Astronomy in the Long 19th Century:

The rise of astrophysics and cosmological speculations

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History of Modern Physical Sciences

Positional Astronomy

Astronomy is the oldest exact science. From ancient times it was concerned with recording the positions of celestial bodies and using mathematical models to predict their positions for times that were not, or have not yet been, observed. This is now called *positional astronomy*. Although astronomy in the 19th century started to employ new – essentially physicals and chemical – methods, there was also much development in positional astronomy.

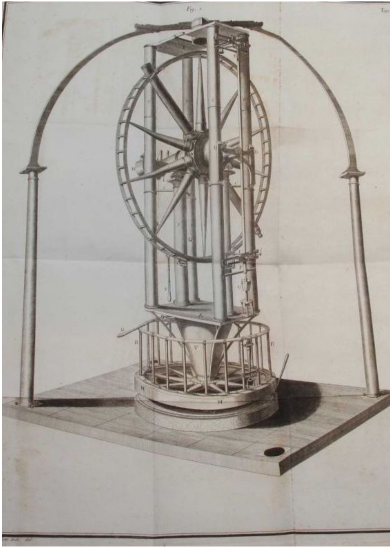
New and more powerful telescopes were built. New planets, and other celestial objects, were discovered. The proper motions and distances of some stars were measured. New celestial objects of various kinds were discovered and cataloged. New observatories were built and run more and more like factories, or corporations, with devision of labor and attention to the errors of the astronomers themselves.

English and German Instruments

At the beginning of the 19th century, most of the best astronomical instruments were made in Britain. By the end of the century, the best shops were in the German lands.

For example, in 1801, the Catholic priest G. Piazzi (1746–1826), working at the royal palace of Palermo, Sicily, used an altazimuth circle made by J. Ramsden (1735–1800) in London, to discover the dwarf planet Ceres in what later came to be known as the astroid belt, between Mars and Jupiter.

In the late 1820s, F.G.W. Struve (1793–1864), working at the Dorpat Observatory, Livonia, Russia, used a 24cm refractor made by J. Fraunhofer (1787–1826) in his Munich optical workshop, to survey the sky at $-15°$ declination from the celestial pole, and produced a description of some 120,000 stars.



Ramsden's Palermo Circle

Fraunhofer's Dorpat Refractor

The Herschels

William Herschel (1738–1822) was a German immigrant to England, following the Seven Years War (1756–1763), where he made a living copying sheet music and teaching and performing organ music. He made a series of increasingly larger telescopes, and with the help of his sister, Caroline Herschel (1750–1848), became a highly proficient observational astronomer. He made numerous surveys of the heavens, cataloging what he found – and regarded himself as a sort of *natural historian* of the skies.

In 1781, W. Herschel discovered Uranus, with a self-made reflector. He and Caroline discovered numerous comets and nebulae – in this way adding many more objects to the list of 110 objects compiled by Charles Messier (1730–1817) in 1784. William produced a number of interesting speculations on the structure and nature of the nebulae and the Milky Way.

Caroline Herschel.

William and Caroline Herschel at work on the mirror of a reflecting telescope. While William polishes the mirror, Caroline applies lubricant.

A lithograph print in color, 1896.

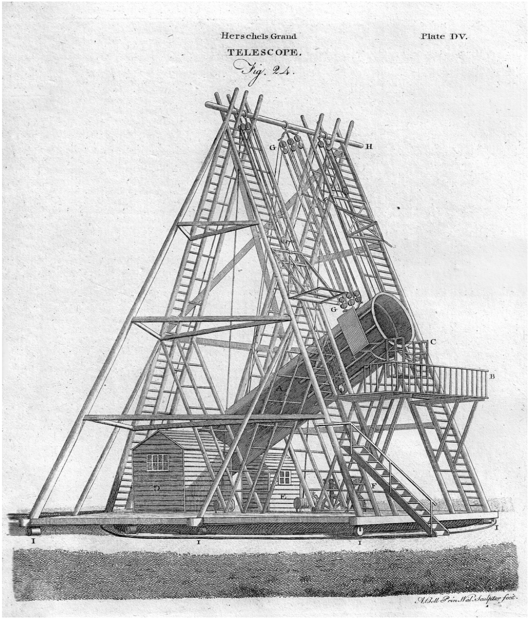
Astronomy as Natural History

W. Herschel proposed that we could study the history of stars and nebulae by considering their variety and trying to organize them into some *classification scheme*.

