galaxy classification remains an important activity that even amateurs now engage in through the Galaxy Zoo crowdsource project (Galaxy Zoo, 2024). Given the difficulties in correlating galaxy morphology with physical significance it is remarkable that galaxy classification systems have proven as useful as they have. In a significant way, the jury is still out on galaxy classification systems and whether the characteristics chosen as the basis for the classification systems are fundamental to the galaxies themselves, and particularly their evolution, although the Hubble and James Webb Space Telescopes have greatly illuminated this connection (NASA, 2024; Wijesinghe et al, 2010).

The cases of planets, stars, and galaxies all lead us to proposition 2:

Proposition 2: Classification takes place both before and after the nature of the objects is known. Initial classifications based on observed phenomena are useful in early detection and interpretation stages of extended discovery. Final classification awaits determination of full understanding of 'the thing itself' based on the physical nature of the body.

Over the decades numerous smaller classification systems have been developed for particular classes of objects ranging from asteroids and comets to nebulae and star clusters, to binary stars and supernovae. Each has been formulated in its own time in diverse ways that have proven useful to the communities that study these objects. But almost never did these classifiers have in mind consistent principles that applied across the diverse discipline of astronomy. We propose such a system in the next section as a way of illustrating the problems and promise of constructing a comprehensive classification system, and its necessity in determining taxon levels such as class.

4 CLASSIFYING THE COSMOS: THE IMPORTANCE OF A COMPREHENSIVE CLASSIFICATION SYSTEM FOR ASTRONOMY

It is surprising that, unlike sciences such as biology (the Five Kingdoms and Three Domains), chemistry (the Periodic Table), and physics (the Standard Model), astronomy has no consistent and comprehensive classification system for its numerous objects. Over the last three decades I have devised such a system for both pedagogic and scientific use (Dick, 2013; 2019, and Table 1). This so-called Three Kingdom System begins with the three *kingdoms* of planets, stars, and galaxies, stipulates six *families* for each kingdom, and distinguishes 82 distinct *classes* of astronomical objects. Like biology, it is hierarchical, extending from kingdom to family to class, with the possible extension to further categories lower in the hierarchy such as type and subtype. As in biological classification it occasionally adds an intermediate subfamily level wherever useful. With the benefit of hindsight, and with utility in mind, the system incorporates some classes as they have historically been defined, and adds others as they might be defined in a more coherent and consistent system.

In constructing such a system (the 3K system for short) one immediately runs into the problem of how to define the categories of kingdom, family and class. The three kingdoms adopted here (planets, stars, galaxies) are the three canonical divisions adopted in astronomy textbooks for almost a century, since it became clear that galaxies were indeed a separate realm from our Milky Way Galaxy, as determined by Hubble in the 1920s. For each kingdom six astronomical families are delineated, based on the object's origin (proto-), location (circum- and inter-), subsidiary status (sub-) and tendency to form systems (systems), in addition to the 'central' family (planet, star or galaxy) with respect to which the other families are defined. These considerations give rise to astronomy's 18 families, and the symmetry of the six families of each kingdom reflects their physical basis in gravity's action in all three kingdoms. Under these 18 families are the 82 classes of objects.

One of the benefits of such a classification system is that we can now see everything in its proper place. In the planetary realm we can see the classes of planets (P2–P5), minus the dwarf planet class (P9) now classed as a subplanetary body due to IAU action. We can see where Herschel's original 12 classes (now six modern classes) fit: reflection nebulae (S28) under the family of interstellar medium, subfamily dust;

Table 1: Astronomy's three kingdoms, 18 families, and 82 classes, a comprehensive classification system for astronomy, first elaborated in Dick (2013) and later in Dick (2019).

