Astronomy's Three Kingdom System: A Comprehensive Classification System of Celestial Objects†

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Abstract: Although classification has been an important aspect of astronomy since stellar spectroscopy in the late nineteenth century, to date no comprehensive classification system has existed for all classes of objects in the universe. Here we present such a system, and lay out its foundational definitions and principles. The system consists of the "Three Kingdoms" of planets, stars and galaxies, eighteen families, and eighty-two classes of objects. Gravitation is the defining organizing principle for the families and classes, and the physical nature of the objects is the defining characteristic of the classes. The system should prove useful for both scientific and pedagogical purposes.

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1.0 Introduction to the Three Kingdom System

This article introduces a classification system of celestial objects developed by the author. In contrast to biology, physics and chemistry, and despite a long and distinguished history of classifying specific objects such as stars and galaxies, astronomy lacks a comprehensive classification system for what has become a veritable celestial zoo. What would such a system look like, and based on what principles? Here we present a system devised for pedagogic use over the last several decades (Figure 1) but that will also be useful for scientific purposes. This so-called "Three Kingdom" system begins with the three "kingdoms" of planets, stars and galaxies, stipulates six "families" for each kingdom, and distinguishes eighty-two 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, 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 the American astronomer Edwin Hubble in the early 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 eighteen families, and the symmetry of the six families of each kingdom reflects their physical basis in gravity's action in all three kingdoms.

For a more general introduction to astronomical classification and its issues see Buta, Corwin et al. (2007), DeVorkin (1981), Dick (2013; 2018), Feigelson (2012), Gray and Corbally (2009), Morgan (1937; 1988), Morgan and Keenan (1973) and Sandage (2005).

2.0 Defining astronomy's eighty-two classes

The Three Kingdom System contains eighty-two classes of objects, as delineated in Figure 1.

But this begs the question: How does one define a class of astronomical objects? More specifically, how does one recognize a new class of objects? We have tackled these questions in previous books, including *Discovery and Classification in Astronomy: Controversy and Consensus* (Dick 2013), and *Classifying the Cosmos: How We Can Make Sense of the Celestial Landscape* (Dick 2018), in which the Three Kingdom System is laid out in full and the history and science of each class is described.

One way of approaching the question of the definition of class is by looking at history, where (exceptions like stars and galaxies notwithstanding) classification has often been ad hoc, haphazard and historically contingent on circumstance. If astronomical history demonstrates anything, it is that the classification of astronomical objects has been based on many characteristics, depending on the state of knowledge and the needs of a particular community at the time. For example, planets could be divided according to their physical nature (terrestrial, gas giant and ice giants) or as the recent discovery of planetary systems has taught us, by orbital characteristics (highly elliptical or circular), proximity to their parent star ("hot Jupiters") and so on. Historically, binary stars have often been classified by the method of observation as visual, spectroscopic, eclipsing and astrometric, or (after more information became known) by the configuration or contents of the system, such as a white dwarf binary, or by the dominant wavelength of its electromagnetic radiation, as in an X-ray binary. While these overlapping systems have served astronomers well and illustrate how the same object may be classified in many ways, such designations are the source of much confusion among students, not to mention indecipherable to the public.

History also demonstrates that at the time of discovery, by the very nature of the problem, it is sometimes difficult to decide whether a new class of object has been discovered. Perhaps by analogy with the Earth's moon, Galileo decided relatively quickly that the four objects he first saw circling Jupiter in 1610 were satellites, proof that the moon was not unique, but a member of a class of circumplanetary objects (even if he did not speak in terms of "class"). But the object he first saw surrounding Saturn was not at all obviously a ring, and awaited the interpretation of Christiaan Huygens more than forty years later. 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.

Inconsistency notwithstanding, the criterion that astronomers have most often used in the astronomical literature for determining class status—and the one we adopt for the Three Kingdom system—is the physical nature of the object. In the planetary Kingdom, for example, rather than orbital characteristics, the definition of planetary classes in our own solar system has been based on their physical characteristics as rocky, gaseous or icy in composition; pulsar planets have also been distinguished by being inferred as physically very different again due to the extreme nature of their environment and probable different origin. As we have noted, new classes of planets will undoubtedly be uncovered as observations of extrasolar planets progress, but thus far not enough is known about their physical nature to do so. Many of the extrasolar planets discovered so far are believed to be gas giants; many are close to their stars and thus called "hot Jupiters." The first terrestrial extrasolar planets have also been claimed, in the form of "super-Earths" and the first rocky transiting system, known as CoRoT-7b.