Herschel, "Catalog of a Second Thousand…," 1789

"The heavens … resemble a luxuriant garden which contains the greatest variety of productions in different flourishing beds; and one advantage we may at least reap from it is, that we can … extend the range of our experience to an immense duration … It is not almost the same thing whether we live successively to witness germination, blooming, foliage, fecundity, fading, withering, and corruption of a plant, or whether a vast number of specimens, selected from every stage through which the plant passes in the course of its existence, be brought at once into our view?"

At this stage, there was still no clear principle by which to know the age of a celestial object.



William Herschel's 40-foot (12m) reflector.

With this telescope he discovered that nebulae he had seen with his earlier 20-foot (6m) reflector could now be *resolved* into many more stars – causing him to revise his views on the nature of the nebulae.

Stellar Parallax

Since the time of Galileo it had been recognized that if the earth was in orbit, it should be possible to detect *annual stellar parallax*. Throughout the 17th and 18th century, a number of astronomers had looked for annual parallax, and had realized that the velocity of light would also have to be taken into account as creating an aberration of stellar position.

In 1837 and 1838, F.G.W. Struve and F.W. Bessel (1784–1864), both announced observable stellar parallax, following some years of investigation. Struve used a Fraunhofer refractor, and Bessel used a Fraunhofer "heliometer" – a telescope with a double view – to produce their results. Struve found about 0;0,8° of arc for Vega, and Bessel found about 0;0,20° of arc for 61 Cygni.

This meant that by such methods, the radial distance of a few objects could be determined, but that of the vast majority of objects was still completely unknown.

Proper Stellar Motion

With Newton's work, it became clear that the ancient concept of "fixed stars" was a purely theoretical conception and the question of whether or not stars had a proper motion would have to be investigated *empirically*. In the 18th century, a number of astronomers undertook this task – in a new era of greatly improved accuracy due to James Bradley's (1693–1762) discovery of the aberration of light.

In 1783, W. Herschel put together a large number of proper motions and argued that the solar system was moving towards the constellation Hercules. There was debate about this for almost a century until F.W.A. Argelander (1799–1875) published some 390 proper motions that essentially confirmed Herschel's position.

In 1844, Bessel pointed out that the proper motion of Sirius wobbles, and argued that it must be orbiting another small, "dark star." Subsequently, many more double stars were found.

Like Father, Like Son

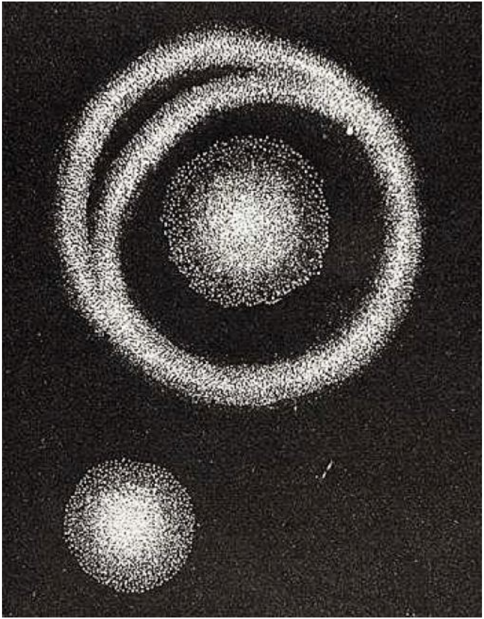
John Herschel (1792–1871), the son of William, was a leading figure in the movement to reform British mathematics, as a member of the Analytical Society, and British astronomy, as a member of the Royal Astronomical Society. In his father's later years, he returned home to take up his father's work.

He collaborated with James South (1785–1867) in producing a catalog of 380 double stars. He reexamined 2,300 nebulae and clusters, using his father's refurbished 20-foot (12m) reflector. He traveled to the Cape of Good Hope, South Africa, with the 20-foot reflector, to investigate the southern sky. He produced a catalog of 1,700 nebulae and clusters and 2,100 double stars.

In this process, he was able to examine M51 – now known as the Whirlpool Galaxy, but this was before the *concept of galaxy*. He made a detailed study and produced a diagram, and remarked, in passing, "Perhaps this is our Brother System."

John Herschel's drawing of M51. Notice the great regularity of the figure.