Kingdom of Planets	Kingdom of Stars	Kingdom of Galaxies
Family: Protoplanetary	Family: Protostellar	Family: Protogalactic
Class P 1: Protoplanetary Disk	Class S 1: Protostar	Class: G 1: Protogalaxy
Family: Planet	Family: Star	Family: Galaxy
Class P 2: Terrestrial (rocky)	Subfamily: Pre-Main Sequence	Subfamily: Normal
Class P 3: Gas Giant	Class S 2: T Tauri	Class: G 2: Elliptical
Class P 4: Ice Giant	Class S 3: Herbig Ae/Be	Class: G 3: Lenticular
Class P 5: Pulsar Planet	Subfamily: Main Sequence (H burning Luminosity Class V)	Class: G 4: Spiral
Family: Circumplanetary		Class: G 5: Irregular
Class P 6: Satellite	Class S 4: Dwarf	Subfamily: Active
Class P 7: Ring	Class S 5: Subdwarf	Class: G 6: Seyfert
Class P 8: Radiation Belt	Subfamily: Post-Main Sequence (He burning and higher elements)	Class: G 7: Radio Galaxy
Family: Subplanetary		Class: G 8: Quasar
Class P 9: Dwarf Planet	Class S 6: Subgiant (Luminosity Class IV)	Class: G 9: Blazar
Class P 10: Meteoroid		Family: Circumgalactic
Subfamily: Small Bodies of Solar System	Class S 7: Giant (Luminosity Class III)	Class: G 10: Satellites and Stellar Streams
Class P 11: Minor Planet/Asteroid	Class S 8: Bright Giant (Luminosity Class II)	Class: G 11: Galactic Jet
Class P 12: Comet		Class: G 12: Galactic Halo
Class P 13: Trans-Neptunian Objects	Class S 9: Supergiant (Luminosity Class I)	Family: Subgalactic
		Class: G 13: Subgalactic Object
Family: Interplanetary Medium	Class S 10: Hypergiant (Luminosity Class 0)	Family: Intergalactic Medium
Class P 14: Gas		Subfamily: Gas
Class P 15: Dust	Subfamily: Evolutionary Endpoints	Class: G 14: Warm Hot IGM
Subfamily: Energetic Particles	Class S 11: Supernovae	Class: G 15: Lyman Alpha Blobs
Class P 16: Solar Wind	Class S 12: White Dwarf	Subfamily: Dust
Class P 17: Anomalous Cosmic Rays	Class S 13: Neutron Star/Pulsar	Class: G 16: Dust
	Class S 14: Black Hole	Subfamily: Energetic Particles
Family: Systems	Family: Circumstellar	Class: G 17: Galactic Wind
Class P 18: Planetary Systems/ Exoplanets	Class S 15: Debris Disk	Class: G 18: Extragalactic Cosmic Rays
	Class S 16: Shell (Dying star)	
Class P 19: Asteroid Groups	Class S 17: Planetary Nebula	Family: Systems
Class P 20: Meteoroid Streams	Class S 18: Nova Remnant	Class: G 19: Binary
Subfamily: Trans-Neptunian Systems	Class S 19: Core Collapse Supernova Remnant	Class: G 20: Interacting
		Class: G 21: Group
Class P 21: Kuiper Belt	Class S 20: Stellar Jet	Class: G 22: Cluster
Class P 22: Oort Cloud	Class S 21: Herbig-Haro Object [See also Protoplanetary Disk (P 1) Planetary System (P 18) Kuiper Belt (P 21) Oort Cloud (P 22)	Class: G 23: Supercluster
		Class: G 24: Filaments and Voids
	Family: Substellar	
	Class S 22: Brown Dwarf	
	Family: Interstellar Medium	
	Subfamily: Gas (99%)	
	Class S 23: Cool Atomic Cloud (H I)	
	Class S 24: Hot Ionized Cloud (H II)	
	Class S 25: Molecular Cloud	
	Class S 26: White Dwarf Supernova Remnant	
	Subfamily: Dust (1%)	
	Class S 27: Dark Nebulae	
	Class S 28: Reflection Nebulae	
	Subfamily: Energetic Particles	
	Class S 29: Stellar Wind	
	Class S 30: Galactic Cosmic Rays	
	Family: Systems	
	Class S 31: Binary Star	
	Class S 32: Multiple Star	
	Class S 33: Association (OB)	
	Class S 34: Open Custer	
	Class S 35: Globular Cluster	
	Class S 36: Population	