This history indicates that a comprehensive classification system for astronomy can perhaps do no better than to use the typological definition of "class" largely discarded by biologists (Mayr 1988, 337): "membership in a class is determined strictly on the basis of similarity, that is, on the possession of certain characteristics shared by all and only members of that class. In order to be included in a given class, items must share certain features which are the criteria of membership or, as they are usually called, the 'defining properties.' Members of a class can have more in common than the defining properties, but they need not. These other properties may be variable—an important point in connection with the problem of whether or not classes may have a history."

But what is the unit of classification for astronomy? For physics, it is elementary particles. For chemistry, it is the elements defined by atomic number in the Periodic Table. For biology, it is species at the macro level, giving rise to biology's "five kingdoms," still favored by some macrobiologists, and genetic sequences of 16S ribosomal RNA at the molecular level, giving rise to Carl Woese's "three domains" of Archaea, Bacteria and Eucarya—favored by most molecular biologists.[1] For astronomy, the unit of classification adopted here is the astronomical object itself, and with some theoretical justification. For as strong and

Astronomy's 82 Classes

Kingdom of the Planets	**Kingdom of the Stars**	**Kingdom of the Galaxies**
Family: Protoplanetary	Family: Protostellar	Family: Protogalactic
Class P 1: Protoplanetary Disk	Class S 1: Protostar	Class G 1: Protogalaxy
Family: Planet	Family: Star	
Class P 2: Terrestrial (rocky)	Subfamily: Pre-Main Sequence	Family: Galaxy
Class P 3: Gas Giant	Class S 2: T Tauri	Subfamily: Normal
Class P 4: Ice Giant	Class S 3: Herbig Ae/Be	Class G 2 Elliptical
Class P 5: Pulsar Planet	Subfamily: Main Sequence	Class G 3 Lenticular
Family: Circumplanetary	(H burning - Luminosity Class V)	Class G 4 Spiral
Class P 6: Satellite	Class S 4: Dwarf	Class G 5 Irregular
Class P 7: Ring	Class S 5: Subdwarf	Subfamily: Active
Class P 8: Radiation Belt	Subfamily: Post-Main Sequence	Class G 6 Seyfert
Family: Subplanetary	(He burning and higher elements)	Class G 7 Radio Galaxy
Class P 9: Dwarf Planet	Class S 6: Subgiant (Luminosity Class IV)	Class G 8 Quasar
Class P 10: Meteoroid	Class S 7: Giant (Luminosity III)	Class G 9 Blazar
Subfamily: Small Bodies of Solar System	Class S 8: Bright Giant Class II)	Family: Circumgalactic
Class P 11: Minor Planet/	Class S 9 Supergiant (Lumin. Class I)	Class G 10 Satellites and
Asteroid	Class S 10 Hypergiant (Lumin. Class 0)	Stellar Streams
Class P 12: Comet	Subfamily: Evolutionary Endpoints	Class G 11 Galactic Jet
Class P 13: Trans-Neptunian	Class S 11 Supernova	Class G 12 Galactic Halo
Objects	Class S 12 White Dwarf	Family: Subgalactic
Family: Interplanetary Medium	Class S 13 Neutron Star/Pulsar	Class G 13 Subgalactic Object
Class P 14: Gas	Class S 14 Black Hole	Family: Intergalactic Medium
Class P 15: Dust	Family: Circumstellar	Subfamily: Gas
Subfamily: Energetic Particles	Class S 15: Debris disk	Class G 14 Warm Hot IGM
Class P 16: Solar Wind	Class S 16: Shell (dying stars)	Class G 15 Lyman alpha blobs
Class P 17: Anomalous Cosmic	Class S 17: Planetary Nebula	Subfamily: Dust
Ray	Class S 18: Nova Remnant	Class G 16 Dust
	Class S 19: Core Collapse Supernova	

Figure 1. The Three Kingdom (3K) System. From Dick (2019, xx-xxi); reproduced with permission.

weak forces are dominant in particle physics, and as the electromagnetic force is dominant in chemistry (except for nuclear chemistry), so in astronomy is it the weakest but most far-reaching force of gravity that predominantly acts on and shapes these astronomical objects. Though other considerations such as hydrostatics and gas and radiation pressure come into play, gravity is the determining factor for the structure and organization of planets, stars and galaxies, their families and classes of objects. To put it another way, the strong interaction holds protons and neutrons together and allows atoms to exist; the electromagnetic interaction holds atoms and molecules together and allows the Earth to exist; and the gravitational interaction holds astronomical bodies together and allows the solar system, stellar systems and galactic systems to exist.[2] Gravity is thus a prime candidate—the one adopted here—to serve as the chief organizing principle for a comprehensive classification system for all astronomical objects.