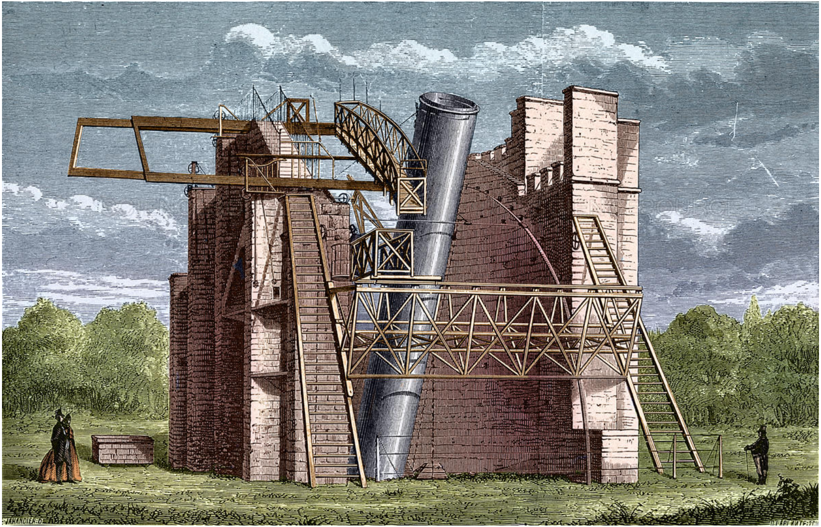
J. Herschel spent a fair bit of time observing this object, which had been cataloged by Messier, but was not well seen by anyone before him. He pointed out that to an observer that was inside such an object it would probably appear to them very much as the Milky Way appears to us.



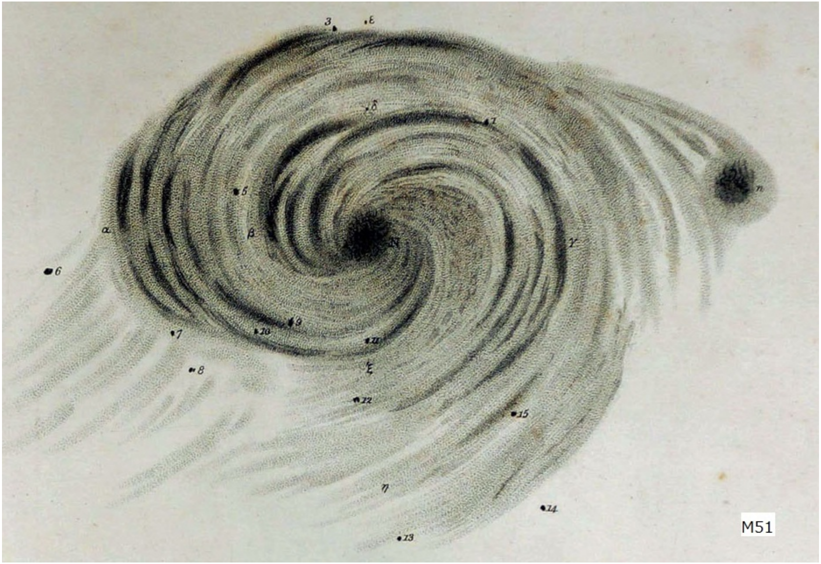
Bigger and Bigger

The last of the great 19th-century reflectors was made by William Parsons, Lord Rosse (1800–1867), of King's County, Ireland. In the 1840s, he had a massive reflector built, with a 6-foot (1.8m) opening. Because it was the largest telescope made up to that time, he had to develop many of the techniques of construction himself.

A major feature of Rosse's work was his attempt to resolve the nebulae. Because he believed that all nebulae were simply collections of stars, he believed that in principle they should all be resolvable into points of light with a sufficiently powerful telescope. Hence, he followed up on the work of J. Hershel and produced many drawings of the nebulae that Herschel had cataloged. He saw, for example, that M51 is spiral in shape and contains many points of light. He took this as support for his belief that all nebulae must actually be collections of stars.



The "Leviathan at Parsonstown," Lord Rosse's giant reflector



Rosse’s diagram of M51

A modern “photograph” of M51, made with the Hubble Telescope

Industrial Observatories

During the 19th century, national observatories began to be run more like commercial firms than former scientific laboratories. The directors, such as Adolphe Quetelet (1796–1874), in Brussels, Johann Encke (1791–1865), in Berlin, and George Airy (1801–1892), in Greenwich, were known as much for their *managerial skills*, as for their scientific achievements.

They divided up the work into discrete tasks and imposed a strict division of labor – often in gendered and age-related hierarchies. Observation was separated from computation, and everything was streamlined and regularized.