H II regions (S24) in the family interstellar medium, subfamily gas; planetary nebulae (S17) in the circumstellar family; globular clusters (S 35) under the stellar systems family; spiral galaxies (G4) in the galaxy subfamily; and binary galaxies (G19) in the galactic systems family. Counting Herschel's discovery of Uranus, now known to be an ice giant planet (P4), we can see (not surprisingly) that Herschel made discoveries in all three Kingdoms of planets, stars, and galaxies.

In the Kingdom of the stars the 3K system illustrates at a glance the various subfamilies of stars from pre-main sequence to main sequence, post-main sequence, as well as the stellar evolutionary endpoints of supernovae, white dwarfs, neutron stars/pulsars, and black holes (S11–S14). Under these subfamilies are the various classes of stars discussed in the previous section, including supergiants (S9, luminosity class I in Morgan's system), bright giants (S8, class II), giants (S7, class III), subgiants (S6, class IV), and the main sequence subdwarfs and dwarfs (S4 and S5, class V). Similarly, in the Kingdom of Galaxies the classes of normal galaxies (G2–G5) and active galaxies (G6–G9) are evident. The symmetries in families among the Three Kingdoms, such as circumplanetary, circumstellar, and circumgalactic, are also clearly evident.

This system also allows one to see how early classification can lead to confusion in nomenclature when the thing itself is finally understood. A case in point is supernovae (S11), catastrophic explosions that result in a sudden brightening of stars such as supernova 1006 mentioned earlier. We now know that such explosions are the result of two very different mechanisms, triggered either when a massive star exhausts its nuclear fuel and collapses under its own weight, or when a white dwarf (S12) in a binary system explodes after accreting 1.4 solar masses, known as the Chandrasekhar Limit. We can therefore speak of two main classes of supernovae: core collapse supernovae that produce neutron stars (S13) or black holes (S14), and white dwarf supernovae, believed to leave behind only material for the interstellar medium or the companion to the exploding white dwarf. Core collapse supernovae produce spectacular circumstellar remnants (S19), while white dwarf supernovae produce a different kind of remnant (S26). Because of historical circumstance stars that collapse to form neutron stars are labelled Type II, but those that form black holes are labelled Type Ib and Ic, while white dwarf supernovae are labelled Type Ia. Supernova 1006, Tycho's supernova of 1572 and Kepler's supernova of 1604 (Figure 15) are Type Ia white dwarf supernovae; the supernova of 1052 now seen as the Crab Nebula with a neutron star at its center resulted from a core collapse (S19, Figure 16).

Astronomers can perhaps be forgiven for the illogical nomenclature of supernovae because of their limited knowledge at the time it was instituted. Until the twentieth century, absolute magnitudes and luminosities were not known well enough even to distinguish novae from supernovae. Astronomers did the best they could at the time with nomenclature and classification because it was based on spectra and an incomplete understanding of the underlying physical nature. Once such a nomenclature is established, however, it is difficult to change to a more logical nomenclature such as Type I for all core collapse mechanisms and Type II for white dwarfs. Note also that in this system novae are not given class status because they are a Type of binary star (S31), one taxon below class, although a nova remnant (S18) is a particular class of circumstellar object.

Whether core collapse supernovae and white dwarf supernovae should be given separate Class status or be placed one taxon down at the Type level is an open question. I have opted for the latter because the 'Type' designation is common astronomical usage for supernovae, and because a white dwarf supernova deserves to be in a separate class no more or less than a nova, which is also a Type of binary star.

