Part I

Foundations

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Chapter 1

The Early History of the Transient Sky

The wonder of the nighttime sky has been a source of awe and mystery since the dawn of mankind. According to the *Yale Bright Star Catalog*, there are almost 10,000 stars visible to the unaided eye (brighter than magnitude 6.5) distributed over the entire celestial sphere. To these fixed points of light, we can add the Moon, a total of six naked-eye planets wandering among the fixed stars, frequent meteors (shooting stars) that quickly dart across the sky, and the occasional passage of comets in their eccentric orbits around the Sun, which add yet another dynamic aspect to the night sky.

Of the earliest cosmologies, Aristotle's classic work *On the Heavens* stands out as the most influential, dominating Western philosophy from the time it was written (350 BC) up through the Middle Ages. Aristotle (384–322 BC) divided the celestial realm into a number of nested crystalline spheres to which the Moon, Sun, and planets were attached. The motions of these bodies were coupled to one another, and to the outermost sphere—the realm of the fixed stars—by a number of intermediate layers. A schematic illustration of Aristotle's Universe is depicted in Figure 1.1.

The whole assembly was animated by a "prime mover" who acted solely in the outermost sphere, which was thought to be immutable and eternal. As Aristotle put it in *On the Heavens*: "In the whole range of time past, so far as our inherited records reach, no change appears to have taken place either in the whole scheme of the outermost heaven or in any of its proper parts." In other words, although celestial objects in the more Earthly realms moved and varied (e.g., the Moon, the planets, meteors, and comets), the stars were strictly fixed and unchanging in his model.

One doesn't have to ponder long to realize that had Aristotle been correct, the study of astronomy would be quite limited. Fortunately, before long it became clear that the realm of the stars was far from the static one that Aristotle had imagined. In the Far East, and worlds away, ancient Chinese sky-watchers were already documenting the appearance of "guest stars" as early as 200 BC (Ho 1962). Figure 1.2 illustrates a page from the Chinese manuscript Lidai mingchen zouyi

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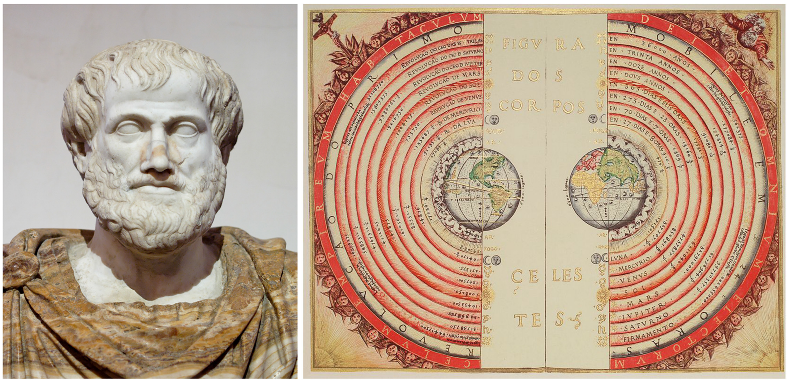
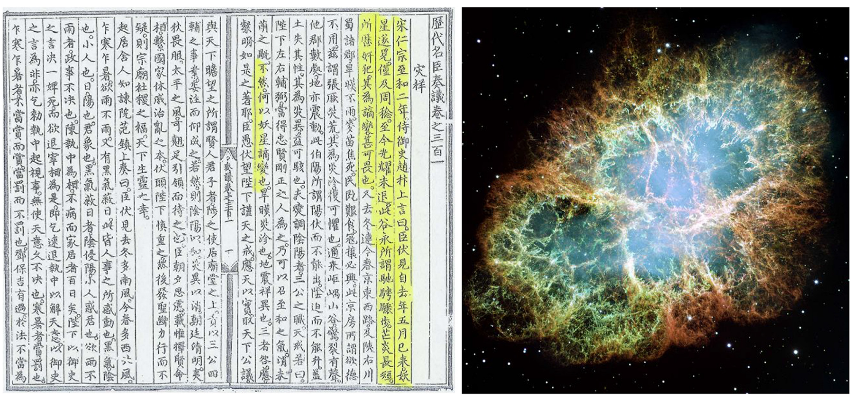


(a) (b)

Figure 1.1. (a) Aristotle (Roman copy in marble of a Greek bronze by Lysippos, c. 330 BC). (b) Bartolomeu Velho's 1561 depiction of a geocentric Aristotelian Universe. (Credit: Wikipedia Commons.)