These observatories developed scientific, and stochastic, methods for treating the idiosyncrasies of observers, and subjected the observers themselves to statistical study. They developed the mathematical tools to study observational error as a branch of statistics, so that this too could be handled.

Astronomical computers

The “computers” of the Paris Observatory, late 19th century.

Physical Astronomy

In the 19th century, people began to turn the methods of the physical sciences to new applications in astronomy. They used classical mechanics to develop models for stellar and solar formation, they used the new science of thermodynamics to model how celestial bodies might change over time, and perhaps most importantly, they began to use new empirical methods to study the physical and chemical composition of the bodies they had previously only observed visually.

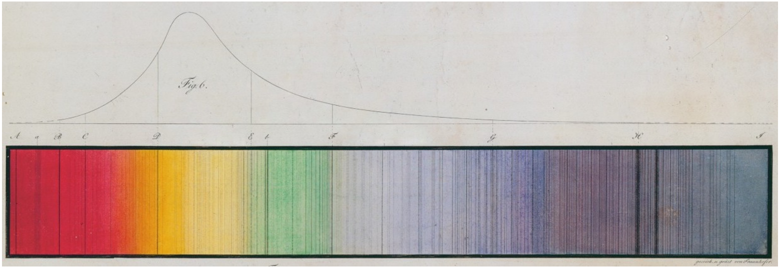
Huggins, "The New Astronomy…," 1897

"Then it was that an astronomical observatory began … to take on the appearance of a laboratory. Primary batteries … were arranged outside one of the windows; a large induction coil stood mounted on a stand on wheels so as to follow the positions of the eye-end of the telescope …; shelves with Bunsen burners, vacuum tubes, and bottles of chemicals … lined its walls."

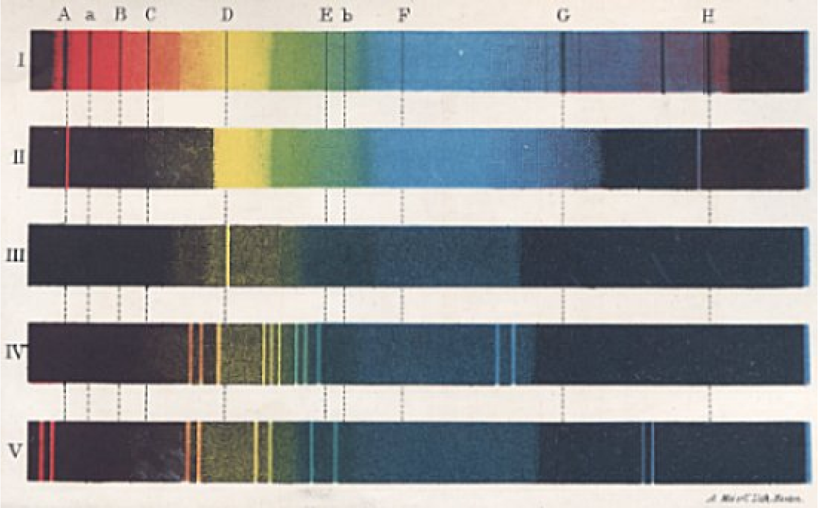
Dark Lines in the Spectra

Around the turn of the 19th century, people had begun to notice that if sunlight were passed through a very narrow slit before being refracted, *dark lines* appeared in its spectrum.

These lines were studied by Joseph Fraunhofer, a lens maker and optical glass expert, in 1817. He studied the light from stars, candles and other substances and used a telescope and micrometer to determine the exact locations of characteristic dark lines – which came to be known as *Fraunhofer lines*.



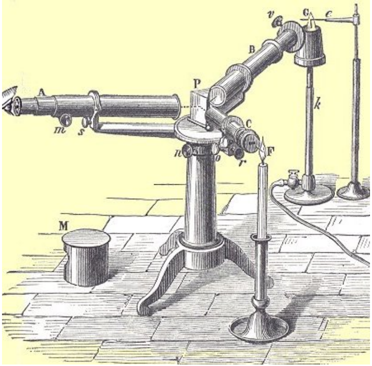
Fraunhofer's diagram of the solar spectrum



I: the sun; II: a blueish star; III: a candle; and so on

In the 1850s, Gustav Kirchhoff (1824–1887), a physicist, and Robert Bunsen (1811–1899), a chemist, began to use these lines to analyze the chemical composition of elements and compounds by burning them. They found that when a chemical is heated to incandescence, it gives off a *characteristic* colored light.