Where does such a definition of class lead in the construction of a classification system? In the "kingdom of the stars," stellar spectra were first classified on what turned out to be a temperature sequence, a system devised at Harvard in the late nineteenth-century with its familiar O, B, A, F, G, K and M stars and so on. Spectra were later classified on a luminosity scale, devised at Yerkes Observatory in the 1940s, the so-called MKK (Morgan-Keenan-Kellman) system with its dwarfs, giants and supergiants.[3] Which to choose to delineate "classes" for stars in a more comprehensive system for astronomical objects? We have adopted the Yerkes/MKK system (now known as the MK system) as a more evolved two-dimensional system based on spectral lines sensitive not only to temperature, but also to surface gravity (g) and luminosity. As astronomers Richard Gray and Christopher Corbally recently put it in their magisterial volume *Stellar Spectral Classification* (2009, 10), in connection with the luminosity classes, "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." The resulting luminosity classes (main sequence, subgiant, giant, bright giant and supergiant labeled from Roman numeral V to I respectively), together with the stellar endpoint classes (supernova, white dwarf, neutron star and

Astronomy's 82 Classes (cont.)

Family: Systems
Class P 18: Planetary Systems/ Exoplanets
Class P 19: Asteroid Groups
Class P 20: Meteoroid streams
Subfamily: Trans-Neptunian Systems
Class P 21:Kuiper Belt
Class P 22: Oort Cloud

Class S 20: Stellar Jet
Class S 21: Herbig-Haro Object
[See also Protoplanetary Disk (P 1);
Planetary System, (P 18)
Kuiper Belt (P 21)
Oort Cloud (P 22)]
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 (H2)
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 Cluster
Class S 35: Globular Cluster
Class S 36: Population

Subfamily: Energetic Particles
Class G 17 Galactic Wind
Class G 18 Extragalactic Cosmic Rays
Family: Systems
Class G 19 Binary
Class G 20 Interacting
Class G 21 Group
Class G 22 Cluster
Class G 23 Supercluster
Class G 24 Filaments & Voids

Figure 1 (cont.)

black hole) not only have significance in the evolutionary sequence but also have a real history of discovery that can be uncovered. W. W. Morgan delineated these luminosity classes to begin with, because he realized each grouping of stars formed a sequence of near constant log g (surface gravity) (Gray and Corbally 2009, 9-10; Morgan 1937, 380 ff.). Thus, gravity as a sculpting force for stars was recognized already by the founders of the MKK system as the dominating force for the luminosity classes.

The choice of luminosity for stellar classes does not subordinate the Harvard system of spectral types. To the contrary, Harvard spectral types are still an integral part of the system. As the originators of the Yerkes/MKK system argued, it is simply the case that their system contains more information and better represents the physical nature of stars, as astronomers gradually separated them (over the thirty years from 1910 to 1940) into supergiants, bright giants, giants and subgiants. In other words, since 1943 with the Yerkes/MKK system, modern astronomy has a formal two-dimensional temperature-luminosity system with distinct classes, building on the Hertzsprung-Russell diagram, which was literally a two-dimensional plot of temperatures versus luminosities when it was first constructed around 1914. Both the Harvard and the Yerkes systems are represented in the full designation of a star, as in Sirius (A1V) as a main sequence star with Harvard spectral type A1.

Thus, choices for class status become more clear-cut once there is a guiding principle such as physical meaning, which goes to the heart of Morgan's quest for "the thing itself." Again in the stellar kingdom, for the interstellar medium instead of "diffuse nebulae" (a morphological classification), classes in the Three Kingdom System are distinguished according to physical constitution of the nebulae: gas (cool atomic neutral hydrogen, hot ionized hydrogen and molecular) and dust (reflection nebulae). These categories are used in astronomy and subsume classifications based on morphology that are historically contingent. In the galactic kingdom, galaxy morphologies (elliptical, lenticular, spiral, barred spiral and irregular) laid out by Edwin Hubble in the 1920s also reflect compositional differences (as Morgan's galaxy classification system showed), so the principle of physical meaningfulness still holds.