(a) (b)

Figure 1.2. A page from early Chinese records, the Lidai mingchen zouyi from the year 1414. The highlighted passages describe the supernova of 1054 that ultimately produced the supernova remnant known as the Crab Nebula that we see today (right, courtesy NASA). The translation reads: 2nd year of the Zhihe reign period of Emperor Renzong of Song [1055]; Attendant Censor Zhao Bian submitted a letter saying: "Your servant considers that, since the 5th month of last year [when] the baleful star appeared, a full year has passed and until now its brilliance has not faded [lit. "retreated"]. This is what Gu Yong meant by 'its rapid movement, the variations in the length of its flaming rays, and the [asterisms] on which it has trespassed successively,' as a censorious anomaly it is greatly to be feared." (Pankenier 2006). (Credit: Wikipedia Commons.)

(circa 1414), describing the "guest star" of 1054, which was later determined to have produced what we now refer to as the Crab Nebula.

In contrast to the East, the medieval Western world seemed surprisingly disinterested in monitoring variation in the night sky. As is well known, it is remarkable that the supernovae of 1006 (the brightest supernova ever recorded) and 1054, which were estimated to have reached apparent magnitudes of −7.5 and −6, respectively, produced little attention in the West. We have to wait until the late

Renaissance or Early Modern period when two of the most spectacular "guest stars," now known by their Latin name, Novae Stella, or "new stars," were observed (within a span of just 32 years!): Tycho's nova of 1572 and Kepler's nova of 1604. Both of these objects were later recognized as supernovae, and were the most recent two such events seen in the Milky Way. A comprehensive discussion of the early history of nova observations can be found in the review by Duerbeck (2008).

As remarked by Warner (1995) in his classic book *The Cataclysmic Variable Stars*, despite the fact that recent observations show that roughly one nova reaches second magnitude or brighter every decade or so, only a single "guest star," Nova Vulpecula 1670 (CK Vul)[1] was recorded between 1604 and the time when Nova Ophuiuchi 1848 (V841 Oph) was discovered.[2] Apparently, the seventeenth and eighteenth centuries did not produce active communities of committed sky-watchers!

Interest in the transient sky picked up noticeably during the second half of the nineteenth century, thanks in large part to the application of photography to astronomy, and the number of novae discovered in the Milky Way skyrocketed. By 1900 a total of some 25 nova candidates had been reported. Table 1.1 summarizes 15 of the most secure nova identifications from that period. Despite the proliferation of nova discoveries, the true nature of novae remained obscure. There was no serious model to explain the phenomena, and it would be another century before the cause of nova eruptions would be finally established (see Chapter 4).

1.1 The Nebulae

The development of the telescope not only revolutionized the study of variable stars, but it opened up a new dimension to the study of the heavens: exploration of the enigmatic "nebulae." The nebulae, diffuse sources of light in the night sky, had been recognized since antiquity. Claudius Ptolemaeus (Ptolemy) (AD 100–170) described several entries in his second century AD star catalog as being "nebulous," many of which are now known to be star clusters. The great nebula in Andromeda, which at an integrated apparent magnitude of ~4 is visible to the unaided eye, was recognized as early as AD 964 by Abu I-Husain al-Sufi in his book "*On the Constellations of the Fixed Stars*" (Kunitzsch 1987). The number and variety of nebulous sources expanded considerably in the eighteenth and nineteenth century due in large part to the telescopic observations of Edmund Halley, Charles Messier, and especially the Herschels (William, his sister Caroline, and later William's son, John). The catalogs compiled over years by the Herschels, and augmented by John Louis Emil Dreyer, were eventually published as the *New General Catalog* (NGC) in 1888 (Dreyer 1888).

[1] Variable star designations are made in the order of discovery and begin with the letter R followed by the name of the constellation. The sequence continues through Z, then RR through RZ, SS to SZ, and so on to ZZ. The sequence then shifts to the beginning of the alphabet AA to AZ, BB to BZ, ending at QZ (the letter J is always omitted). This sequence contains 334 names, after which the variables are named V335, V336, etc. The nomenclature was devised by Friedrich Wilhelm August Argelander (1799–1875) in the nineteenth century.