In 1859, Kirchhoff found that the solar spectrum viewed through a sodium flame, had an even darker D line.



The Physics of the Spectrum

Kirchhoff and Bunsen argued that each element, when heated, emits light only at certain specific and characteristic wavelengths. And when light at these wavelengths is passed through a vapor of the same substance, it is then absorbed (not transmitted). That is, *elements absorb the same light that they emit*. These patterns could then be taken as individual *identifying characteristics* – a sort of fingerprint for the chemical elements.

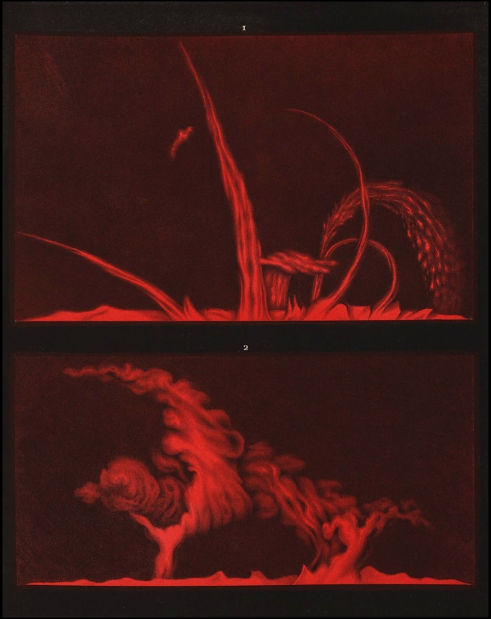
In 1860, they discovered the element Caesium, based on its blue spectral lines. In the following year, Rubidium and Thallium were discovered using a spectrograph.

Because some the lines in stellar spectra could not be identified in the lab, a number of new elements were proposed, such as "Coronium," "Nebulium," and "Asterium." (The full explanation for these lines would have to wait for quantum theory.)

By simulating a solar eclipse through instrumental means in the telescope, astronomers were able to study *solar prominences*.

By passing the telescopic images of the prominences to a spectrograph, they were able to study the chemical elements in the solar atmosphere.

(Solar Prominences. Drawings made at the Harvard Collage Observatory.)



Helium

By studying solar prominences, Jules Janssen (1824–1907) and Norman Locklear (1836–1920), independently, discovered a new line near the sodium D lines, called D_3. This line did not correspond to any known chemical element, and hence they thought it might correspond to a new element that existed only in the sun. Locklear called it Helium.

Locklear also found the D_3 line in the spectra of other stars, and he proposed that in stars the chemical elements are broken down to smaller and more fundamental forms of matter. Since, this supposed helium was considered to be either extremely rare, or not found on the earth at all, most chemists did not consider it to be real – or at least not a real element.

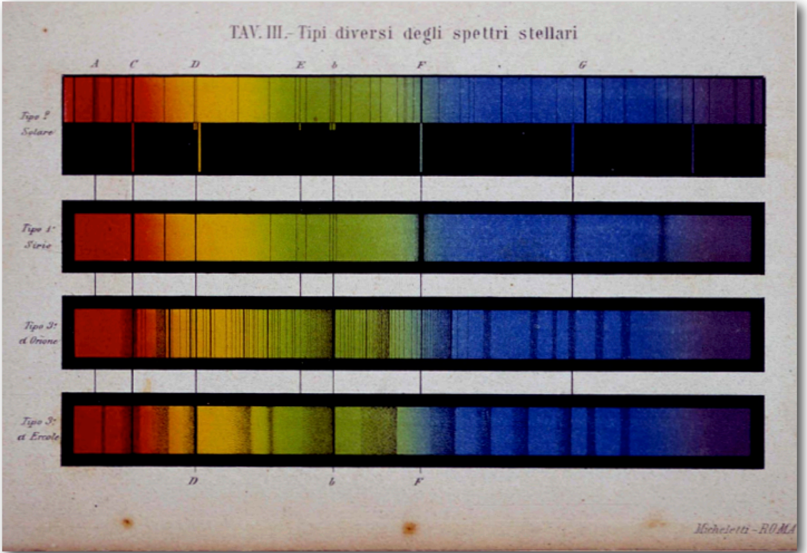
This later changed in 1895, when William Ramsay (1852–1916) identified helium given off from the terrestrial mineral cleveite, UO_2. Nevertheless, since it was inert it was considered to be extremely rare and little more than a curiosity.