3.0 Classification principles in the Three Kingdom System

As we have stipulated, by definition kingdoms are delineated by the three central prototypes of objects in the universe—planets, stars and galaxies, as enshrined in canonical textbooks since the 1950s. Families are delineated by the various manifestations of the gravitational force acting on astronomical objects, e.g., protoplanetary, planetary, circumplanetary, subplanetary, interplanetary and systems. As in any classification system, there will be ambiguities of placement in lower taxon levels. These can be mitigated by a system of classification principles. For the Three Kingdom System, these include the following when it comes to the determination of classes and the placement of objects in classes:

1) Classes are delineated based on the physical nature of the object, defined as physical composition wherever possible.
2) An object should always be placed in its most specific class.
3) To the extent possible, classes already in use are retained, as in the luminosity classes of the MK system and the Hubble classes for galaxies, supplemented by new knowledge.
4) The recommendations of the International Astronomical Union are followed; e.g., a dwarf planet is not a class of planet.
5) Potential, but unverified, classes are not included.

Figure 1 shows the result of applying these principles to astronomical objects. For those who do not recognize their favorite objects, it is likely because they exist at a taxonomic level below that of "class." The plethora of variable stars, for example, are not classes of objects in this system, on the same level as giant and dwarf stars and so on. Rather, they are types of these stars that could be elaborated in a more complete system.

It is important to emphasize that classification in astronomy has similarities and differences with classification in biology, chemistry and physics. The most obvious difference between the classes (species) in biology and the classes in astronomy, at least as depicted in our Three Kingdom System, is the sheer number of species. E. O. Wilson, the Harvard naturalist who is one of the chroniclers of the diversity of life, has estimated that by 2009, 150 years after Darwin's *Origin of Species*, some 1.8 million species had been discovered and described, out of perhaps tens of millions that now exist. And this does not include what Wilson (in a rare astronomical analogy employed in the domain of biology) calls the "dark matter" of the microscopic universe, which could be tens or hundreds of millions of species of sub-visible organisms.[4]

The number of "species" or classes in astronomy is obviously put to shame by the effusive and creative diversity of biology, no matter how one defines class or what classification system one uses. In terms of number, astronomy's classes, at least as defined in the Three Kingdom System, are more comparable to elements in chemistry (ninety-three natural and fifteen artificial), or to the phyla (thirty-two) and classes (ninety) in just one of Lynn Margulis's five kingdoms (*Animalia*) of biology, which contains almost a million species by itself. Any such comparison depends not only on how one defines a class of astronomical objects, but also whether the classes as defined here in the Three Kingdom System are really analogous to species in the biological hierarchy of classification, or to elements in the linear classification. That is also a matter of definition, and in part a subjective matter based on relation to higher and lower categories in the system. One can argue whether a giant star of Luminosity Class III in the MK system should be called a class or a type, but one cannot argue that a particular member of the class, a type of giant star such as an RR Lyrae, for example, should be placed at a higher level in the system than the class of which it is a member.

This classification exercise also illustrates a problem that astronomical taxonomy has in common with biological taxonomy: classification characteristics do not necessarily conform to evolutionary relationships. The class of giants as defined by the MK system definition was not precisely the same as the class of giants that Henry Norris Russell declared about 1910, nor is it entirely coextensive with the evolutionary states of the giant stars as known today. Russell's definition (and the Mt. Wilson system) was based on size and luminosity, as determined by their distances and apparent magnitudes, which could be converted to luminosity. The MKK definition was based on spectroscopy, in particular "line ratios" defined by standard stars. If an unclassified star matched the standard in a spectroscopic sense, it became a member of that class, such as a giant, without regard to its internal structure or evolutionary status. While luminosities and MK definitions are still used, today astrophysicists often think of giant stars and other stellar classes in terms of their evolutionary state, which for a giant is normally undergoing core helium fusion, but varies depending on the star's mass and where it stands in the spectral temperature sequence. Moreover, a particular class may be adjusted based on new data; in the early 1990s the Hipparcos satellite determined distances ten times more accurate than ground-based parallaxes, and correspondingly more accurate luminosities. The data showed that many of the luminosities were in error, and in the post-Hipparcos, and now the Gaia spacecraft era, the modern concept of a giant star (core helium fusion with shell hydrogen burning via the CNO cycle) is by no means co-extensive with MK class III defined by spectral line ratios. Nevertheless, the general classes of stars remain, but with a broader definition than determined by the MK system.

In short, astronomical classes have evolved in a way analogous to biology, where "the way it looks" (the phenotype) was primary in the five kingdom classification embraced by zoologists, as opposed to the deeper structure based on genetic makeup (the genotype). But whereas in biology Woese's "three domain" system caused an uproar in biology with its finding of a completely new domain of life and different relationships for parts of the classification system, the classification of stars by how they physically operate rather than by how they appear has thus far led to broader thinking with only minor adjustments.[5]

4.0 Uses of the system and future development

A good classification system must not only be useful but should also lead to deeper understanding and advance its subject. The uses of the Three Kingdom System are at least threefold, all of which may potentially lead to deeper understanding for different audiences.