All these considerations lead to our next Proposition:

Proposition 3: Class status is best determined within a comprehensive classification system that specifies taxon levels such as Families, Class, Type, or Sub-type.

There is room for constructive argument about certain classes: for example, black holes have been placed under stellar evolutionary endpoints, but there are also intermediate and supermassive black holes. The formation mechanism of supermassive black holes that lie at the centers of active galactic nuclei (AGNs) remains the subject of active research. They may well be the result of the collapse of a conglomeration of massive stars or star clusters, but the very early ones being discovered by JWST may be the result of massive gas clouds rather than stars. Thus, whether there should be a separate Class for supermassive black holes will depend on more research—as it should in any developing system.

It is also essential to emphasize that because all classes and classification systems are

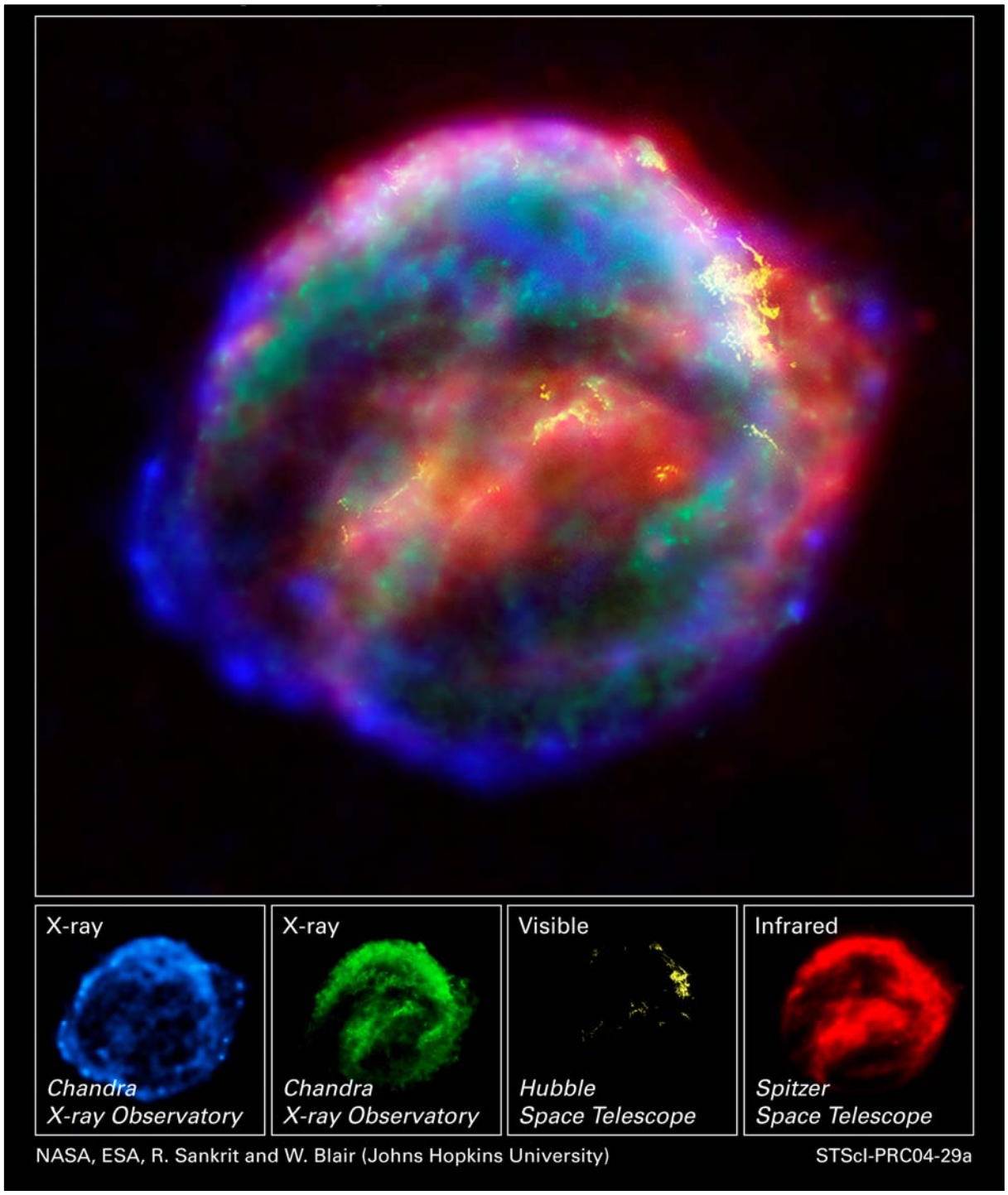


Figure 15: The remnant from Kepler's supernova of 1604, now known to be a white dwarf supernova. The Hubble, Spitzer and Chandra Telescopes combined to produce this image (courtesy: NASA, ESA, R. Sankrirt, and W. Blair (Johns Hopkins University)).

socially constructed, the Three Kingdom system for astronomy is not the only system that could be proposed. But in the end, like the other classification systems, its *raison d'être* and its staying power are dependent on its accuracy, simplicity and utility, both in scientific and pedagogical terms. Such features are an asset for astronomical classes and classification systems in general.

For the most part any additions and revisions will be made at the Class and Type level, for example, as new classes of planets are discovered, or new classes of baryonic dark matter objects are revealed, or newly detected objects are analyzed. It is not out of the question that a new Family could be added, though this seems unlikely given our definition of Family. At the Kingdom level, surprisingly, one can already