The Spectra of Stars and Nebulae

In the 1860s and 70s, astronomers began to study the *spectra* of stars and nebulae. William Huggins (1824–1910), working in his home observatory, extensively studied the nebulae. He argued, on this basis, that some of them were gaseous – that is, not resolvable into a multitude of stars – and proposed a new element that he called "Nebulium."

The process of classifying stellar spectra was begun by P.A. Secchi (1818–1878) in the 1860s, and brought to its final form by Annie Cannon (1863–1941), originally one of the "computers" at the Harvard College Observatory. In 1901, Cannon published a list of the spectra of over 1,000 stars, divided up into 10 classes, in very nearly the classification still used today. This work was done using data produced by another new technique of astronomy developed in the 19th century – photography.

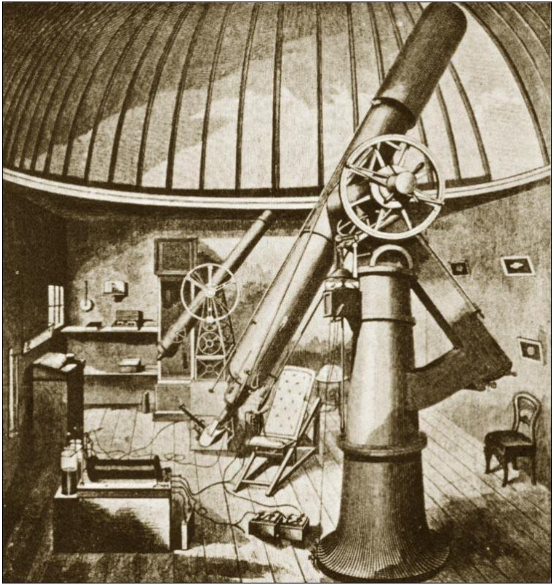
Secchi's Stellar Spectra



2: like the sun; 1: like Sirius; 3: like Beteleuse; 4: like α Herculis.

W. Huggin’s refractor telescope with a spectrograph objective.

Here we see the astronomical observatory as laboratory: batteries and Leiden jars are attached to the refractor.



The Doppler Effect on Absorption Lines

In 1842, Christian Doppler (1803–1853) gave a theoretical argument that if a light source, like a star, is moving relative to an observer, then the radial velocity will be computable by a relationship involving the velocity of light and a change in wavelength, $\lambda = c/f$. Hence, in principle, if one knows the speed of light, c, and the *stationary wavelength* of a Fraunhofer line in a given star, it should be possible to compute its velocity towards or away from us – its radial velocity.

In 1868, W. Huggins found that Sirius is red-shifted so as to give a radial velocity of about -47.3 km/s – that is, away from us. (By modern computations, this is an order of magnitude too fast.) Following this, in the 1890s, a number of astronomers in Prussia and the US determined the radial velocity of a handful of stars to a high degree of precision and accuracy.

The Photographic Revolution

The lengthy development of photography through the 19th century had an effect on many of the sciences, but its effect on astronomy was profound. Photography allowed astronomers to visualize – and hence see – things that they could not see with their eyes, even looking through the best telescopes. Through the 1850s to 70s, astronomical photography was mostly advanced by amateurs, and they were mostly concerned with the techniques of photography itself.

Starting from about the 1880s, however, astronomers began to use photographs to make visible things that could not otherwise be seen – by using longer exposures to collect more light, by optimizing the photographic plate to the emissions of the celestial object, or by visualizing part of the spectrum that the human eye cannot see, such as ultraviolet light. In this process, it came to be understood that observation time was better spent producing permanent images, which could then be later studied at leisure, and repeatedly.

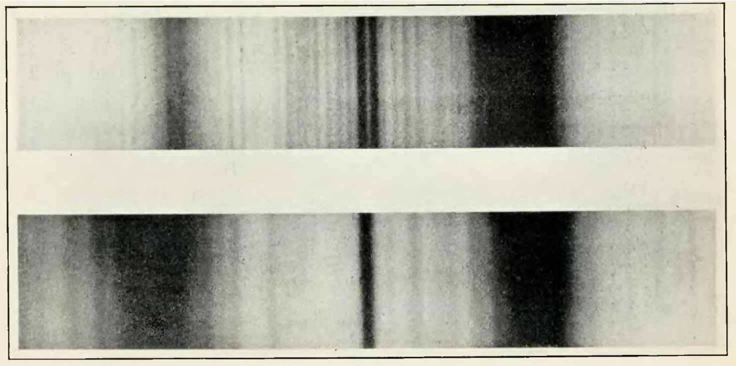
D. Gill's photograph of the great comet of 1882, showed far more stars than were visible to the eye in the telescope, and convinced astronomers of the value of photography.