[2] The identification of CK Vul as a classical nova is now questioned (Hajduk et al. 2013), however, Warner's comment remains accurate as Nova Sagittae 1783 (WY Sge) was not included in his discussion.

Table 1.1. Well Established 19th Century Novae

Nova	Name	Peak mag	Type	Discoverer	Reference
N Sgr 1900	HS Sgr	11.5 p	NB:	I. E. Woods	Woods (1927)
N Sgr 1900	AT Sgr	11.0 p	NA:	H. S. Leavitt	Pickering (1904)
N Sgr 1899	V1016 Sgr	8.5 p	NB:	A. J. Cannon	Pickering (1910)
N Aql 1899	V606 Aql	6.7 p	NA	W. Fleming	Fleming (1900)
N Oph 1898	RS Oph	4.3 v	NR	W. Fleming	Fleming (1901)
N Sgr 1898	V1059 Sgr	4.9 p	NA	W. Fleming	Fleming (1899)
N Car 1895	RS Car	7.0 p	N	W. Fleming	Fleming (1895)
N Nor 1893	IL Nor	7.0 p	NB	W. Fleming	Fleming (1893)
N Aur 1891	T Aur	4.2 p	NB	Th. D. Andersen	Copeland (1892a, 1892b)
N Per 1887	V Per	9.2 p	N	W. Fleming	Fleming (1891)
N Cyg 1876	Q Cyg	3.0 v	NA	J. Schmidt	Schmidt (1877)
N CrB 1866	T CrB	2.0 p	NR	J. Birmingham, W. Barker	Lynn (1866a, 1866b); Hind et al. (1866)
N Sco 1863	U Sco	8.8 v	NR	N. R. Pogson	Pogson (1908)
N Sco 1860	T Sco	7 v	N:	E. Luther, A. Auwers	Luther & Auwers (1860)
N Oph 1848	V841 Oph	4.2 v	NB	J. R. Hind	Hind (1848a, 1848b)

Note. N: Nova of undetermined speed class; NA: fast nova; NB: slow nova; NR: recurrent nova.

Dryer later supplemented the NGC catalog with additional nebulae in his *Index Catalog*, IC (Dreyer 1895, 1908).

By the mid-nineteenth century several thousand nebulae had been identified, but the true nature of these objects remained a mystery. William Herschel (1738–1822) had originally believed that the nebulae were simply unresolved clusters of stars. However, in 1790 he noticed that one roughly circular nebula (now known as NGC 1514, and one of the objects that he referred to as a "Planetary Nebula") was centered on a 9th magnitude star. He correctly associated the nebulosity with the central star, which caused him to re-think his conjecture that all nebulae were unresolved star clusters.

A major step forward in our understanding of the nature of nebulae was made possible in the 1840s thanks primarily to advances in telescope technology; in particular, to the construction of a giant 72 inch reflector, the "Leviathan" at Parsonstown by William Parsons (1800–1867), aka Lord Rosse, the 3rd Earl of Rosse (see Figure 1.3). The increased aperture and quality of the mirror figure compared with previous instruments dramatically improved the level of detail one could discern in the spatial structure of nebulae. Of the many discoveries made with the 72 inch telescope perhaps the most consequential was the discovery by Rosse of the spiral structure of M51 (see Figure 1.4). Over the next several decades, aided by the increasing application of photography to the study of nebulae, it became apparent that a spiral structure was not uncommon among the nebulae.

Just two decades after the discovery of spiral nebulae, a new and powerful tool was brought to bear in the attempt to understand the nature of the nebulae: the spectroscopic analysis of nebular light by William Huggins (1824–1910). Huggins