First, for scientific purposes, as a comprehensive system for all astronomical objects based on consistent physical principles, the Three Kingdom System brings a consistent set of classification principles to discussions such as the status of Pluto as a planet. It suggests that the definition of a planet should not be based primarily on hydrostatic equilibrium, or roundness, or dynamical considerations, but on physical constitution—just as stellar classification was based on consistent physical principles as determined by spectroscopy. Other criteria may indeed enter any classification decision, but they should be secondary. The Three Kingdom System thus brings consistency to astronomical classification, and more clarity in making classification decisions. In the process it might also, over the longer term, bring consistency to astronomical nomenclature as far as taxa such as class and type are concerned.

Secondly, again for scientific purposes, the symmetric structure of the Three Kingdom System facilitates comparisons at three different scales. In the comparison of families across kingdoms, one can ask, for example, how the interplanetary, interstellar and intergalactic media compare, and analyze what this tells us about the nature of the cosmos. Similarly, for protoplanetary, protostellar and protogalactic processes, and so on. Such comparisons are sometimes already made, but the Three Kingdom System cries out for such comparison in a systematic way. Comparisons of classes across kingdoms may also prove enlightening. Planetary rings, stellar rings and galactic rings in the form of stellar streams have much in common as broken up remains, but at vastly different scales and energies. Similarly, for planetary, stellar and galactic jets, or subgalactic, substellar and subplanetary objects. However, since the bedrock definition of a class is that at least one representative object must have been observed, we have not included a class of planetary jets, even though the discovery of brown dwarf jets in 2007 led to speculation that planetary jets might exist during the accretion phase of gas giants. Based on symmetry among families in the three kingdoms, we might also predict the existence of such jets, as well as other objects. While some might argue that volcanic eruptions or water spouts from Europa or Enceladus might qualify as jets, this does not seem to me quite analogous to stellar and galactic jets formed by energetic processes. But one could argue.

Thirdly, there is an educational advantage for the teaching of astronomy. The Three Kingdom System allows students to perceive immediately where an object fits in the scheme of astronomical objects. In assessing a new discovery, for example, whether the object is a type, class, family or kingdom should help a student to see its relative importance in the astronomical zoo. Thus, definitive proof of a new kingdom in astronomy would be vastly more important than, say, a new type of subgiant star. Moreover, the decision as to whether a particular class should be placed in a particular family can lead to fruitful discussion among students, and maybe even scientists. For example, the question of whether a globular cluster is circumgalactic or not will lead students to realize that these objects are not found just surrounding the galaxy, but also within the galaxy, and so on.

Finally, as new discoveries are made in astronomy the Three Kingdom System may well be elaborated. For the most part, the 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 such as the mysterious "G objects" at the center of our galaxy that look like gas clouds but behave like stars (W. M. Keck Observatory 2018). 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 glimpse a possible new entry: the universe itself may be one of a class of objects in what has been called the multiverse. Because this is a kingdom that, so far, we have not seen, but only inferred from concepts like the anthropic principle, it has not been included in the Three Kingdom System at present. Only time will tell. More fundamentally we must always remember we are classifying baryonic objects composed of protons, electrons and neutrons, and that baryonic matter constitutes only 4.6 % of the matter and energy content of the universe. Non-baryonic dark matter is 23%, and dark energy (believed to be responsible for the accelerating universe) is

72%. But we have no idea what that dark matter and dark energy may be. Classification of the objects that we know notwithstanding, plenty of work remains for future astronomers based on what we do not yet know.

Finally, it is essential to emphasize that because all classes and classification systems are 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.

Notes

1. On the "three domain" versus "five kingdom" controversy in biology see especially Sapp (2009). On classification in physics and chemistry see Gordin (2004), Pickering (1984) and Gell-Mann (1994).
2. Davies (2007), especially chapter 4. Isaac Asimov has made the same point in his popular books; for example, Asimov (1992, 263).
3. For more on these classification systems for stars see Dick (2013, chapter 4). A recent popular account of the development of the Harvard system is Sobel (2016).
4. Wilson (2010, xi). In 2011 a group of biologists using a novel analysis estimated 8.7 million eukaryotic species exist, give or take a million. Eukaryotic species contain a nucleus, in contrast to prokaryotes. (Strain 2011).
5. Taxonomy has also evolved, see Mayr (1982, 145), for stages in classification, and microtaxonomy vs macrotaxonomy.

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