H. Draper's 1882 photograph of the Orion Nebula, M42.

Exposed for 51 minutes.

I. Robbert's 1888 photograph of the Andromeda Nebula (now Galaxy), M31.

Taken on a Grubb's silver-on-glass reflector. Exposed for 3 hours.



A photograph of the spectrum of β Aurigae taken at Harvard College Observatory, 1889.

The Beginnings of Cosmology

There was no discipline known as cosmology in the 19th century. Nevertheless, astronomers and natural philosophers used the new developments in astronomy and physics to speculate about both the structure and the historical formation of the whole cosmos.

A number of different theories were put forward to explain the overall structure of the Milky Way, and other nebulae, as well as to describe how these structures had formed over time. The new field of thermodynamics was used to address the question of the formation and age of the sun and other stars, and to discuss the long-term evolution of the cosmos.

A number of paradoxes or anomalies that could not be explained using classical physics were raised and discussed, but at the time they were not taken very seriously.

Cosmological Speculations

In 1755, Immanuel Kant, the idealist philosopher, published his *Allgemeine Naturgeschichte und Theorie des Himmels*, meant for a general readership, and which described the history of the cosmos as resulting purely from natural laws.

He speculated that the universe began with a primeval, divinely created chaos of particles at rest, distributed uniformly throughout an infinite void. Then, the gravitational forces acted more strongly on denser particles and repulsive forces kept them from forming a single mass.

He claimed to be able to explain the formation of the solar system and the Milky Way as a large disk of star systems revolving around its own center, and orbiting some other, common center. He suggested that the nebulae were other "universes, and so to speak, Milky Ways." The cosmos consisted of "island universes" floating in an empty void.

The Nebular Hypothesis

Following the ideas of the French naturalists G.-L.L. de Buffon and G. Cuvier, Laplace, in his 1796 *Exposition du système du monde*, put forward a narrative of the evolution of the solar system as forming naturally out of a primeval cloud, or nebula.

He argued that comets and planets, and their satellites, formed through the condensation of an atmosphere or evaporating fluid, and went on to make a stochastic argument that the planes of the orbits could not have been produced by chance, but must have been the result of some sort of physical cause.

Throughout the 19th century, there was debate about this hypothesis, and it was hoped that better and better telescopes could provide an empirical answer to the question of whether or not star systems formed from primeval gas clouds. As we saw above, the new methods of spectroscopy were also used in this debate.

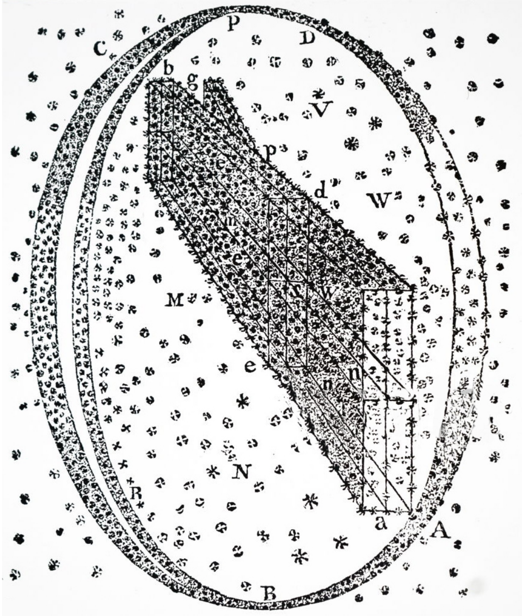
The Milky Way Universe, or an Island Universe

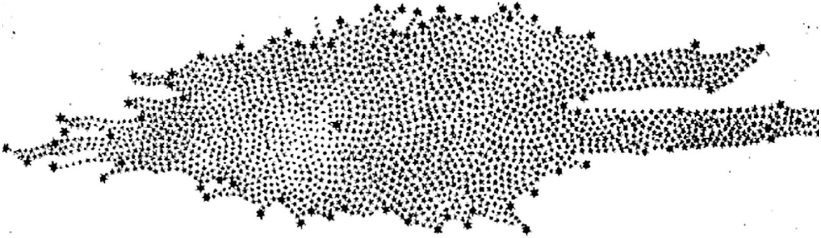
Following the speculations of natural philosophers and the empirical studies of Herschel and others, astronomers began to develop theories of the structure and arrangement of the Milky Way. Although there was still no way to know how big it was, by the end of the 19th century, there was a growing group of astronomers who believed that it was shaped like a spiral, and that we are not in its center.