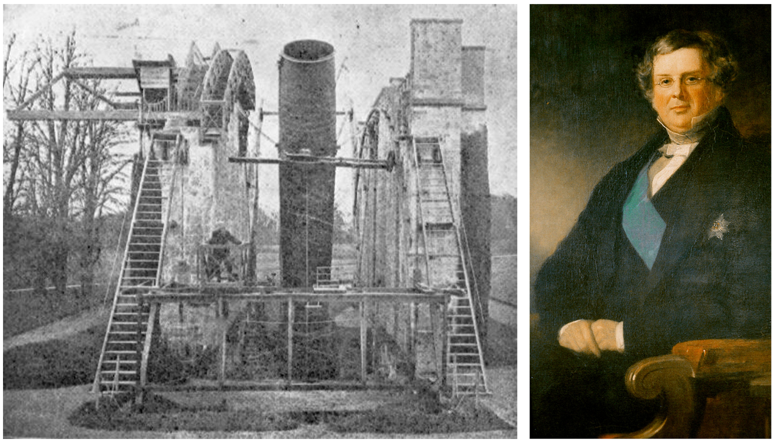


Figure 1.3. (Left) The Leviathan of Parsonstown was a 72 inch reflecting telescope used by William Parsons, 3rd Earl of Rosse, in his study of spiral nebulae. It was the largest telescope in the world until the completion of the Mount Wilson 100 inch "Hooker" reflector in 1917 (undated photo). (Right) Portrait of Lord Rosse by Stephen Catterson Smith. (Credit: Wikipedia Commons.)

Figure 1.4. A Sketch of the spiral structure of M51 by Lord Rosse (left) compared with a modern image from the *Hubble Space Telescope* (right, Credit: ESA/Hubble). (The Rosse sketch is courtesy of the Birr Castle Archives from a folio scrapbook entitled "Astronomical Drawings of Lord Rosse," Rosse Papers, L/3/2.)

(shown in Figure 1.5) conducted spectroscopic observations that revealed many nebulae to have bright-line (emission) spectra, therefore suggesting that they were gaseous in nature (Huggins & Miller 1864). Quoting from Huggins & Miller (1864) concerning his spectroscopic analysis of NGC 6543, the "Cat's Eye" planetary nebula in Draco: "I then found that the light of this nebula, unlike any other ex-terrestrial light which had yet been subjected by me to prismatic analysis, was not composed of light of different refrangibilities, and therefore could not form a spectrum. A great part of the light from this nebula is monochromatic, and after passing through prisms remains concentrated in a bright line occupying in the instrument the position of that part of the spectrum to which its light corresponds in refrangibility."

Thus, Huggins had established that a substantial fraction (roughly a third) of the nebulae were in fact *not* unresolved systems of stars as Herschel had long assumed,

Figure 1.5. Portrait of Sir William Huggins by John Collier in 1905. (Credit: Wikipedia Commons.)

but were bright (emission) line objects such as the Orion nebula. Nebulae that displayed strong, bright lines at 4959 and 5007 Å (which wouldn't be understood for another 75 years as forbidden lines of doubly ionized oxygen) were often the planetary nebulae found by Herschel, and based on their color, were referred to by Huggins as the "Green Nebulae." The remaining nebulae apparently characterized by continuous spectra were referred to as the "White Nebulae." Once photographic images of the White Nebulae became common, it became clear that most of these objects were in fact Spiral Nebulae. It is worth noting that Huggins has the distinction of being the first to obtain a spectrum of a nova (Huggins & Miller 1866), specifically the recurrent nova T Corona Borealis discussed further in Chapter 4.

Observations of nebulae compiled in the *General Catalogue of Nebulae and Clusters of Stars* published by Sir John Herschel in 1864 confirmed what had been suspected for some time, namely that the nebulae tended to avoid portions of the sky with a high density of stars, i.e., the Milky Way (or *Via Lactea*; Abbe 1867). The region populated by the nebulae was subsequently described by Proctor (1869) as the "Great Vacant Zone," or the "Zone of Dispersion." Thus, the complementary spatial distributions suggested that nebulae and stars were not necessarily associated with one another as Herschel had originally believed.

As the nineteenth century was drawing to a close, the number of nebulae was increasing dramatically as a result of the implementation of photographic surveys. The observations of James E. Keeler (1857–1900) using the Lick Observatory's Crossley reflector suggested that the number of spiral nebulae distributed over the whole sky accessible to the Crossley telescope would number of order 120,000 (Keeler 1899). Whatever their nature, it was already clear that the spiral nebulae represented a major constituent of the visible Universe.