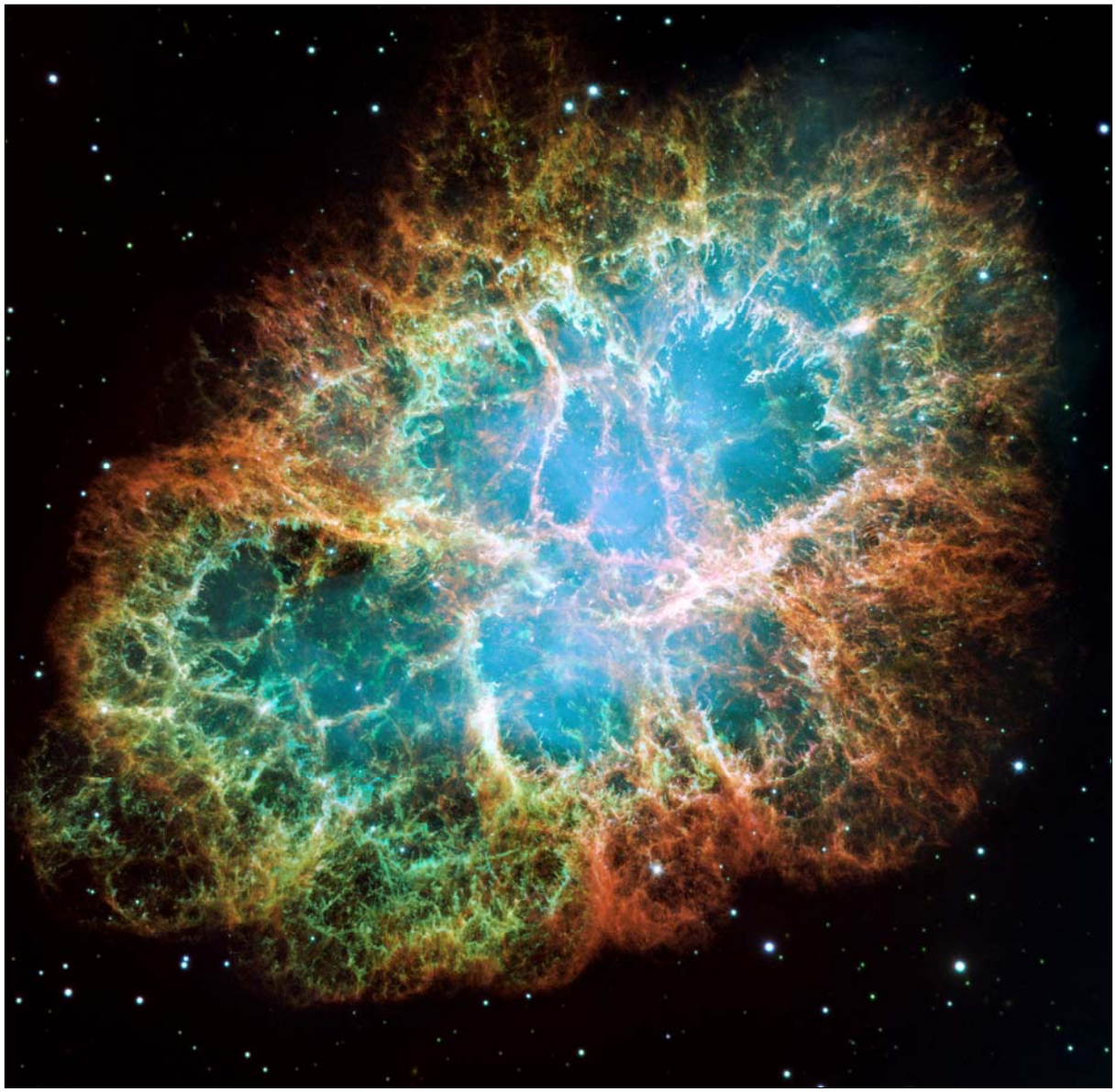


Figure 16: Crab Nebula supernova remnant 6,500 light years away and six light years in diameter. The colors in this composite of 24 images indicate elements expelled during the explosion: blue in the filaments of the outer part of the nebula is neutral oxygen, green is ionized sulfur, and red is ionized oxygen (courtesy: NASA, ESA, J. Hester, and A. Loll (Arizona State University)).

glimpse a possible new entry: the Universe itself may be one of a class of objects in what has been called the multiverse. But this is as yet too speculative to include in any astronomical classification system.

5 DISCOVERY, CLASSIFICATION, AND PHILOSOPHY OF ASTRONOMY

The problems of discovery and classification are arguably part of a new field called philosophy of astronomy. While established fields exist for philosophy of biology, chemistry, and physics (Hull and Ruse, 2007; Lange 2012; Mayr, 1988; Scerri and McIntyre, 2015), until recently no such field has existed for philosophy of astronomy and cosmology, sporadic attempts notwithstanding. An anthology compiled 25 years ago by the Canadian philosopher John Leslie), *Modern Cosmology and Philosophy*, provides a good starting point (Leslie, 1998). A few scholars like cosmologist George Ellis and philosopher George Gale have written on the subject (Ellis, 2006; Gale, 1993). The biennial Notre Dame History of Astronomy workshops have hosted several sessions on this subject (Notre Dame, 2009; 2015). More recently, a rather technical volume on *The Philosophy of Cosmology* has appeared (Chamcham et al., 2017), as well as a volume on *The Philosophy of Astrophysics* (Boyd et al., 2023). Some of these volumes are quite limited in scope, and there has really been no systematic survey of critical

issues in philosophy of astronomy, which I take to include cosmology, astrophysics, and astrobiology.

Such a survey would include at least seven categories of issues in the astronomical context (Dick, 2020): 1) the metaphysical foundations of astronomy and how they have evolved; 2) the influence of metaphysical preconceptions and non-scientific worldviews on astronomy, evidenced, for example, in the work of Arthur S. Eddington (1882–1944) and many other astronomers; 3) the nature of reasoning, including the roles of observation, theory, simulation, and analogy, as well as the limits of reasoning, starkly evident in the anthropic principle, fine-tuning, and multiverse controversies; 4) the problematic nature of evidence and inference, especially since the objects of astronomical interest are for the most part beyond experiment and experience; 5) the epistemological status of astronomy and its central concepts, including space, time, and gravity; the process of discovery and classification; and the nature of life and intelligence; 6) the role of technology in shaping the discipline of astronomy and our view of the universe; and 7) the mutual interactions of astronomy and cosmology with society over time.