There were two competing theories about the role of the Milky Way in the universe as a whole. Going back to Kant, the *island universe* hypothesis claimed that the Milky Way is just one of many "universes," which are all, like the Milky Way, made up of a multitude of individual stars, but appear to us as nebulae. The other, the hypothesis of the *Milky Way universe*, proposed that the Milky Way made up the entire universe and that the nebulae were clouds of gas and star clusters inside the Milky Way itself. In the 19th century, there was no way to decide.

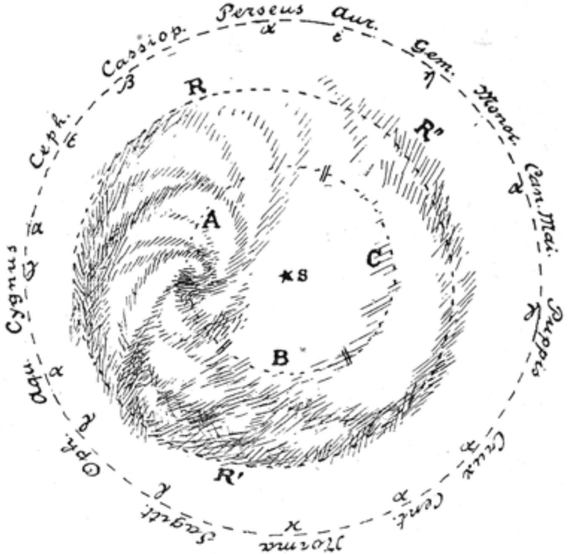
In a paper of 1785, W. Herschel sought to determine the structure of the Milky Way by taking sample counts of the stars in various regions of space.

He argued that the Milky Way must have roughly the shape depicted in this figure, with the solar system at *S* on plane *de*. The figure is purely schematic.





Based on the visual structures that he could see with this telescopes, Herschel produced a hypothesized cross-section of the Milky Way. The darker dot near the center is the location where he proposed to place our solar system.



Cornelis Easton, a Dutch journalist, put forward a new theory of the Milky Way in a 1900 review article for the *Astrophysical Journal*.

S marks the location of the solar system, and the center of the galaxy is over to the left, between *A* and *B* on circle *ABC*.

The Problem of a Dark Night Sky

In the 18th century, it was realized that a dark night sky is incompatible with an infinite universe filled with stars interspersed in void spaces. Some natural philosophers, such as J.-P.L. de Chéseaux (1718–1751) and H.W. Olbers (1758–1840), attempted to explain the dark night sky by supposing that as light travels through space it is absorbed (its intensity diminished by 3%) by the medium through which it travels – an ethereal fluid, the ether, or dust and gas. But thermodynamics showed that this was impossible, because the medium would absorb too much heat.

Another possible solution was to claim that more distant matter is inherently less luminous – but this struck people as artificial.

Another possibility, put forward in the mid-century, was to suppose that the universe is not eternal, so that only light from the beginning of the universe has had time to reach us – but this seemed highly speculative.

The Problem with Gravity

In the late 19th century, Carl Neumann (1832–1925) and Hugo von Seeliger (1849–1924) showed that in an infinite universe even the slightest differences in mass distribution would lead to an undefined function for potential energy – that is, singularities in the function for potential energy. Seeliger then showed that a purely Newtonian universe would predict that some motions that started with a finite velocity would reach an infinite velocity in a finite time. This was clearly a problem.

There were three main ways to try to resolve this problem: (3) the law of gravity was changed so that it dropped off at great distances, (2) the density of matter was assumed to be arranged so as to drop off further from us, or (3) the total mass of the universe was limited to the zone around us. Although theorists worked on all of these, they were fairly fringe topics, and most astronomers simply ignored the problem.

Overview

In the 19th century, the traditional methods of positional astronomy were extended through the development of newer and more powerful telescopes, the collection of data through photography, and the introduction of more efficient work-flow through division and regularization of labor.

New methodologies were also introduced through the physical sciences. It became possible to know something about the chemical construction of celestial objects through spectroscopy, and physical theory was used to advance theoretical models to explain the evolutionary development of the sun and other stars.

Finally, natural philosophers, astronomers and physicists began to turn their attention to general topics concerning the overall cosmos – such as its development in time and its overall structure.