1.2 Novae in Nebulae!

In 1885 a "nova," S Andromedae (S And), was observed close to the center of NGC 224 (M31), the great nebula in Andromeda. Official credit for the discovery of S And on 1885 September 20 would go to Hartwig (1885); however, the object was apparently observed in the preceding days by a number of amateur astronomers (see de Vaucouleurs & Corwin 1985 for a detailed account of the discovery). Little did Hartwig know that this object was to play a pivotal role in the debate on the nature of the spiral nebulae that would unfold over the next 40 years. It wouldn't be until the 1930s that the true nature of S And would be revealed as a supernova in M31. The remnant of explosion was finally recovered more than a century after S And erupted (see Figure 1.6). It would be another decade before the next supernova was discovered in the field of a spiral nebula.

During the latter part of the nineteenth century, Edward C. Pickering (1846–1919), director of the Harvard College Observatory (HCO) from 1877 to 1921, employed a staff of mostly female assistants (colloquially known as "computers"), who were trained to do routine data processing tasks, e.g., measuring the positions, brightnesses, and colors of stars. While some of the women had formal training in the sciences, not all of them did. One notable example was Williamina Fleming née Stevens (1857–1911). Williamina Stevens was born in Scotland in 1857, but immigrated to the United States with her husband, James Fleming, when she was 21. Shortly after arriving in Boston, Mrs. Fleming, who was pregnant at the time, was abandoned by her husband. Although she had been previously employed as a teacher in Scotland, times were now more desperate, and in 1879 Fleming applied

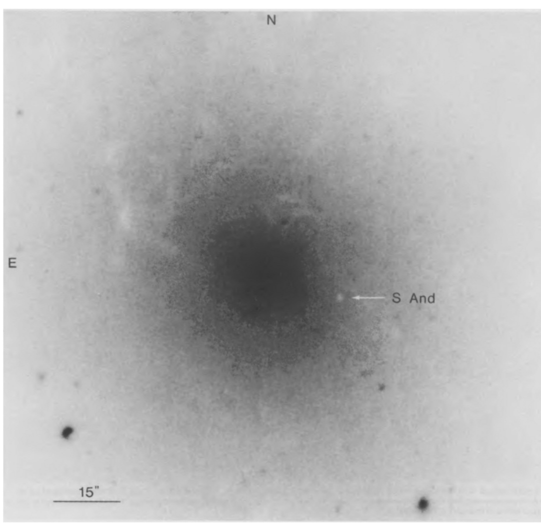


Figure 1.6. The remnant of S Andromadae as revealed by isolating Fe I emission commonly observed in Type Ia supernovae. Note the proximity of S And to the nucleus of M31. (Reproduced from Fesen et al. 1989. © 1989. The American Astronomical Society. All rights reserved.)

for and was offered a position as E. C. Pickering's maid. At the time, Pickering employed several men as assistants at HCO who primarily were charged with the tedious and repetitive work of examining and classifying the spectra of stars. Pickering was not particularly impressed by the quality of work provided by his assistants, and was said to have remarked that even his "Scottish maid" could do better. Apparently Pickering was not being facetious, and in 1881 he hired Williamina Fleming as a "computer" at HCO. Shortly thereafter, Fleming was put in charge of hiring additional women to help with the work, and the group known as "Pickering's Harem" was born (see Figure 1.7).

Over the next several years, Fleming would go on to hire such notable women as Annie Jump Cannon and Henrietta Levitt, two women who would later make significant contributions to astronomy in the areas of stellar classification and the Cepheid period–luminosity relation, respectively. Fleming herself made many important contributions, including classifying the majority of stellar spectra used in the Henry Draper Catalog (published in 1890). She would also make many notable discoveries, including the first recognition of the "Horsehead Nebula" in 1888 on a plate that had been taken years earlier by Pickering. Her discoveries also included over 200 variable stars, several of them novae (see Table 1.1), one of which was the second "nova," after S And, to be associated with a spiral nebula. That apparent nova, Z Centauri, erupted near the center of NGC 5253, and reached

Figure 1.7. Staff at work at the Harvard College Observatory Computer room in 1891. Known informally as "Pickering's Harem": the women were engaged in a variety of data analysis tasks. HCO director E. C. Pickering looks on (left), with Williamina Fleming (standing center). (Image courtesy of the Harvard University Archives (HUV 1210 (9-4), olvwork289689).)

magnitude 7.2 sometime between 1895 June 14 and July 8. It was subsequently discovered by Mrs. Fleming while examining plates on December 12 of that year (Pickering & Fleming 1896). As it happened, novae were to play a major role in the birth and development of extragalactic astronomy.

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