The problems of discovery and classification fall squarely into category 5, along with other concepts such as space and time (overlapping with the philosophy of physics), life and intelligence (overlapping with philosophy of astrobiology; Dick, 2012), and various elements of the philosophy of cosmology. We have seen how discovery and classification, far from being straightforward endeavors, can be problematized to take into account their anatomies, histories, philosophical foundations, and challenges, all of which can illuminate current discovery strategies classification challenges.

In addition to these epistemological, metaphysical, and societal questions, more specific philosophical concepts are directly applicable. One of them is ‘natural kinds’, how nature itself carves out certain categories of objects, and whether these categories should be the basis for any classification system (Bird and Tobin, 2024; Kendig, 2016). This concept, which the philosopher Thomas Kuhn (2022) emphasized in his last writings, also fits well with W.W. Morgan’s idea of ‘thing itself’, which can be traced back all the way to Carl Linnaeus (1707–1778):

> The first step in wisdom is to know the things themselves. This notion consists in having a true idea of the objects; objects are distinguished and known by classifying them methodologically and giving them appropriate names. Therefore, classification and name-giving will be the foundation of our science (Linnaeus, 1735: 19).

Thus, gravity may be seen as a sculpting force for astronomical objects that applies equally to family and class taxa, as we have noted in the case of stars where gravity was recognized by the founders of the MK system as the dominating force for the luminosity classes. As astronomers Richard Gray and Chris Corbally put it in their definitive volume on *Stellar Spectral Classification*:

> Stars readily wanted to be grouped according to gravity as well as according to temperature, and this grouping could be done by criteria in their spectra. (Gray and Corbally, 2009: 10).

The authors have unwittingly stumbled across a definition of the philosophical concept of natural kinds for astronomy.

For planetary scientists the idea of natural kinds resonates with the argument over whether the basis for classification of objects such as Pluto should be based on physical nature or dynamical considerations such as formation or ‘clearing its neighborhood’. As the philosopher Alisa Bokulich points out, some philosophers have recently expanded the definition of natural kinds to historical and relational properties such as formation or relation to other objects (Bokulich, 2014: 465). While astronomers such as Stern and Levison (2002) argued for Plutonian planet status based on typological natural kinds defined as intrinsic physical properties, under this expanded definition dynamical astronomers could claim that their definition of planet also defines a natural kind (Soter, 2006), though arguably of a weaker kind. Astronomers in general are not familiar with the philosophical concept of natural kinds, and therefore did not use that terminology. But placing their arguments in that context gives an added philosophical dimension to the controversy. This will be relevant for the foreseeable future as thousands of exoplanets are classified and new objects are discovered.

These considerations lead to our fourth proposition:

Proposition 4: Discovery and classification are important central concepts of astronomy. Clarifying their epistemological status is an integral part of the newly evolving field of philosophy of astronomy, where philosophical concepts can help in the practice of classification.

In the end the history of astronomy teaches us that while preliminary classifications are useful and may continue to be useful based on

phenomenal or secondary characteristics, because of the extended nature of discovery final classification must await knowledge of their physical nature, representing both the philosophical and scientific ideals of natural kinds and the thing itself.

We thus end with our final proposition, anchored in Proposition 2, but now in the form of a methodological recommendation to all those involved in the practice of astronomical classification:

Proposition 5: To the maximum extent possible the final classification of astronomical objects should be based on the physical nature of the objects being classified.

The philosopher Immanuel Kant (1724–1804) argued that at another level the thing itself (Ding an sicht) can never be reached by the human mind. But when it comes to classification in astronomy it seems optimal to approach that ideal as closely as possible.

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